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IEA Wind TCP Task 49

The IEA Wind Task 49 Reference Floating Wind Array Design Basis

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Authors:

Matthew Hall
National Renewable Energy Laboratory, United States

Ericka Lozon
National Renewable Energy Laboratory, United States

Fiona Devoy McAuliffe
University College Cork, Ireland

Matteo Baudino Bessone
Delft University of Technology, Netherlands;
Offshore Renewable Energy Catapult, United Kingdom

Ilmas Bayati
PEAK Wind, Denmark

Malcolm Bowie
First Energy Development / Encomara, United Kingdom

Pauline Bozonnet
IFPEN, France

Michel Castagné
IFPEN, France

Ju Feng
Technical University of Denmark, Denmark

Stein Housner
National Renewable Energy Laboratory, United States

Marek Jan Janocha
University of Stavanger, Norway

Zhiyu Jiang
University of Agder, Norway

Yong Yook Kim
Institute for Advanced Engineering, South Korea

Donghee Ko
Shimizu Corporation, Japan

Konstanze Kölle
SINTEF, Norway

Chern Fong Lee
University of Stavanger, Norway

Malakonda Reddy Lekkala
National Renewable Energy Laboratory, United States

Guodong Liang
University of Agder, Norway

Mohammad Youssef Mahfouz
University of Stuttgart, Germany

Madhan Mohan
Interocean, United Kingdom

Daniel O'Connell
Bureau of Ocean Energy Management, United States

Muk Chen Ong
University of Stavanger, Norway

Julien Prieur
SBM Offshore, Monaco

Vishnu R. N. Rajasree
NTNU, Norway

Anja Schnepf
University of Stavanger, Norway

Thor Snedker
PEAK Wind, Denmark

Jean Thurston-Keller
Bureau of Ocean Energy Management, United States

Chris Wright
Gavin & Doherty Geosolutions, Ireland

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List of Acronyms

ABS	American Bureau of Shipping
AEP	annual energy production
AHTS	anchor handling tug support vessel
ALS	accidental limit state
API	American Petroleum Institute
CLV	cable laying vessel
CTV	crew transfer vessel
DLC	design load case
DNV	Det Norske Veritas
DTU	Technical University of Denmark
FLS	fatigue limit state
FOWT	floating offshore wind turbine
GW	gigawatt
HLV	heavy-lift vessel
HMPE	high-modulus polyethylene
Hz	hertz
IEA Wind	International Energy Agency Wind Technology Collaboration Programme
IEC	International Electrotechnical Commission
kg	kilogram
km	kilometer
kN	kilonewton
kV	kilovolt
LCOE	levelized cost of energy
m	meter
MBL	minimum breaking load
MCF	manufacturing complexity factor
mm	millimeter
MN	meganewton
MW	megawatt
N	newton
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
RMS	root-mean-square
ROSCO	Reference Open-Source Controller
ROV	remotely operated vehicle
SOV	service operations vessel
SWL	still water level
t	tonne
TDP	touchdown point
TLP	tension-leg platform
ULS	ultimate limit state
W	watt
WACC	weighted-average cost of capital
WP	Work Package

Executive Summary

This report provides a general design basis for the development of reference floating wind farm designs. These reference array designs will extend the scope of existing reference floating wind turbine designs to facilitate research on array-level floating wind technology challenges and innovations. The design basis promotes coordination and consistency in developing the reference array designs.

International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 49 on Integrated Design of Floating Wind Arrays is an international collaboration aiming to advance the development of large-scale floating wind farms by providing open-access resources to the research and development and planning communities. The work of Task 49 focuses on array-level challenges related to the colocation of many floating wind turbines; their layouts, mooring systems, and cabling systems; failure risks; logistical considerations; marine spatial planning needs; and future research needs and innovation directions. Task 49 is a 4-year effort that began in December 2021 and that includes representatives from project developers, technology providers, universities, consultancies, regulatory agencies, and research institutions from 12 countries. Its four work packages (WPs) have the following objectives:

- WP1: Curate a set of site conditions representative of the global floating wind pipeline
- WP2: Develop reference array designs for typical site conditions and technology types
- WP3: Catalogue array-level failure risks, consequences, and mitigation strategies
- WP4: Identify critical innovation opportunities and marine spatial planning requirements.

This design basis report is the first major output from WP2, and it presents the approach for developing reference floating wind array designs. The contents of this design basis were developed from extensive discussions among WP2 participants, including five working groups focused on different areas during the first phase, and a group of three design teams that identified more specific challenges and approaches during the start of the design phase.

Floating wind farm design involves many additional factors relative to individual floating wind turbines or fixed-bottom wind farms. Further, reference designs have different requirements than real projects. Therefore, this design basis contains important information and decisions to give definition to the reference floating wind array design effort.

Reference Array Design Scope

The main purpose of the reference designs is to support floating wind research and development at the array scale by serving as ready-made inputs for testing analysis methods, standardized designs upon which different innovations can be developed and evaluated, and baselines that different design variations can be compared against.

The scope of the design effort was converged upon after extensive input and discussion. The reference designs will use existing reference floating wind turbine/platform designs and will focus on developing mooring systems, cabling, and array layouts to suit different scenarios. The scope ends at the location of the substation to maintain focus on the array-level issues. By combining these array-level design aspects with existing established unit designs, floating arrays will be developed that extend from and maintain alignment with existing unit reference designs.

There are three reference design scenarios distinguished primarily by water depth:

- Shallow (60 m): Shallow-water mooring/cabling design challenges and innovations
- Intermediate (300 m): Seabed feature constraints on anchor positions, and innovations on anchoring
- Deep (800 m): Deep-water constraints on mooring layout and turbine spacing, use of suspended power cables and deep-water mooring innovations.

There will be a reference array design for each scenario that provides a regular design over uniform conditions. These reference designs will use the IEA Wind 15-megawatt (MW) reference wind turbine and will have approximately 1-gigawatt (GW) of installed capacity. Mooring systems will be semi-taut, catenary, and taut (respectively, for increasing depth). Lazy-wave dynamic cables will be included, with the addition of fully suspended dynamic array cables in the deep case. The layout and cabling will follow a regular grid with division into several modules that are repeated to reach the 1-GW total. These first designs will use the VolturnUS-S semisubmersible platform. After these baseline reference designs are created, some design variations are recommended for each scenario to provide more specialized and inclusive reference designs, such as by accounting for seabed variations or using spar or tension-leg platforms.

The design stage in WP2 focuses on "component design," where subsystems such as mooring lines and dynamic cables are designed for each scenario, before considering the full array design. The floating wind turbine unit (turbine and platform) will leverage existing designs—the VolturnUS-S semisubmersible being the most established. The WindCrete concrete spar may be considered for later design variants. A tension-leg platform design for the IEA Wind 15-MW wind turbine is not currently available. For mooring systems, a number of designs exist in the literature, as well as assumed properties of various mooring line materials that can be used when designing new mooring systems. For dynamic cables, existing designs and property information are sparse, but new reference cable properties have been established for the purpose of Task 49.

Design Requirements

Design requirements for the reference designs are a combination of existing standards and common-sense necessities for array design. The reference designs are intended to generally align with available design guidelines and standards, as relevant to the scope of the reference array design efforts related to the turbine, platform, mooring lines, anchors, and power cables. Standards and recommendations from Det Norske Veritas and the American Bureau of Shipping are the main sources being considered, but there is flexibility in which standards the reference designs follow.

The main design requirements for the floating wind turbines will be that the turbine loads and platform motions stay within the range of the original reference design values. For the mooring systems, the main requirements relate to ultimate and fatigue limits as well as to keeping sensitive components like rope from contacting the seabed. For sizing dynamic cables, the driving requirement is power transmission capacity. Considerations related to floating platform offsets, wake losses, electrical losses, and other array-level factors are generally considered economic trade-offs between multiple design aspects, so they are not specified as limits a priori but rather will be adjusted during the design process. The choice of requirements to use for the reference designs was refined through experience gained from the initial stages of the reference array design efforts. As a result, the listed requirements strike an ideal balance between following existing recommended practices and having a pragmatic array-level design pathway.

Site, Cost, and Logistics Inputs

The site conditions for the reference designs come from site-specific datasets developed under WP1, which are also described in a dedicated report that provides detailed wind, waves, and current data at 11 representative sites. The WP2 design teams each chose a site for their reference design and further processed the meteorological and ocean (metocean) data to obtain inputs for design-driving load cases. The reference arrays will then be designed to withstand the expected environmental loading at the chosen site. Additional relevant site data include the water depth, bathymetry, soil properties, and local infrastructure. Some of these site properties will be idealized in the first reference array designs—for example, assuming a uniform water depth without bathymetry—but then may be incorporated in follow-on design variants.

General cost and logistics assumptions have been specified for the reference designs based on published literature and expert estimates. Cost assumptions are provided for key components that will be designed, such as mooring systems, power cables, and anchors. To model installation costs, the installation activities are mapped out, with assumptions for duration, required equipment, and metocean condition limitations. Vessel, crane, and port rates are provided, which can then be used to calculate the cost of each installation activity. Site-specific metocean data can be applied against the specified wave height and wind speed limits to consider the availability of operations for a specific reference design installation. Additionally, maintenance costs and failure rate data can be used to model the cost of operations and maintenance. These cost coefficients and logistics parameters will allow modeling during and after the reference design process that captures the wide range of reference array life cycle costs.

Design Conventions and Methods

This report outlines the conventions and methods to use during the design process, with the intent to establish common definitions and core requirements but leave flexibility in how designs are developed. A system for describing the reference array designs (the floating array ontology) is presented to provide a common method for describing floating wind farm designs. This includes an array-level coordinate system to ensure consistent definitions when dealing with environmental headings and the layout of array components. A rough outline of the overall reference array design process is presented as a nonprescriptive example for how the many considerations and requirements in the design basis can be woven together. This outline suggests steps in the component-level and array-level design processes, cross-referencing with earlier sections of the design basis, but the exact design process is intended to be open-ended and flexible for each reference array design team to choose.

To simplify the reference array design process, key design load cases (DLCs) were identified that result in the largest ultimate loads on the mooring systems and power cables (DLCs 1.6 and 6.1) along with a collection of cases that collectively describe the joint probability of metocean conditions that cause fatigue loads on the system. These fatigue cases, or bins, were chosen using a clustering method that can account for the distribution of wind and wave conditions reasonably well with 100 metocean bins. Additional DLC considerations are identified, including wind-wave directionality, mooring line failures, and hurricane, tsunami, and cyclone events; however, these are determined to be optional for the reference arrays.

Use of the Design Basis

The design basis provides a comprehensive overview to guide the development of reference array designs within Task 49 and beyond. At time of writing, three initial reference designs are underway—with water depths of 60 m, 300 m, and 800 m—based on the VolturnUS-S semisubmersible and IEA Wind 15-MW floating wind turbine. A selection of additional variants on these designs are proposed as future efforts to provide a greater variety of site conditions, support structure types, and design challenges. When these reference designs are completed and in use, this design basis will help explain the founding assumptions behind those designs and facilitate development of additional designs that can be fairly compared.

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1 Introduction

International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 49 on the Integrated Design of Floating Wind Arrays is an international collaboration aiming to advance the development of large-scale floating wind farms by providing resources to the research and development and planning communities. As floating wind technology expands to larger scales and a wider range of site conditions, the industry faces a set of unique challenges to scale from existing demonstration projects to commercial-scale floating arrays. These challenges are not constrained to individual turbine systems, but instead encompass multidisciplinary considerations, including the mooring, anchor, and cabling design; array layout optimization; installation and operational logistics; environmental and marine spatial planning impact; and failure modes and analysis for utility-scale floating wind projects. Considering holistic design principles from the earliest stages of the industry will streamline the growth of cost-effective, globally deployed floating wind projects.

Task 49 is a 4-year effort that began in December 2021. The task aims to facilitate solutions to some of the challenges mentioned above by developing open-access reference information and designs. The task will provide baseline tools and data for the research community, including reference site conditions, reference array designs and toolsets, an array-level risk assessment framework, and a register of major research and planning questions faced by the industry. Combining these resources into a unified repository will help provide a standardized foundation for future innovation, development, and industrialization of floating wind projects worldwide. Task participants include representatives from project developers, technology providers, universities, consultancies, regulatory agencies, and research institutions from 12 countries, which enable a global perspective on the questions facing the industry.

Task 49's four work packages (WPs) focus on specific areas of need, with the following objectives:

- WP1: Curate a set of site conditions representative of the global floating wind pipeline
- WP2: Develop reference array designs for typical site conditions and technology types
- WP3: Catalogue array-level failure risks, consequences, and mitigation strategies
- WP4: Identify critical innovation opportunities and marine spatial planning requirements.

As shown in Figure 1, the development of reference array designs in WP2 plays a central role in the task, with interactions with WP1 on site conditions and WP3 on failure risks.

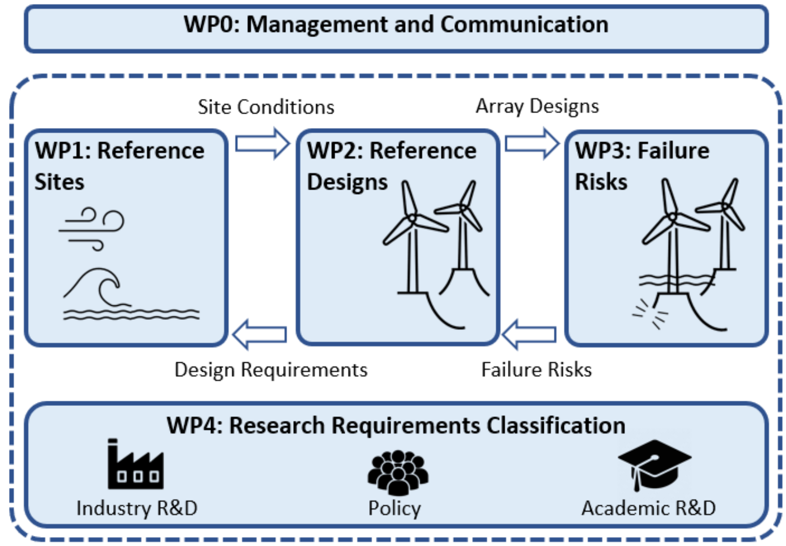


Figure 1. Task 49 work packages and main interactions

This document provides the design basis for the development of the Task 49 reference floating wind array designs in WP2. Like a traditional design basis, it discusses input data and assumptions for use in the design process along with design requirements, the scope of design, and an outline of the design procedure. However, the content of this design basis is scoped for reference array designs rather than designs that will be built. Additionally, due to the novel nature of the design effort, the design basis was not finalized ahead of time but was expanded and refined as WP2 progressed through the early stages of the design process.

The main purpose of this design basis is to record the design assumptions used in the Task 49 reference designs and to ensure the design process is consistent and agreed upon by task participants. Additionally, it provides a reference for future research to develop additional reference designs or variations on the Task 49 designs that have consistent assumptions with the original reference designs.

The content of the design basis includes information from various sources:

- Reference design scoping from WP2 working groups—collective brainstorming and work sessions that were held in autumn 2022
- Literature review and synthesis from key contributors
- Input about assumptions and feedback from WP2 participants
- Input site condition data from WP1.

In addition, the design basis has been iterated on and updated to include new realizations about the practical approach of designing reference floating wind farms through the first year of the design effort.

1.1 Purpose of the Reference Array Designs

The main goal of WP2 is to answer the need for reference floating wind array designs. This need was expressed by researchers and industry representatives during IEA Wind Topical Experts Meeting (TEM) 99, which was the TEM that led to the creation of Task 49 [1]. The TEM highlighted that many novel design questions arise with floating wind farms, and it is difficult for researchers to explore these questions because they would first have to create a floating wind farm design; there are no publicly available floating wind farm designs to use as starting points.

Reference designs for wind turbines or floating wind turbine support structures have played an important role in floating wind turbine research to date. The National Renewable Energy Laboratory (NREL) 5-megawatt (MW) offshore reference turbine [2], IEA Wind 15-MW reference turbine [3], and the OC3-Hywind spar[1] [4], OC4-DeepCwind semisubmersible [5], and VolturnUS-S semisubmersible [6] reference support structures have been widely used in research projects. Their definition reports are some of the most cited references in the floating wind literature. These reference designs allow researchers and technology developers to study the behavior of floating wind turbine systems without having to design every part of those systems and without having to get access to a wide range of information that is often confidential. They provide a baseline upon which specific variations or innovations can be applied. And they provide a point of commonality for comparing different modeling tools and methods, such as has been done in the OC3–OC6 projects under IEA Wind Task 30. Lastly, reference designs ensure that designs used in research efforts are, to some extent, representative of the designs used in industry.

As the floating wind industry grows, and large, commercial-scale projects are planned, array design is an increasingly important topic. No reference floating wind array designs currently exist. The reference arrays designed in this work package will fill that void and will be a resource for array-level research and development. A full description of several reference floating wind farms will be developed to facilitate the research and development activities of the floating wind community and efficient scale change of the floating wind industry (from pilot to commercial farms). These designs will provide standardized baselines upon which different innovations can be developed and their benefits evaluated.

As examples, the reference array designs could be used for purposes such as the following:

- Study the dynamic behavior of floating wind turbines in an array context (the reference designs provide simulation input files that can be used with minimal effort)
- Develop and design suitable mooring systems or power cable systems at the array scale
- Simulate installation or operations and maintenance (O&M) methods in detail
- Optimize layouts (reference designs provide a baseline or starting point)
- Develop and evaluate array-level turbine control strategies for floating wind farms
- Study grid integration of floating wind farms with detailed simulation of power output.

To be suitable for use cases such as those mentioned above and to fit within the ecosystem of existing reference turbine designs, the reference array designs should provide the same level of detail as existing reference floating wind turbine designs, such as the IEA Wind 15-MW reference turbine on the VolturnUS-S floating support structure [6]. This level of detail allows

[1] The OC3–OC6 projects are defined as follows: Offshore Code Comparison Collaboration (OC3), Offshore Code Comparison Collaboration Continuation (OC4), Offshore Code Comparison Collaboration, Continued with Correlation (OC5), and Offshore Code Comparison Collaboration, Continued, with Correlation and unCertainty (OC6).

for loads analysis as well as cost and logistics modeling. Consistent with existing reference designs, the reference arrays should be representative of the current state of the art and should achieve a good level of performance. They do not necessarily need to represent a completely optimized design, since the main goal is to provide a baseline.

1.2 Reference Design Scope

The reference array designs need to include all aspects of a floating wind farm that would enable the level of analysis and types of use cases discussed in Section 1.1. Information about the site conditions—including meteorological and ocean (metocean) conditions, water depth and seabed characteristics, available area, port infrastructure, etc.—is assumed to be fixed and provided by the reference site condition sets developed by Task 49 WP1. Accordingly, the reference design definitions developed by WP2 need to cover the installed components that make up the floating wind farm for whatever site is selected.

Within the designs that WP2 will define, some aspects will be taken from preexisting resources, some aspects will be developed within Task 49, and some will be outside the scope of the reference designs. Previous IEA Wind tasks and other projects provide a number of resources that can be used, such as the reference wind turbine and floating platform designs from Task 37. By using existing resources, Task 49 can focus on the aspects most important for floating wind farms at the array level, such as designing and optimizing components that may vary throughout a floating wind farm.

To scope the design efforts in Task 49, the design aspects were organized into a hierarchical structure; then, discussions were held across four breakout groups to decide which aspects should be designed within the Task 49 effort, drawn from existing work, or excluded from the reference design scope. Specifically, the aspects were assigned to four categories:

1. To design: These parameters will be varied during the design process to achieve design objectives and constraints.
2. To select: These parameters will be chosen from a preexisting list of options during the design process.
3. Fixed: These parameters will be assumed to help fill in the design information but will not be part of the design process.
4. Excluded: These parameters will not be part of the design in any way.

Using these categories, the design scope from the consensus of discussions is as follows:

- **Array and Layout**
  - **Turbine capacity (fixed):** A single turbine capacity should be assumed for each reference array, without variation or optimization.
  - **Number of turbines (mostly fixed):** The number of turbines in each reference array could be an optimized variable, especially in cases with layout optimization; in simpler cases with a fixed layout, the number of turbines will be set a priori.

- **Turbine layout (mostly fixed):** The array layout and turbine spacing should be set a priori based on established methods for most reference arrays. Select reference arrays could include optimized spacing or layout.
- **Site area (fixed):** The site area of each reference array should be fixed based on reference site definitions from WP1.
  - **Accommodations (excluded):** Special accommodations (such as for fishing lanes and specific environmental aspects) are generally out of scope, although key reference site features specified by WP1 could be considered.

- **Floating Offshore Wind Turbine (FOWT) Unit**
  - **Turbine (fixed):** Existing reference turbine designs should be selected ahead of time.
  - **Floating platform (fixed):** Existing established floating platform designs, dedicated to the selected turbine, should be selected ahead of time. Ballasting or sizing may be adjusted if needed for the design integration and adaptation to the selected site.
  - **Turbine control (fixed):** Baseline controllers for each wind turbine/platform system should be used based on those specified for the existing reference FOWT designs. Fine-tuning will be performed if required.
  - **Farm control (excluded):** Array-level control strategies are out of scope for the reference arrays but could be applied for future use cases.
- **Stationkeeping**
  - **Mooring general configuration (to design):** Choose mooring configurations that suit the site and are representative of current technology.
    - **Mooring line design (to design):** Design/optimize mooring lines on a per-turbine basis to meet standards and performance objectives for the given site conditions, including possible depth variations.
    - **Consideration of mooring/cable interference (to select):** Select appropriate margins for avoiding interference between mooring lines and power cables.
  - **Anchors**
    - **Anchor technology type (to select):** Preselect or choose appropriate anchor types from common existing options and depending on soil nature and FOWT system.
    - **Anchor sizing (to design):** Size anchors (collectively or individually) according to loads in accordance with standards.
    - **Anchor design (geometry, etc.) (fixed):** Changes to anchor geometry or technology features are out of scope.
- **Electrical**
  - **Intra-array cabling**

- **Cable arrangement and sizing (to design):** The intra-array cable capacities and arrangements should be designed and optimized as part of the reference arrays because they are coupled with mooring and layout design considerations.
- **Dynamic cable design (to design):** Dynamic cable configurations should be designed and possibly optimized as part of the reference arrays because of their large influence on system design and response.
    - **Dynamic cable subcomponents (to select):** Detailed internal properties and components (such as buoyancy modules or bend stiffeners) of dynamic cables should be assumed or selected from available options. These are at the edge of the reference array scope.
- **Static cables (to select):** Static cable types should be assumed or selected from available options. Static cable routing should be designed or possibly optimized.

- **Substation (to select):** The substation position and type can be included in the reference array, but its detailed properties or response characteristics are out of scope. The substation is at the edge of the reference design scope—it is primarily included for the sake of defining the intra-array cables that connect to the substation.
- **Export cable (to select):** The export cable position and type can be included in the reference array, but its detailed properties or response characteristics are out of scope.

1.3 Reference Design Features of Interest

After scoping the bounds of the reference array designs in general, specific aims for each reference design needed to be identified. To do this, a brainstorming spreadsheet was shared with all Task 49 participants. This spreadsheet presented the general categories within the design scope and asked participants to enter “design features of interest” for each category. Twenty-one participants responded, and a total of 122 entries were provided. After discussing the entries, the overall findings of design features of interest were summarized (Table 1).

Table 1. Summary of Design Features of Interest

Feature	Greatest Interest	Secondary Interest	Comment
Layout	Regular rectangular	Triangular, irregular, optimized	Approach progressively
Turbine size	15 MW	~20 MW or a range of sizes (12, 15, 18 MW)	Confined by available reference turbines
Turbine number	Multiple array sizes in the range of 20–100 turbines	As few as 7–10 turbines	Will depend on site selection; different densities may be valuable
Platform type	Steel semisubmersible	Spars, tension-leg platforms (TLPs), barges, concrete construction	Use existing designs
Mooring configuration	All basic types (from catenary to TLP)	Different rope materials, shared configurations, load reducers, multiple anchor types, seabed dependence	
Dynamic cable configuration	Lazy wave	Catenary free-hanging, suspended W, etc.	
Intra-array cable rating	66 kilovolts (kV) and 132 kV		
Depth	Shallow, medium, and deep options		
Miscellaneous	Seabed changes and anchor/mooring implications	Substation, cable connections, and export cable	

Key points from the table, which were raised during discussions in September 2022 are as follows:

- Start with regular layouts and consistent designs, potentially customize in second stage
- Use 15-MW turbine for near-term relevance and availability
- Feature different support structure configurations across the array designs
- Some design choices (e.g., anchor type) are independent of the rest of the design and can be varied later.

During later working group discussions, a number of additional points were converged upon. Among platform types, semisubmersible and spar configurations were of first and second interest, respectively, which is consistent with these two topologies having the greatest record of deployment to date. Similarly, there was greatest interest in considering steel and, second, concrete platforms. The point was made that the increased weight of concrete platforms lends itself most easily to spars. As a result, a steel semisubmersible was identified as the platform type to use in most cases, and a concrete spar would be a variation to feature in some designs. Using a steel semisubmersible and concrete spar is consistent with the majority of platform types deployed thus far.

1.4 Proposed Reference Designs

The reference designs should include the design features of interest as described above in order to be applicable to studying a wide range of floating wind array design phenomena. However, the list of reference designs must be kept relatively small so that they can be feasibly developed within the task. As a solution, the reference designs are proposed to have three general designs and then variations of each design to include different features. This allows covering the design features of interest while retaining some commonality between designs to avoid excessive complexity.

Table 2 presents the three proposed array scenarios, each with variations targeted at certain design challenges or features. The scenarios are based on the water depth, ranging from shallow to deep. Each begins with a basic scenario with uniform seabed and regular array layout. Variations then add complexity in the form of seabed variations or design variations. The table represents a high-level plan based on information and discussions from WP2 participants. Entries in gray indicate features/variants that may be trimmed from the most essential designs, depending on progress. If time does not allow these variants to be explored in the current effort, they may instead be considered in follow-on Task 49 efforts. Section 6.5 provides additional details.

Table 2. Proposed Reference Array Design Scenarios and Features

Scenario	Shallow	Intermediate	Deep
Key features	Shallow-water mooring/cabling design challenges and innovations	Seabed feature constraints on anchor positions, and innovations on anchoring	Deep-water constraints on mooring layout and turbine spacing, use of W-shaped cables and deep-water mooring innovations
Design variants (sequential)	V1: uniform *Secondary options*: V2: depth gradient with adapted mooring designs V3: spring option	V1: uniform *Secondary options*: V2: complex seabed, adapted layout and anchor positions V3: shared anchor option V4: cable layout designs	V1: uniform *Secondary options*: V2: depth gradient with adapted layout, moorings, cables V3: shared mooring option V4: TLP option
Metocean	Sørlige Nordsjø II	Utsira Nord	Humboldt
Depth	60 meters (m) *Secondary option*: sloped 40–120 m	300 m *Secondary option*: irregular 200–400 m	800 m *Secondary option*: irregular 600–1,000 m
Seabed	Generic	Generic *Secondary option*: irregular with bedrock/ridges	Generic
Array layout	Rectangular	Rectangular *Secondary option*: varied	Rectangular *Secondary option*: varied
Platform type	Semi	Semi or Spar *Secondary option*: TLP	Semi or Spar *Secondary option*: TLP
Mooring configuration	Semi-taut shallow water	Catenary chain (+wire?) *Secondary option*: semi-taut intermediate water	Taut synthetic *Secondary options*: shared taut, TLP
Mooring layout	Regular	Regular *Secondary option*: varied	Regular
Anchors	Drag embedment *Secondary option*: suction pile	Drag embedment *Secondary option*: shared suction pile	Suction pile *Secondary option*: drag embedment
Cable configuration	Lazy wave	Lazy wave	Fully suspended
Cabling layout	Regular	Regular or irregular if seabed constraints	Regular

It is useful to consider ways in which the reference designs can be flexible for representing different scenarios. Depending on the characteristics and level of detail of the reference designs, some aspects may be changeable after the fact. For example, each reference design will include assumptions about the soil characteristics and anchor types used in the design, but someone using the reference design could assume different soil conditions and anchor types while still using the other parts of the design unchanged (assuming comparable anchor capacities). Also, for regular array layouts, the designs could potentially be scaled up or down by simply changing the number of rows/columns/cells that are repeated in the array, along with appropriate assumptions about changes in array cabling and substation location.

The following features were identified as being of interest but are not currently incorporated in the above proposed designs:

- Hurricane-resistant designs (different floating platforms would need to be developed for different extreme ocean conditions, such as tropical cyclones)
- Different numbers of mooring lines (and levels of redundancy)
- Comparison between platform types (semi/spar/barge, steel/concrete).

These features are left for future variations that could be made to the planned reference designs.

1.5 Steps for Developing the Reference Array Designs

It is helpful to have a common language for the aspects in the design process. To perform any engineering designs of floating wind turbine structures, we must consider design objectives, design parameters, and design requirements and constraints. Here, the design objective is to find a feasible and economic design. Cost, or levelized cost of energy (LCOE), could be considered as the objective to minimize, although a formal optimization process is not necessarily required for the reference designs. Design variables are the parameters describing the design that will be varied during the design process, such as dimension of structural components (e.g., floating platforms, mooring lines, power cables), material choice, and turbine positions in the array. Requirements and constraints are the specifications that must be met by the design, such as those for strength provided in the design standards.

Following completion of the design basis work, which is encapsulated in this report, development of the reference array designs will proceed through several phases:

1. Collection of existing component designs
2. Selection and adaptation of component designs for specific conditions
3. Integration of component designs
4. Tuning and optimization.

The first phase gathers existing designs of components, such as mooring lines and dynamic cables, that are available for use. Collecting and categorizing existing designs will ensure the task does not duplicate work and is informed with the best available starting points. Selections of existing component designs have been identified and are provided in Section 2. These component designs are divided into three subsystems: the floating wind turbine unit (comprising wind turbine and floating platform), the mooring system, and the intra-array power cables. Designs from each subsystem can be selected and combined according to compatibility with the site conditions and design constraints to serve as starting points in the design process.

The next phase designs the individual parts of the floating array, especially the mooring systems and dynamic cables. The most suitable component designs will be identified and adapted to suit the specific needs and constraints of the reference array designs, or they will be developed from scratch where needed. The details of this selection and adaptation or design process will vary depending on the needs of each design. For example, the mooring system and cable designs could be adapted for a different water depth or platform type. Also at this phase, subsystem-level interactions will be considered, such as how the power cables must be able to accommodate the watch circle determined by the mooring system, while the cables also exert forces on the floating platforms and therefore effect the watch circle. This stage considers the requirements and constraints appropriate for each subcomponent, as detailed in Section 3. Although this phase of the design effort does not consider the full array design, it should be forward-looking in terms of creating designs that are expected to work when integrated into an array situation.

Once the component designs are prepared, the designs will be integrated to create initial descriptions of the full floating wind farm reference designs. Layout aspects will also be considered at this stage, such as the turbine spacing, mooring line positioning, and cable routing. Design at this stage will likely be confined to regular layouts, such that the layout of a smaller subsection of the array with only a few turbines can likely be repeated throughout the array. The integration process should check that the requirements and constraints appropriate for each subcomponent are still adhered to.

Lastly, these combined designs will be evaluated using coupled analysis methods, and then improvements and optimizations will be applied to ensure good performance of the final reference array designs. Cost and logistics modeling will be added at this stage to provide a more complete view of the designs' key attributes and the factors that may drive design optimization decisions. The specific optimization approach will depend on the needs and goals of each reference design and may follow a sequential or nested approach where different subsystems are improved at different stages (e.g., mooring design to reduce cost, then dynamic cable design to survive offsets, then layout to increase annual energy production [AEP]). The general goal is to effectively co-optimize the mooring systems, power cables, and array layout with respect to LCOE while adhering to a range of technical constraints (e.g., following design standards) and ensuring typical performance levels (e.g., capacity factor). Representative site-specific factors such as those relating to environmental impacts, siting constraints, or navigability for other ocean users may also be considered in the optimization process. It should be noted that this final phase is intended to ensure the quality of the designs rather than necessarily achieving the most optimal designs. As long as the reference designs are viable and perform reasonably well, more comprehensive optimization efforts can be left to future work by users of the reference designs.

1.6 Purpose and Contents of the Design Basis

This design basis report is intended to lay out the design assumptions and principles behind the Task 49 reference array designs so that the approach is well defined and transparent. This makes it possible for others to modify the reference designs while following the same assumptions and constraints in the original designs, enabling an important role for the designs as baselines. In addition, the design basis can serve as a source of information for other floating wind array design efforts.

The remaining sections of this report present each part of the Task 49 design basis. Section 2 presents an overview of the different subsystems and what existing design information is available in each. Section 3 discusses design requirements and constraints that should be followed when developing the reference designs. Section 4 presents the approach to be used for representing the conditions of the site for each reference design, which is informed heavily by the work of WP1. Section 5 discusses the approaches and assumptions to be used for cost and logistics modeling, which are essential for providing a consistent basis upon which to assess designs and compare costs. Section 6 gives an overview of existing applicable design tools. Finally, Section 7 presents conventions and approaches that will be used in the process of developing the reference designs.

2 Component Design Inputs

The focus of the Task 49 reference array designs is array-level design aspects and how different design aspects are integrated. As such, the arrays will use or build from existing designs for components or subsystems where possible. This section discusses the three distinct subsystems that will be considered in the reference array design process: the floating wind turbine unit, the mooring system, and the intra-array power cables. For each subsystem, we provide a brief review of typical types and design considerations, and a listing of available reference or research designs that can be used as starting points.

2.1 Wind Turbine and Floating Platform

The floating platform and the wind turbine on top of it are referred to as a FOWT unit. From the scoping done in Section 1.2, the FOWT unit is intended to be selected for a given reference design, without design adjustments aside from any change to ballasting required by changes in mooring system tension.

There are a number of open-source FOWT unit designs used within the research community. The FOWT unit designs are usually divided into available reference models of the wind turbine itself and the design of the floating platform that it rests upon. For the reference wind turbine models, the three most commonly used reference wind turbines [7] are the NREL 5-MW offshore reference turbine, the Technical University of Denmark (DTU) 10-MW reference turbine (and an adjusted design, the IEA Wind 10-MW turbine), and the IEA Wind 15-MW reference turbine. The floating platform designs published for these three reference turbines are summarized in Table 3.

Table 3. Publicly Available Floating Wind Turbine Reference Designs

Turbine	NREL 5 MW [2]	DTU 10 MW [8]	IEA Wind 15 MW [3]
Semisubmersible or barge designs	OC4-DeepCwind semi [5] CSC semisubmersible [9] ITI Energy Barge [10]	Nautilus OO-Star [11]	VolturnUS-S [6] Activefloat [12]
Spar designs	OC3-Hywind spar [4]	NREL 10-MW spar [13]	WindCrete (spar) [14]
TLP designs	MIT/NREL TLP [15]	CENTEC TLP [16]	

Task 49 focused on the IEA Wind 15-MW reference wind turbine because it is most representative of the floating wind turbine sizes expected in large floating wind arrays. We provide brief summaries of the 15-MW turbine properties and two publicly available platform designs that can be used with the turbine: the VolturnUS-S semisubmersible and the WindCrete spar. Full details of these designs should be obtained from their definition reports and associated input file sets. There is not an existing open-source TLP design for the 15-MW turbine, so a TLP is not currently considered for the reference array designs, but is identified as an area needing reference design development in the future.

2.1.1 IEA 15 MW Reference Turbine

The IEA 15 MW reference wind turbine [3] is a Class IB direct-drive machine, with a rotor diameter of 240 m and a hub height of 150 m. It was jointly designed by NREL, sponsored by the U.S. Department of Energy, and DTU, sponsored by the European Union's H2020 Program. Its development happened through IEA Wind Task 37 on Wind Energy Systems Engineering. Table 4 provides a summary of turbine properties.

Table 4. IEA Wind 15-MW Reference Wind Turbine Properties [3]

Parameter	Value
Power rating (MW)	15
Turbine class	International Electrotechnical Commission (IEC) Class 1B
Specific rating (watts per square meter [W/m^2])	332
Rotor orientation	Upwind
Cut-in wind speed (meters per second [m/s])	3
Rated wind speed (m/s)	10.59
Cut-out wind speed (m/s)	25
Design tip-speed ratio	9
Minimum rotor speed (rpm)	5
Maximum rotor speed (rpm)	7.56
Maximum tip speed (m/s)	95
Rotor diameter (m)	240
Hub height (m)	150
Hub diameter (m)	7.94
Hub overhang (m)	11.35
Rotor precone angle (deg)	-4
Blade prebend (m)	4
Blade mass (tonnes [t])	65
Drivetrain	Direct drive
Shaft tilt angle (deg)	6
Rotor-nacelle assembly mass (t)	1,017

The tower of the IEA Wind 15-MW turbine is a conventional steel-tube construction, of which there are multiple developed versions. The most widely used tower for the turbine on floating platforms is a version that was updated in March 2022 to increase its stiffness and move the first tower bending natural frequency out of the 3P[2] frequency range of the turbine [17]. The tower will be discussed further along with the summary of the VolturnUS-S platform.

The Reference Open-Source Controller (ROSCO) [18] is a modular reference wind turbine controller that has been tuned to the IEA Wind 15-MW turbine with the VolturnUS-S semisubmersible platform. The ROSCO controller includes peak shaving, which reduces the maximum rotor thrust force by about 25%. Updated ROSCO input files are provided by IEA Wind Task 37 on their GitHub repository.[3]

2.1.2 University of Maine VolturnUS-S Semisubmersible

The VolturnUS-S platform is a steel semisubmersible platform design developed by the University of Maine with support from NREL as part of IEA Wind Task 37 [6]. It has three radial columns and one central column connected by rectangular pontoons. The central column is connected to the outer radial columns through horizontal rectangular pontoons at the draft. The IEA Wind 15-MW turbine is placed on top of the central column. The geometry and dimensions of the columns and pontoons of the VolturnUS-S are shown in Figure 2.

The design properties of the floating platform are shown in Table 5. The mass of the system comprises the mass of the steel creating the platform and the mass of the ballast. There are two types of ballast in the VolturnUS-S: fixed ballast, which is an iron-ore-concrete ballast divided equally between the three outer columns, and seawater ballast in the pontoons connecting the outer columns to the center columns. There is also a mass of 100 t representing the transition piece where the tower interfaces with the platform.

[2] 3P refers to the frequency at which any of the blades of a three-bladed rotor passes the tower.
[3] https://github.com/IEAWindTask37/IEA-15-240-RWT

Table 5. VolturnUS-S Semisubmersible Design Properties

Parameter	Value
Hull displacement (m^3)	20,206
Hull steel mass (t)	3,914
Fixed ballast mass (t)	2,540
Fluid ballast mass (t)	11,300
Tower interface mass (t)	100
Draft (m)	20
Freeboard (m)	15
Vertical center of gravity from still water level (SWL) (m)	-14.94
Vertical center of buoyancy from SWL (m)	-13.63
Roll inertia about center of gravity (kilogram-square meters [kg-m^2])	1.251e+10
Pitch inertia about center of gravity (kg-m^2)	1.251e+10
Yaw inertia about center of gravity (kg-m^2)	2.367e+10

Placing the IEA Wind 15-MW turbine on the VolturnUS-S float platform necessitated modifications to the tower design so it could withstand the higher inertial and gravity loads of a floating versus fixed-bottom turbine. The result was a tower with a mass of 1,263 t, 47% heavier than the tower designed for a monopile foundation [6]. This tower design has a base diameter of 10 m, a top diameter of 6.5 m, and a length of 129.495 m. The turbine hub height is kept at 150 m. Later, researchers noticed that the non-fixed base resulted in a lower tower bending natural frequency, putting it within the 3P frequency range of the wind turbine. Therefore, the Task 37 team designed a stiffer tower to increase its natural frequency above the 3P range. This stiffer tower has a mass of 1,468 t. It was released in March 2022 and is the version found in the GitHub repository for the VolturnUS-S design [19].

Another adjustment of the VolturnUS-S floating platform and tower for the IEA Wind 15-MW turbine was made in the European Horizon 2020 project HIPERWIND [20]. In this project, the mooring system and platform ballast were adapted to suit a water depth of 150 m, and a new tower was designed to avoid resonance issues with the 3P frequency range. These tower modifications are similar in nature to those made by the Task 37 team, with a tower mass of 1,515 t compared to 1,468 t. Task 49 will use the design developed by the Task 37 team released in their GitHub repository, as it is the more widely used version.

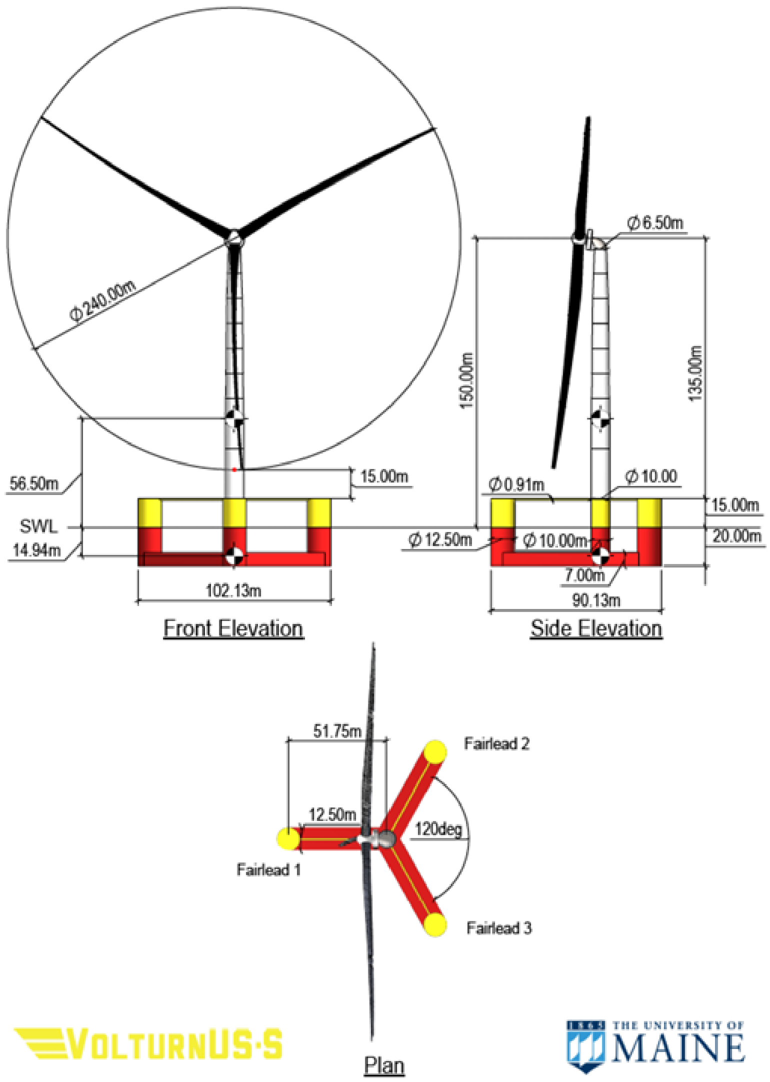


Figure 2. VolturnUS-S platform designed by the University of Maine [6]

2.1.3 WindCrete Spar by UPC

WindCrete is a spar floating wind turbine support structure developed by Universitat Politècnica de Catalunya (UPC) within the Horizon 2020 project COREWIND [14]. The WindCrete's spar substructure and tower are one monolithic concrete structure with no connection joints between them to avoid weak points. The geometry of the WindCrete platform is shown in Figure 3. The substructure from the mean sea level has a tapered transition section with diameters of 13.2 m and 18.6 m and a length of 10 m. A hollow cylinder of length 135.7 m is attached to this transition piece. Its bottom is a hemisphere. A ballast with a density of 2,500 kg/m^3 occupies the bottom of the spar up to 44.15 m.

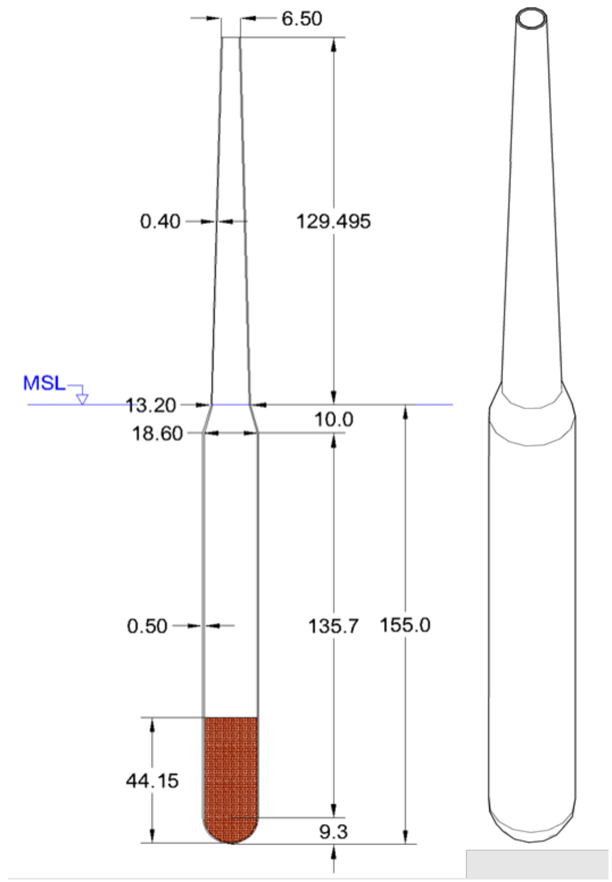


Figure 3. WindCrete geometry (dimensions are provided in meters)

The design properties of WindCrete are given in Table 6. The design of the WindCrete platform is based on a static predesign to assess the main platform characteristics to verify the design basis. The initial design goals are for the static platform pitch angle at the maximum thrust force to be less than 4 degrees and for the natural motion periods of the platform in heave, pitch and roll to be greater than 30 s. Moreover, the relations of platform and tower draft, diameter, and thickness ensure the structural response of the platform and the disposition of the reinforcement steel and the post-tensioning.

Table 6. WindCrete Design Parameters

Parameter	Value
Hull displacement (m^3)	4.054e+04
Mass including ballast (t)	3.9805e+04
Draft (m)	155
Vertical center of gravity from SWL (m)	-98.41
Vertical center of buoyancy from SWL (m)	-77.29
Roll inertia about center of gravity (kg-m^2)	1.5536e+11
Pitch inertia about center of gravity (kg-m^2)	1.5536e+11
Yaw Inertia about center of gravity (kg-m^2)	1.9025e+09

The rest of the hydrodynamic properties are introduced in detail in [21], [22]. This includes the hydrodynamic damping and first- and second-order wave forces [14]. WindCrete is designed for a specific site at Gran Canaria Island introduced within the COREWIND project. For that site, the hub height for this design is decreased to 135 m instead of the 150 m of the IEA Wind 15-MW design for fixed-bottom offshore wind turbines. The lower hub height decreases the costs of the tower and the loads on the tower base due to the platform's motions. The decrease in height for this site is acceptable because the average wave height for the site is low, which allows for a lower hub height without affecting the air gap between the blade tips and SWL. Similar to the VolturnUS-S, the natural frequency of the WindCrete's tower is higher than the turbine's 3P frequency region to avoid resonance.

We do not plan to use the WindCrete design in the initial reference array designs of Task 49; however, given the expressed interest in spar platforms and concrete materials, it may be a good choice for use in later reference design variants. In that case, the adjustment of the tower construction and hub height to match the initial designs will be a topic for discussion.

2.2 Mooring System

The mooring, or stationkeeping, system is responsible for keeping the floating wind turbine on-station by limiting its horizontal displacements to an acceptable range. It usually consists of three or more mooring lines—each made of rope, wire, and/or chain—attached to anchors in the seabed. The permissible horizontal motion envelope (often called the watch circle) that the mooring system must enforce is often defined by the range of motion that the power cables can accommodate. In addition to maintaining the watch circle, the mooring system is also the source of yaw stiffness for a floating structure, so its design is important to the system's yaw stability.

As floating offshore wind farms move into deeper waters, the design of compatible and cost-effective mooring systems has become increasingly important. The oil and gas industry has influenced floating offshore wind mooring design practices [23], but the engineering and economic drivers of floating wind turbines differ, where not one but many mooring systems will be installed in a farm, and where the mooring footprint can impact the number of turbines and their positioning within the predefined space. Compared to other floating offshore installations, FOWTs are subjected to greater environmental excitations and strong yaw moments due to aerodynamic loads on the wind turbine (e.g., horizontal wind shear and wind gusts). These differences result in important design differences relative to oil and gas, such as a tendency to use more compact mooring arrangements with fewer lines and to consider overlapping or sharing of mooring lines or anchors.

The next subsections discuss common mooring configurations, existing designs, and general mooring line property assumptions. The design requirements and constraints for mooring systems are discussed further in Section 3.2.

2.2.1 Mooring System Configurations

Mooring system configuration selection depends on the platform type, the water depth, and site-specific conditions and performance requirements. Most mooring systems applicable to floating wind turbines can generally be categorized into four main configuration types: catenary, semi-taut, taut, and tension-leg (Figure 4), each of which is discussed next. There are also other configurations that do not fall in these categories, which will be mentioned afterward. Across the various configurations, there can be significant crossover in componentry and arrangements.

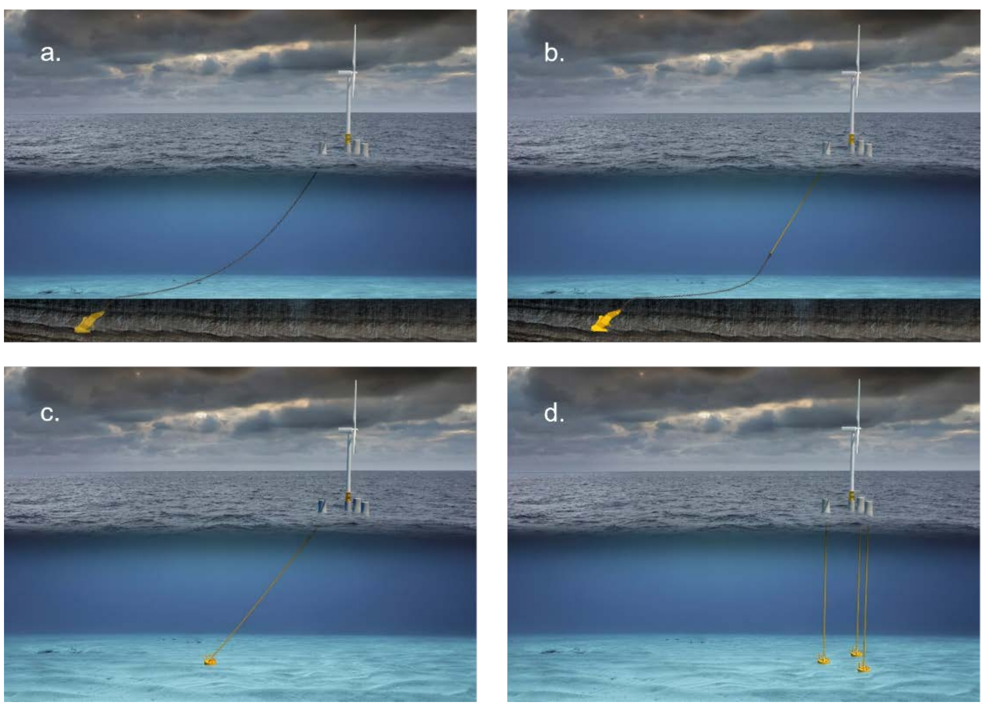


Figure 4. Four common mooring line configurations: (a) catenary, (b) semi-taut, (c) taut, (d) tension-leg platform.

Illustrations by Josh Bauer, NREL

Most types of floating wind turbine platforms, including spars and semisubmersibles, use the mooring system primarily for stationkeeping rather than stability. These designs typically use spread mooring systems with either catenary, taut, or semi-taut mooring lines, as shown in Figure 4a–c.

A catenary mooring system (Figure 4a), named for its curved mooring line profile shape, is normally composed of chain and/or wire rope. The restoring stiffness of a catenary mooring system is provided by the weight of the mooring lines. Weight along the mooring line where it transitions on and off the seabed results in a change in mooring tension as the platform displaces. In catenary mooring systems, a significant length of chain rests on the seabed to prevent uplift angle at the anchor, which would mean the catenary has become taut and is prone to sharp increases in tension. This avoidance of vertical anchor loading allows for the use of many anchor types, including drag embedment anchors, which have been used in many existing installations. Catenary mooring systems face challenges in very shallow water, where their nonlinear response is prone to snap loads, and in deep water, where their weight can become impractical, but they perform well at intermediate depths. Because catenary mooring systems involve significant length of chain on the seabed, they may require more space than other configurations. Moreover, the chain dragging across the seabed can disturb the benthic ecosystem more than other options. The large amount of chain used in catenary mooring systems can also be more demanding in terms of cost, installation equipment, and supply chain strain than other configurations that use rope.

Taut mooring systems (Figure 4c) use mooring lines that are tensioned to have a nearly straight profile shape, rising diagonally from the seabed. Most of the mooring line length is typically composed of synthetic fiber rope, which provides a controlled degree of elasticity and very little weight. Comparatively short lengths of chain at the top and bottom ends of the mooring line are common to facilitate hookup and tensioning and to avoid rope contact with the seabed. The restoring stiffness in a taut mooring system is determined mainly by the elasticity of the mooring lines. Taut mooring configurations perform well in deep water because they have less weight and length than catenary mooring configurations. They can also be advantageous in shallow water if the rope material is sufficiently compliant, since catenary mooring lines are limited in their geometric stiffness and can experience large snap loads [24]. In general, taut mooring lines can be shorter than other configurations, and their use of fiber rope makes them lighter than alternatives; they have the least use of steel components. Because taut mooring lines do not lie along the seabed, they reduce seabed disruption compared to catenary configurations. The main challenges with taut mooring configurations are that the lack of chain along the seabed makes them more difficult to pretension and more sensitive to rope creep (stretch over time). Taut mooring lines must by grounded by anchors capable of withstanding both vertical and horizontal forces, so they do not work with all anchor types.

Semi-taut mooring systems (Figure 4b) are characterized by a combination of elastic and weight-based restoring characteristics. The most common format is a length of chain that makes seabed contact and a length of rope spanning the water column up to the platform; this format combines the catenary restoring effect of the chain weight at the seabed with the elastic restoring effect of fiber rope. As with taut mooring configurations, a short section of chain near the platform attachment is common to accommodate hookup and possibly tensioning, although tensioning can also be done with the chain at the lower end using inline tensioners. Maintaining near-horizontal anchor loads allows the use of many anchor types, including drag embedment anchors. Because the rope section provides a degree of elasticity that can reduce the severity of tension peaks if the line goes taut, a small amount of uplift at the anchor may be permissible, which can allow for shorter overall length and significantly less chain than a catenary system. This benefit can be greatest in shallow water, where catenary mooring systems have the most nonlinear behavior.

Tension-leg platforms are unique from other configurations in that they rely on the mooring system for hydrostatic stability. Their tension-leg mooring systems consist of stiff tendons that are spaced and pretensioned to provide a high degree of pitch, roll, and heave stability on a floating platform (Figure 4d). These tendons typically have a vertical or near-vertical inclination and are made with stiff materials to restrain the platform from motion along each tendon's axial direction. In the oil and gas industry, TLPs have typically used steel pipe tendons for their high stiffness, although the significant weight and installation complexity of steel pipe means that other materials may be preferable for floating wind applications.

There are a number of variations and alternatives to the four general mooring configurations mentioned above. Bridle arrangements—where each mooring line splits into two horizontally spread mooring line segments before connecting to the platform—are often used with spar platforms to increase yaw stiffness for stability, since the small diameter of spars may not provide enough yaw stiffness for single mooring line attachments. Alternatively, some floating platforms are designed for a single-point moorings system, in which a spread mooring system attaches to a floating pivot point, and the platform is free to weathervane around this point. This arrangement allows the FOWT to weathervane and passively align with the wind; however, its orientation is also by waves and current, so the design considerations become more complicated. Additionally, pivoting around a central body requires bearing and high-voltage swivel equipment to transmit power and mechanical loads.

Shared mooring arrangements are another variation that can be applied. Shared mooring lines, where lines connect adjacent platforms directly, can be used to potentially reduce the length and cost of mooring lines in an array [25]. The complexity of installation, coupled behavior, and failure modes require additional design effort because the platforms are interdependent. Shared anchors, where a multiline anchor supports mooring lines from multiple platforms, can also be used to reduce the number of anchors and therefore the cost [26]. This arrangement requires the array layout to be compatible with collocated anchor points. Modified anchor designs may be required to handle the multidirectional anchor loads.

2.2.2 Mooring Line and Anchor Selection Considerations

Common mooring line materials include chain, wire rope, and synthetic fiber ropes. Chain has been a traditional and long-standing choice for spread mooring systems due to its strength and durability. It is also the only mooring line type that is practical to apply length adjustments to because of its use of rigid links; winches can provide tensioning at the platform, or inline tensioners can connect two lengths of chain and pay one end in or out to adjust the overall length. Chain is also the most robust mooring line type for seabed contact, so it is often used for any line length that will touch the seabed.

Chain is susceptible to corrosion, especially near the water surface, out-of-plane bending, wear, and fatigue. It also involves significant supply chain constraints related to steel material use and manufacturing requirements. It is also the heaviest option, which can be beneficial for catenary mooring systems but can increase demands for installation equipment. Chain sizes greater than 152 millimeters (mm) are difficult to handle, and there is a small range of vessels that can handle chain sizes greater than 172 mm. There is also very limited production capacity for chain sizes larger than 172 mm, so smaller chains are the practical choice from a supply chain perspective.

Mooring line materials other than chain are attractive for having fewer supply chain constraints, lower cost, lower weight, and less demanding installation requirements. Wire rope provides an alternative that still has enough weight and stiffness for catenary configurations but is more efficient and easier to manufacture at various sizes. Spiral-strand wire is a counterwound wire layered rope similar to those used in bridges and is usually protected by a sheath. It has approximately 20% of the weight of equivalent chain and has enough abrasion resistance to be used in contact with the seabed.

Synthetic fiber ropes are nearly neutrally buoyant in water and have significant strength and convenient stiffness for taut and semi-taut configurations. They have long been used in deep-water oil and gas applications, where the long chain lines become too heavy. In floating offshore wind applications, where the chain mooring systems are subject to extreme snap loads, fiber rope lines are beneficial in shallow water because they can allow considerable compliance. There are a number of synthetic fiber material options. Polyester has been used for decades in permanent mooring applications for oil and gas and has suitable stiffness for deep-water taut mooring configurations. Recently, there has been growing interest in nylon, which has a lower stiffness than polyester and thus can be used to lower peak mooring line tensions, especially for shallow applications. High-modulus polyethylene (HMPE) fiber is another newer mooring line material. It is much stiffer than polyester, which makes it advantageous for reducing offsets in deep-water mooring systems [27]. The high stiffness of HMPE and other fiber rope materials may hold promise as a more cost-efficient alternative to steel for TLPs, but further investigation is required, which is beyond the focus of Task 49.

Mooring lines often incorporate additional components for logistical, performance, and robustness reasons. Because chain is the easiest mooring line type to hook up and adjust, it is common to have a length of chain near the top end of mooring lines, even if the rest of the line is mode of wire or fiber rope. The presence of short sections of chain (e.g., less than 30 m) at the upper end of the mooring lines generally has minimal effect on the response. It is more a concern for corrosion and fatigue life, because it is a component that may undergo significant wear and may require replacement during the design life. Mooring systems that have fiber rope components should generally be designed to avoid any contact of the fiber rope with the seabed to prevent abrasion and damage to the rope. In addition, the downwind lines must be kept under reasonable tension to avoid whipping effects and compressive forces. For these reasons, some length of chain near anchors is common, even in taut mooring configurations. Clump weights and buoys can be used to impact the shape and response curve of mooring lines. In semi-taut configurations, clump weights are often attached along the chain near the touchdown point to give additional stiffness to the mooring system and reduce the amount of uplift that could be experienced at the anchors.

Anchor types can be categorized based on either their holding capacity mechanism or their installation method. The two primary holding capacity mechanisms in seabed soils are frictional resistance and bearing resistance. In general, pile anchors use the frictional resistance from their length, and plate anchors use the bearing resistance of the surrounding soil. Other holding capacity mechanisms include suction and gravity. In terms of installation, anchors are primarily installed through drag embedment, driven embedment (i.e., driven, drilled, suction), or dynamic embedment. Drag embedment anchors are plate anchors that primarily rely on bearing resistance and are installed by drag embedment. They have a very limited vertical load capability; large uplift loads can result in the anchor being dragged toward the surface and unembedding. Vertical load anchors have similar capacity and installation mechanisms but reorient themselves after embedment so that they can accommodate significant uplift angles. Suction pile anchors are pile anchors that use both frictional resistance and suction and are directly embedded. Many other types of anchors exist, such as drilled piles or vertical load anchors, that are designed for certain seabed types or mooring loads. Both the capacity mechanism and installation mechanism affect the suitability of a given anchor type to specific ground characteristics. For example, drilled and grouted piles are not suitable in sand, while suction piles are not installable in rock. In Task 49, anchor capacity characteristics and installation mechanisms will be considered to select appropriate anchor types, and anchors will be sized to provide sufficient capacity for the mooring loads.

2.2.3 Available Mooring Designs

Existing and planned floating wind turbine projects have mooring designs that include a variety of configurations within shallow and moderate depth ranges. Table 7 outlines mooring system configurations that are featured in recent or proposed projects for which some information is available.

Table 7. Mooring System Examples From Recent and Proposed Projects

Project	Mooring Arrangement	Mooring Line Configuration	Expected Reasoning
WindFloat Atlantic	3 semi-taut rope-chain mooring lines	HMPE rope through the water column and chain at the seabed, with clump weights distributed near the touchdown point and reduced chain diameter nearer the anchor, drag embedment anchor	Using HMPE mooring lines enables lower mooring cost and weight compared to spiral-strand steel wire or chain during installation and future disconnection
Hywind Scotland	3 catenary chain mooring lines	Ballasted catenary chain mooring line with a weight near the midpoint, suction pile anchors	Clump weight near line midpoint provides additional tension and restoring
Hywind Tampen	3 catenary chain and wire rope mooring lines	Spiral-strand steel wire rope through water column and chain at the seabed, inline tensioner on some lines, suction pile anchors (some shared)	Wire rope provides greater weight and cost efficiency for greater depth and a larger array
FLAGSHIP	3 catenary chain mooring lines	Catenary chain with 162-mm chain in the upper 50 m and142-mm chain in the lower part, use of clump weights in some	Large top chain used to account for expected corrosion and a large chain grade is chosen to protect against fatigue damage
Eolink	Single-point mooring with 2	Buoy provides single mooring point, 2 nylon	Single-point mooring configuration allows the floating platform and

Project	Mooring Arrangement	Mooring Line Configuration	Expected Reasoning
	nylon hawsers and 3 semi-taut mooring lines	hawsers tether the platform to the single-point, 3 semi-taut mooring lines connect to suction pile anchors	turbine to weathervane with the wind and allows a single point of mooring/cable disconnection for marine operations
FloatGen	6 mooring lines made of synthetic fiber (nylon)	Nylon mooring lines with chain segments at the anchor and fairlead	Nylon absorbs wave-induced platform motions, has adequate fatigue performance, and does not corrode. Chain length was minimized to minimize the mooring radius. Use of chain near the seabed avoids rope chafing degradation at the seabed.
Provence Grand Large	TLP with 3 double tension legs (6 tendons total)	Three bundles of two mooring legs each. Tension legs are majority wire rope with short top and bottom chain sections for connection/installation, attached to gravity-suction anchors	TLP platform requires stiff high-tension mooring lines, as provided by wire rope. Suction-gravity anchors are suited for TLP because weight provides steady vertical capacity and suction can provide strong capacity against dynamic loads.
DemoSATH	Single-point turret mooring with 6 semi-taut rope-chain mooring lines	Single-point mooring from turret rigidly attached to platform, 6 semi-taut mooring lines with rope and chain, drag embedment anchors	Concrete platform is directional and designed to face into the waves, so a single-point mooring allows weathervaning and simplifies installation
New England Aqua Ventus I	3 lines considering catenary, semi-taut, and taut configurations	Catenary chain, semi-taut rope-chain, or taut rope configuration (with minimal if any chain at seabed), drag embedment anchors	Three options offer trade-offs between minimizing seabed impact and logistical simplicity

Many existing mooring system designs from research projects and studies are available in enough detail to serve as starting points for use in the reference designs. Table 8 lists parameters of a selection of existing mooring designs that are available to Task 49 and that can inform the starting point of mooring system designs for the reference arrays. These are provided as examples rather than being a complete list.

Table 8. Available Mooring Designs From Previous Projects

Type	Water Depth (m)	Turbine Size (MW)	Nominal Diameter (mm)	Linear Density (kg/m)	Total Length (m)	Anchoring Radius (m)	Source
Chain	200	15	185	685	850	838	Univ. of Maine
Chain	50	15	185	685	381	431	NREL
Chain	200	15	216	286.56	832		COREWIND
Chain and clump weights	150	15	185	597	835	837.6	HYPERWIND
Chain and nylon	100	15	Asymmetric mooring design more detailed design in COREWIND D2.2				COREWIND
Chain and polyester	870	15	Asymmetric mooring design more detailed design in COREWIND D2.2				COREWIND
Polyester	600	10	175	24	1374	1300	NREL
Nylon	36	2	216	30.5			[28]

2.2.4 Mooring Line Property Assumptions

For consistency in the reference designs, a common set of mooring line material property assumptions is specified. These provide relations that define the following properties as a function of a mooring line's diameter, depending on the line type:

- Nominal diameter: the diameter defining the mooring line size—typically, the rope diameter or the diameter of the bars used to form chain links
- Volume-equivalent diameter: the diameter of a cylinder having the same buoyancy force or volumetric displacement as the mooring line
- Linear mass density: the mass per unit length of the mooring line
- Minimum breaking load (MBL): the rated tensile strength of the mooring line
- Axial stiffness (EA): the sectional stiffness of the mooring line (dividing this by the mooring line length will give the spring constant of the mooring line).

Chain mooring line property assumptions are shown in Table 9, where d is the nominal diameter in meters.

Table 9. Studless and Studlink Chain Property Scaling Functions of *d* (in m)

Chain	Volume-Equivalent Diameter (m)	Linear Mass Density (kg/m)	Minimum Breaking Load (Newtons [N])	Axial Stiffness (N)
Studless Chain (R4)	$1.80\ d$	$20.0e3\ d^2$	$-2.19e9\ d^3 + 1.21e9\ d^2 + 9.11e2\ d$	$8.56e10\ d^2 - 3.93e7\ d^3$
Stud Link Chain (R4)	$1.89\ d$	$21.9e3\ d^2$	$-2.19e9\ d^3 + 1.21e9\ d^2 + 9.11e2\ d$	$8.80e10\ d^2$

Table 10 shows the mooring line properties for the synthetic rope line options, including the specific gravity of the material. The volume-equivalent diameter can then be calculated using the density of the material and the mass. Additionally, both the static and dynamic stiffness of synthetic ropes should be considered in the design and modeling of the mooring lines. Modeling the nonlinear elastic characteristics of fiber ropes is an active research topic. For practicality in the reference designs, we use a simplified set of assumptions consisting of a quasi-static stiffness for slow/mean response and a dynamic stiffness for wave-frequency response, which can be scaled with the mean mooring tension. In the equations, the mean load, L_m, is taken as a fraction of the MBL. The stiffness values are assumed to scale with the mooring line strength, and so are presented as a relative factor. Note that the HMPE properties were determined using regression curves across a wide range of available options, so they reflect generic, averaged HMPE properties.

Table 10. Synthetic Fiber Rope Property Scaling Functions of *d* (in m)

Rope	Volume-equivalent diameter (m)	Linear mass density (kg/m)	MBL (N)	Quasi-static EA/MBL (K_{rs}) (-)	Dynamic EA/MBL (K_{rd}) (-)
Polyester	$0.79\ d$	$679\ d^2$	$308e6\ d^2$	14	$11.615 + 0.396 L_m$
Nylon	$0.81\ d$	$585\ d^2$	$207e6\ d^2 + 230e6\ d^3$	5	$2.08 + 0.39 L_m$
HMPE	$0.80\ d$	$496\ d^2$	$580e6\ d^2 + 651e6\ d^3$	56	$59 + 0.54 L_m$

Properties of sheathed steel spiral wire are provided in Table 11.

Table 11. Wire Rope Property Scaling Functions of *d* (in m)

Rope	Volume-equivalent diameter (m)	Linear mass density (kg/m)	MBL (N)	EA (N)
Sheathed wire rope	$1.18\ d$	$5{,}293\ d^2$	$1{,}022e6\ d^2$	$97.1e9\ d^2$

2.3 Power Cables

Power cables in a floating wind array include array cables that transmit power between turbines and to the substation and an export cable from the substation to shore. The array cables typically have dynamic sections (suspended in the water column) and static sections (lying along the seabed). As described in Section 1.2, the scope of the reference designs includes the array cables (both static and dynamic sections) but excludes the export cable.

Power cables are classified by their intended operating voltage according to the IEC-60183 [29] format: U_0/U (U_m), where U_0 is the rated root-mean-square (RMS) voltage between any conductor and the screen (neutral), U is the RMS voltage between any two conductors, and U_m is the maximum voltage between any two conductors. The main difference between different voltage ratings is the degree of insulation between the conductors; higher voltages require thicker insulation and perhaps different insulation materials.

Typical voltages of power cables used in offshore wind farms are as follows [30]:

- 18/33 (36) kV – typical array cable voltage in existing floating offshore wind farms.
- 36/66 (72.5) kV – typical array cable voltage for large wind farms with >5-MW turbines.
- 76/132 (145) kV – typical export cable voltage in the UK
- 127/220 (245) kV – potential export cable voltage for large wind farms.

Cables are typically referred to by the U value, which is what will be used here.

Considering a floating wind array with a power capacity in the range of 300 MW to 1 gigawatt (GW), the array cables would be expected to be 66 kV or 132 kV. Cables rated at 66 kV are already in use for large FOWTs in operation today [31], and data for such cables are available [32]. There is a growing demand for 132-kV cables, and research is ongoing to address the challenges of these higher-voltage cables, especially for dynamic cables where the deflections and loads are greatest [33], [34]. To follow existing technologies, the array cables considered in Task 49 will be 66 kV.

Export cables have higher voltages to efficiently transmit the total output of a floating wind farm over large distances. The export cable for an array of 300 MW or greater is expected to be at a voltage of 132–250 kV. However, the export cable is out of scope for the Task 49 reference array designs.

The other variable that determines a power cable's capacity is its conductor area—the cross-sectional area of its conductors. The conductor area determines the cable's current capacity, which is multiplied by the voltage rating to determine the power transmission capacity. Cables are typically manufactured according to standard conductor area sizes, which will be discussed in the next subsections. The conductor material is also an important variable. Copper is the most common choice and is the assumed material for the reference designs.

2.3.1 Array Cable Topology

Individual array cables connect multiple FOWTs to form a feeder or string. A wind farm can have several feeders. From each feeder, a terminal cable connects to one or more offshore substations [35]. The feeders can also connect to one FOWT instead of an extra substation, depending on the array size. This approach is common in the current operating floating wind arrays, which do not have large numbers of turbines. From the substation, an export cable transmits the power to the transmission grid onshore (or, in the case of Hywind Tampen, to an offshore load).

The network topology of the array cables can follow a variety of forms (Figure 5). Radial networks feature strings of turbines with only one line, minimizing cost but risking transmission of multiple turbines if a cable fails. Ring topologies feature a loop that provides redundancy, avoiding interruptions if a cable fails. The specific array cable design must also consider the locations of the turbines along with seabed constraints to determine the most practical choice of topology and cable routing.

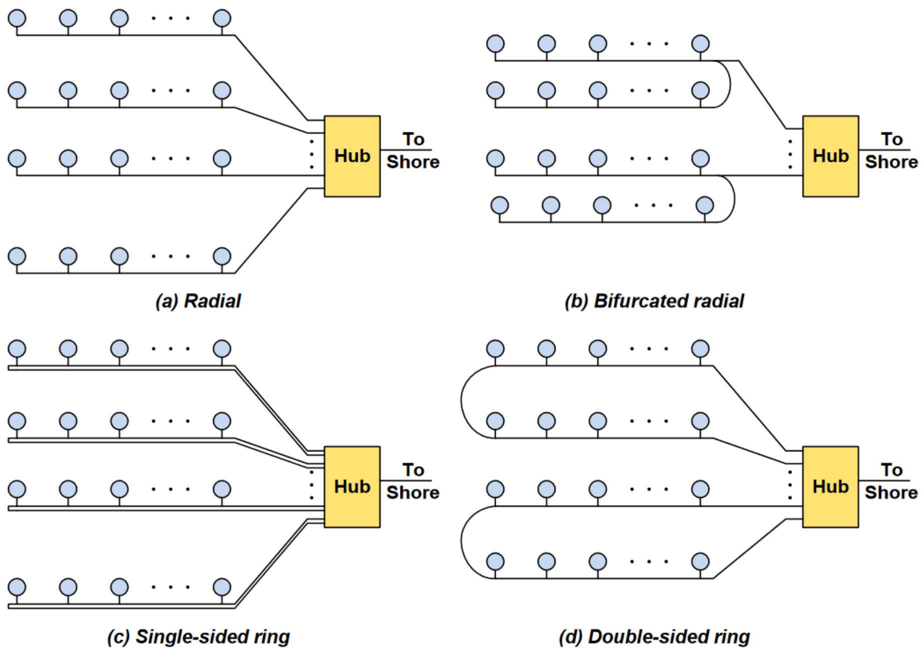


Figure 5. Array cable topologies: (a) radial, (b) bifurcated radial, (c) single-sided ring, and (d) double-sided ring [36]

Power transmission capacity and efficiency are important factors in the choice of cable and topology. The cable conductor cross-sectional area scales the power capacity of the cable and also has a large effect on the cable cost. While the array cable voltage needs to be uniform, the conductor area can be varied across an array for efficiency. In some cases, it is most practical to use a single cable size for all array cables in an offshore wind farm. In other cases, smaller cable cross sections are used at the end of the feeders to reduce cost, and larger cables are used closer to the offshore substation because those cable sections have to transmit power from more turbines (for example, the Lillgrund offshore wind farm in southern Sweden uses three different cable sizes [37]). The cable cross section determines how many turbines can be connected upstream of the cable section in question.

Different cable sizes will also affect the cost of the dynamic cable section and its ancillary components such as buoyancy modules, bend stiffeners, and clamps. The installed costs of the dynamic cables and their ancillary components can be significant and should be considered in cost analyses.

Figure 6, taken from [38], shows an example of an optimized cable layout for a FOWT array.

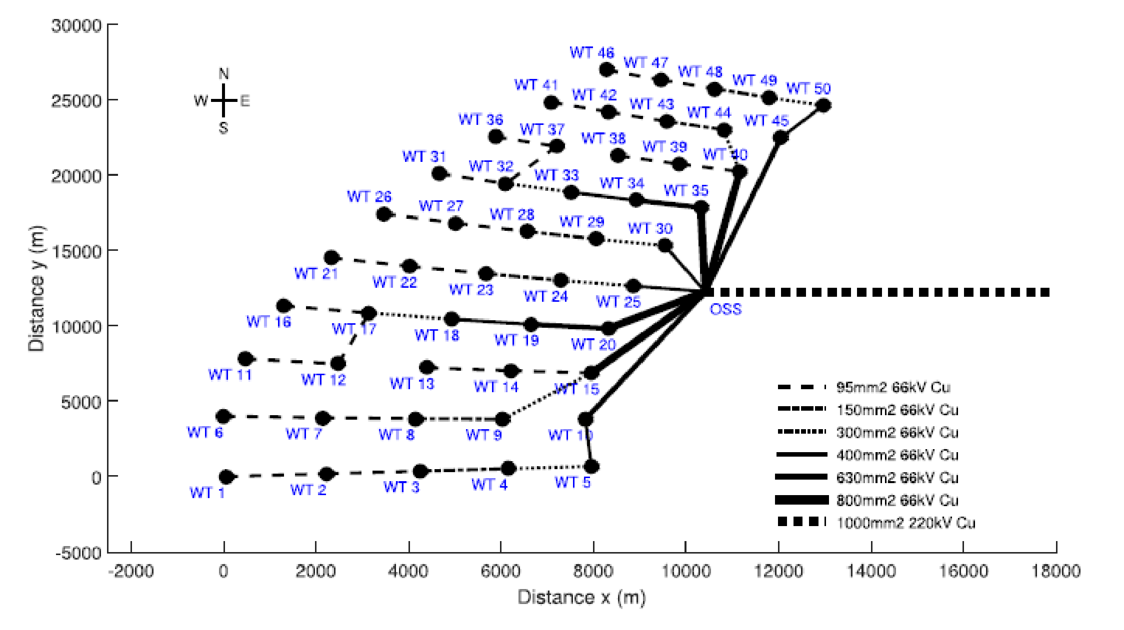


Figure 6. Example array cable network with varied sizes [38]

2.3.2 Dynamic Cable Types and Considerations

Dynamic power cables experience continuous dynamic loads throughout their service life. These cables are suspended from a floating platform, and typically extend to the seabed where they connect to a joint or junction that transitions to a static cable that is laid on the seafloor or buried in a trench. Dynamic power cables must survive environmental loads such as extreme weather conditions and fatigue loading due to waves, current, and movement of the floating platform, as shown in Figure 7.

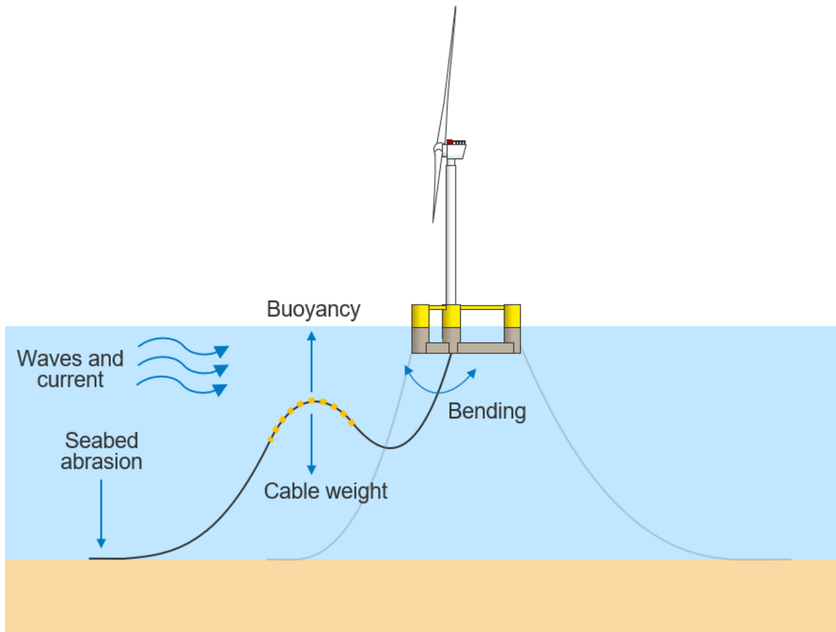
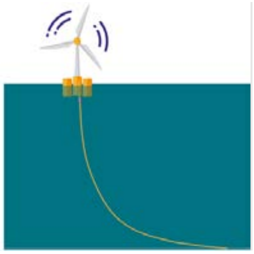
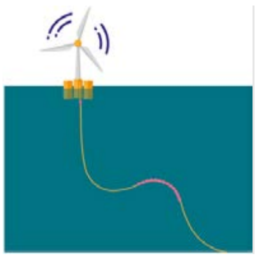
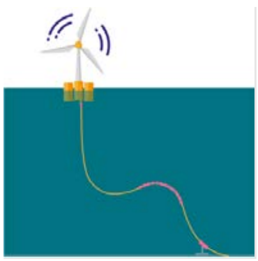
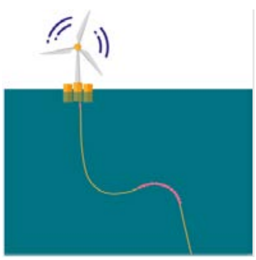
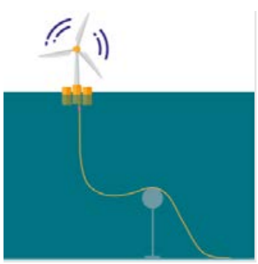


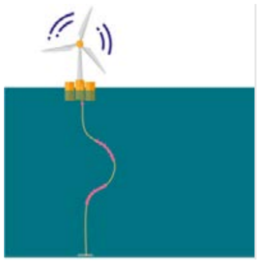
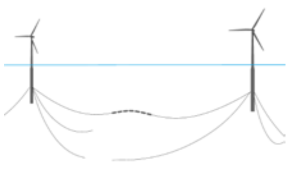
Figure 7. Environmental loading on dynamic cables for floating wind turbines

The fundamental challenge when designing a dynamic cable configuration is achieving a cable profile that will accommodate the motions of the floating platform without straining the cable beyond its limits. To achieve this, specific cable profiles are created. The primary tool for creating these profiles is the positioning of buoyancy modules that add an upward arc to certain sections (buoyancy sections) of the cable. Buoyancy modules are also useful for reducing the weight-driven tension of long cables. In addition, bend stiffeners are normally added at certain points to reduce localized bending and tethers to the seabed and can help to reduce motion at the touchdown point or resist current-induced motions and wear.

The main challenges with dynamic cables depend on water depth. In shallow water, dynamic cables tend to have lower tensions but larger bending and torsional variations. In deeper water, long suspended cable lengths cause larger tensions for dynamic cables, whereas bending is milder. The state of the art of dynamic cables is described in several references [39], [40], [41], [42], [43], [44], [45]. Table 12 summarizes typical dynamic cable configurations.

Table 12. Dynamic Cable Profile Types [46], [47]

	Configuration Type	Ancillaries	General Comments
	Catenary (freely hanging)	Bend stiffener (at hang-off), cable protection at touchdown point (TDP)	Does not decouple the motions of the FOWT from the TDP (critical for damage) Use in deep water would require distributed buoyancy to avoid excessive tensions due to weight
	Lazy wave	Buoyancy modules, bend stiffeners, cable protection (at TDP)	A common configuration; currents could cause excess TDP motion (critical for damage)
	Tethered wave (reverse pliant wave)	Tether, clamp, buoyancy modules, bend stiffeners, hold-down/hold-back anchors	A common configuration; the tether limits TDP motion, making it more suitable for areas where currents or shallow water would otherwise lead to large TDP motion
	Steep-wave	Buoyancy modules, subsea base, bend stiffeners	Cable vertically connected to a subsea base through a bend stiffener; difficult to install
	Lazy S	Buoy with anchor and tether system, clamp, bend stiffener (at hang-off)	Like lazy wave but uses a tethered subsea buoy instead of buoyancy modules

	Configuration Type	Ancillaries	General Comments
	Chinese lantern	Buoyancy modules, bend stiffener, subsea base	Often used to connect hoses to oil and gas offloading buoys; not practical for power cables
	Suspended configuration	Buoyancy modules or subsea buoys, bend stiffeners	Used for offloading hoses in oil and gas applications; coupling analysis effects

A variety of ancillary equipment is often attached to the dynamic cable to control its shape and motions and to mitigate localized bending at key locations:

- Buoyancy modules are typically axisymmetric composite bodies that are clamped around the cable at even intervals over a certain length (called a buoyancy section). Attaching buoyancy modules to the cable may be necessary to reduce the topside tensions as well to create a profile shape that decouples the touchdown point from the motions of the FOWT.
- Bend stiffeners are tapered polymer moldings that surround the cable at its attachment to the floating platform J-tube or at any attachment, such as clamps, that will cause large, localized bending. They are designed to gradually increase the cable bend stiffness where the cable is connected to the FOWT or other attached structure to avoid high localized bending [48].
- I-tubes or J-tubes, similar to a bend stiffener, control the cable's bending at the hang-off location. They have a bellmouth where the cable exits that limits how much the cable can bend.
- The seabed tether, including tether clamps, tether, and anchor, restricts the cable movement near the seabed and allows for more buoyancy on the cable for greater stability.

The hang-off section is usually the most critical location for cable bending, so common practice is to use a bend stiffener or an I-tube or J-tube with a bellmouth at that location. Either of these components is intended to limit the local bending of the cable to prevent the minimum bending radius from being reached. The shape and orientation of the bend stiffener or I/J-tube bellmouth would be carefully chosen based on the cable profile over the range of expected motion of the floating system. Bellmouths are not used as often as bend stiffeners and are less of an engineered solution because only the radius can be varied. Moreover, marine growth can damage the outer sheath.

For some cable profile types, the touchdown location is also a critical location for bending or abrasion. Depending on the soil conditions, a sleeve to provide abrasion protection or reduce bending might be necessary. Another approach is to use a tether that is anchored on the seabed and attached to the cable with a clamp to restrict touchdown point motion.

Details of cable ancillary equipment are at the edge of the Task 49 reference design scope. These components should be considered at the conceptual level but do not necessarily need to be specified in quantitative detail in the reference designs, except for where they play a large role in the cable profile and dynamic response. For example, it is important that the effect of buoyancy modules on the cable profile and dynamic response be accounted for, but details of a J-tube bellmouth are not required, as the neutral angle of the cable sets the J-tube angle.

2.3.3 Dynamic Cable Property Assumptions

For consistency in the reference designs, a standard set of cable property assumptions should be used in Task 49. Table 13 provides a set of assumed properties for 66-kV dynamic cables that can be used in the reference designs. The parameters are as follows:

- *A*: conductor cross-sectional area
- *D*: outer diameter of the cable
- *M*: linear density or mass per unit length
- *EA*: axial stiffness
- *EI*: bending stiffness (this is the approximate value after slippage is occurring within the cable)
- *MBL*: minimum breaking load, the axial load limit of the cable
- *MBR*: minimum bending radius, the radius below which cable damage will occur
- Power: the rated power transmission capacity of the cable
- Resistance: the electrical resistance per unit length of the cable; used for losses and temperature calculations.

It should be noted that the internal construction of power cables creates a nonlinear and coupled between axial and bending mechanical properties and limits. The listed MBL and MBR are approximate values to which safety factors need to be applied, considering also that combined tension and bending loads cause combined stresses for which the individual MBL and MBR limits may not apply in combination.

These values are based on reference dynamic cable models for 630 mm^2 dynamic cable [32] along with relationships to scale the properties to other conductor areas based on manufacturer data sheets and modeling assumptions.

Table 13. 66-kV Dynamic Power Cable Properties

A (mm^2)	D (m)	m (kg/m)	EA (MN)[a]	EI ($kN\text{-}m^2$)[b]	MBL (kN)	MBR (m)	Power (MW)	Resistance (ohm/km)
95	0.138	23.02	334.1	7.13	334	2.07	46	0.25
120	0.142	24.87	352.5	8.56	353	2.12	52	0.20
150	0.145	26.99	373.6	10.35	374	2.18	59	0.16
185	0.150	29.36	397.2	12.51	397	2.24	66	0.13
200	0.151	30.34	407.0	13.45	407	2.27	68	0.12
300	0.161	36.66	469.6	19.92	470	2.41	85	0.08
400	0.169	42.66	528.9	26.61	530	2.53	99	0.06
500	0.176	48.45	586.0	33.44	587	2.64	111	0.05
630	0.184	55.76	658.0	42.47	659	2.76	125	0.04
800	0.194	65.06	749.5	54.45	752	2.90	142	0.03

[a] MN = meganewton
[b]The bending stiffness values correspond to the slipping stiffness at 50 kilonewtons (kN) effective tension

Similar properties for static cables are not specified because their specifications do not have an impact on the dynamic response or floating system design.

Considering the full network of array cables, it is possible to use either a combination of dynamic cables and static cables or just dynamic cables for the array design. If both dynamic and static cables are used, then they are connected with a factory splice or a submarine joint at the seabed. If solely dynamic cables are implemented, parts of the cables will be statically placed at the seabed. The static cables or sections can be buried, stabilized with rocks or concrete mats, or placed in different ways according to the seabed conditions

2.3.4 Available Dynamic Cable Designs

Dynamic cable designs are available in the literature. Table 14 summarizes the profiles and water depths of a selection of such designs that may be relevant as starting points or comparison points for the reference array designs.

Table 14. Dynamic Power Cable Designs in the Literature

Voltage Capacity (kV)	Conductor Material	Water Depth (m)	Profile	Source
33, 66, 132	Copper	200	Lazy wave	[36]
66	Copper	320	Suspended	[49], [50], [62], [65]
66	Aluminum	200	Tethered lazy wave	[51]
11	(Unknown)	50–200	Lazy wave, catenary	[35]
6–10	Copper	200	Suspended	[64]
66	Copper	1,000	Suspended	[52]
66	Copper	200	Lazy wave	[53]

Specific designs are not chosen here for the array design and will instead be developed during the reference design work. The configuration depends heavily on the environmental conditions at the site, especially current speeds and water depth.

3 Design Requirements and Constraints

The reference designs should generally adhere to available requirements and standards for floating wind farms so that they are representative of upcoming designs. These requirements are generally aimed at ensuring the survival and safety of the technology. This section discusses general requirements for the turbine, floating platform, mooring system, and dynamic cable when designing the reference floating wind arrays. Specific load cases used to check these requirements are discussed in Section 6.4.

The design requirements generally fall into categories of position, motion, ultimate load, or fatigue load constraints. Load constraints are often dictated by safety factors that are specified in the design standards. The position/motion constraints often relate to compatibility between different parts of the system (e.g., designing the mooring system to keep platform motions within the range of the dynamic cables) and can be determined during the design process.

Some common types of constraints are as follows:

- Minimum distance between turbines
- Maximum turbine offset (absolute or relative to water depth)
- Turbine pitch and acceleration limits
- Ultimate load safety factors and fatigue life safety factors
- Ability to install and maintain
- Spatial constraints on component positions from lease area boundaries or exclusion zones
- Clearance requirements between mooring lines from different FOWTs.

Current design standards and guidelines that give comprehensive coverage of floating wind turbine systems include IEC-61400-3 [54], Det Norske Veritas (DNV) standard DNV-ST-0119 [55], and American Bureau of Shipping (ABS) Guide for Building and Classing Floating Offshore Wind Turbines [56]. These standards specify a set of design load cases (DLCs) for wind turbine structures that span a wide range of operational and nonoperational load conditions (wind and wave load, controller action, and fault scenarios). The load cases fall into different categories related to the applicable scenarios and potential failure mechanism. In DNV terminology they are referred to as limit states; in ABS terminology they are referred to as design conditions. The four categories are as follows:

- Strength or ultimate loads analysis: This may be associated with the most extreme environmental loading conditions. DNV terms this the ultimate limit state (ULS), and ABS terms this a strength analysis (“S”) under normal conditions (“N”). Regardless, the focus is assessing the ultimate structural loads that could cause failure associated with the most extreme conditions.
- Lifetime fatigue analysis: assessing the fatigue damage that could cause failure in fatigue from accumulated loading. DNV terms this the fatigue limit state (FLS), and ABS terms this the fatigue analysis (“F”).
- Failure case analysis: assess the ultimate loads in the event of a component failure. DNV terms this accidental limit state (ALS), and ABS terms this abnormal (“A”) design conditions.

- Marine operations analysis: assessing the loads and motions during temporary activities such as installation, inspection, maintenance, and repair operations. DNV terms this the serviceability limit state, and ABS terms this the temporary operations ("T") design condition.

Each of the design conditions or limit states above has certain applicable safety factors that are defined in the standards and certain specifications for what environmental conditions should be assumed. Load cases that provide the key environmental inputs for designing each part of the floating wind arrays need to be selected. The load cases should reveal the worst-case line tensions, platform offsets, cable extensions, and more, so that the designs can be iterated on to safely pass these constraints. The environmental loadings are site-dependent, and reference site conditions to be used for each reference design were developed in WP1. Section 4 provides more information on the required site condition information, and Section 6.4 provides information on the driving load cases.

The dominant design conditions used in developing the Task 49 reference designs are the ultimate and fatigue cases. A brief overview of the design conditions or limit states as considered by Task 49 is presented before going into more detail on the requirements for each component.

- An analysis of **ultimate loads** should check extreme loading on the array design (or individual parts of the array design) to ensure that peak loads and motions stay within the safe limits for each component or subsystem. Analyses for the ultimate design condition or limit state should use extreme wind, wave, and current conditions corresponding to a specific return period, depending on the specific case (typically the highest return period is 50 years). The wind, wave, and current values can be selected based on contours or distribution fits to the metocean conditions of the site. The standards describe a large set of load cases; the Task 49 reference designs will focus on the most design-driving cases. The most critical DLCs are generally those that result in the greatest loads (such as when the wind turbine is at maximum thrust force with severe waves) and under the most unfavorable wind, wave, and current directions that can be reasonably expected to occur.
- An analysis of **fatigue loads** should use a range of load cases that are representative of the system's lifetime environmental conditions. The lifetime distribution of metocean conditions (whether using discrete data points or joint probability distributions) should be binned into discrete load cases with assigned probabilities of occurrence. The condition set can be shrunk by not considering cases with very low probability, using larger bins, or even neglecting certain metocean parameters that do not have a significant effect on fatigue loads. As discussed in Section 6.4.2, currents may have a negligible role in the fatigue analysis. The mooring systems are especially sensitive to the leading directions because, unlike the wind turbine, they are at fixed headings. The design life is a key factor in the determination of ultimate load cases and the required fatigue life. Task 49 will design its reference arrays for **a design life of 25 years**.
- Analysis of **failure or fault cases** (the accidental limit state or abnormal design conditions) is not explicitly defined for the reference designs in Task 49. Relative to ultimate and fatigue load conditions, load cases for failure situations are less established and defined in the standards, and their relevance depends on judgements related to design redundancy, which are also somewhat ambiguous. Handling these considerations is considered an optional level of refinement for the reference designs.

- Analysis for **serviceability or temporary operations** is also less straightforward than the ultimate and fatigue loads analyses, and it is at the margin of the Task 49 reference design scope. It will be considered an optional aspect for the designs.

The following subsections discuss the various design requirements and constraints that apply to each part of a floating wind array system. The focus is on the requirements that will affect the scope of the reference array design efforts related to the turbine, platform, mooring lines, anchors, and power cables. For generality, we do not confine the discussion to a single set of standards, and we discuss configurations in general, though the degree of depth is based on the needs of the Task 49 reference designs. Local rules and regulations should be considered, and the regional supply chain could play a large role in design decisions. However, the scope of WP2 is to use general assumptions and constraints that are broadly representative.

3.1 Wind Turbine and Floating Platform

This section describes constraints on the floating wind turbine global response caused by turbine or serviceability requirements. The constraints are in terms of allowable motions and are divided into four categories:

- **Survival limits** beyond which the mechanical components of a parked wind turbine can be damaged
- **Operational limits** under which the wind turbine can operate at full capacity without damage or unacceptable wear on the blades and the drivetrain
- **Workability limits** under which service can be performed on the turbines
- **Transferability limits** under which technicians can be safely transferred to turbines from a vessel.

These four categories focus on constraints dictated by the turbine or by the need for personnel to work on the floating platform. Maximum horizontal offsets affect the power cable loading and can also affect the array layout and wake effects. Therefore, horizontal motion constraints will be determined during the array design process rather than being specified up front.

3.1.1 Turbine

As the floating wind industry is still evolving, characterized by ongoing innovation in a broad range of concepts, it is impractical to predict the roles of various contractors in future floating wind projects. For example, Siemens delivers both the steel towers and the turbines to Hywind Tampen while Norwegian contractors construct and assemble the concrete platforms and transport them to the site. Conversely, the tower and platform of WindCrete are designed as a single concrete structure. In addition, a variety of more complex support structures involving both single- and multi-legged towers resting on semisubmersibles have been proposed. The constraints discussed in this section therefore focus on the rotor-nacelle assembly, excluding the tower and floating platform. This separation is useful because the turbine itself, as understood here, is a fixed and externally imposed constraint on the site-specific design of the floating support structure.

Motions related to the rotor tilt and nacelle acceleration are of greatest concern for the wind turbine. Tilt and accelerations can impact turbine survivability, and mean tilt can affect power production. These constraints will, to various degrees, impact the design of the support structures and the configuration of floating arrays. A targeted wind farm capacity factor may dictate hub acceleration and tower tilt angle limits, which in turn may drive the floating platform and mooring system designs. The cut-out wind speed affects the uptime of the wind turbine and thus the fatigue damage. The rotor thrust is typically well below its maximum value at cut-out wind speed. Still, the combined wind and wave loads at cut-out wind speed may affect the extreme loads for a FOWT.

A survey among turbine manufacturers, energy companies, and research institutions carried out by NORCE in a previous project suggests approximate values for maximum tower tilt angle and hub acceleration. Another set of rotation limits is provided in the COREWIND design basis. Table 15 provides the data from NORCE and COREWIND.

Table 15. Turbine Angle and Acceleration Limits From COREWIND and NORCE

	COREWIND	NORCE
Operation		
Pitch (10-minute [min] average)	2°	
Pitch (10-min std. dev.)	1°	
Pitch (max)	5°	5°–7°
Yaw (10-min. std. dev.)	3°	
Yaw (max)	15°	
Tower top acceleration (max)[a]		0.3 g
Idling/survival		
Pitch (10-min average)	5°	
Pitch (max)	7°	10°
Tower top acceleration (max)		0.6 g

[a] g is gravitational acceleration

These numbers provide general context and guidance, although they are not universal. For example, the 2-degree limit on mean pitch from COREWIND is more stringent than many existing designs. For the purposes of the Task 49 reference designs, we do not specify absolute limits but instead specify that the array design should not worsen the operating conditions on the turbine. This approach is suited to the use of the IEA Wind 15-MW reference turbine, where the turbine constraints are not as well defined as those of a real turbine. As such, the response of the floating wind turbine within the reference array designs should not surpass the original constraints of the reference floating wind turbine design.

The VolturnUS-S reference floating wind turbine design definition report [6] identifies the following maximum response values:

- Maximum platform pitch: 7.5°

- Maximum platform heave: 7 m
- Maximum nacelle acceleration: 2.2 m/s^2
- Maximum blade tip deflection: 20 m.

These maximum values are specific to the load cases analyzed for the original reference design and may need to be reconsidered if the metocean conditions are significantly different.

3.1.2 Workability

O&M costs make up a significant portion of overall wind farm costs, estimated to be 25%–30% of a farm LCOE [57]. A floating wind farm O&M strategy includes both scheduled and unscheduled maintenance, which in either case can require technicians to do work onboard the asset. Understanding the motions of FOWTs is essential for preparing an O&M plan compliant with health, safety, and environment requirements; human comfort; and the general ability of technicians to perform the work. O&M strategies are especially important for floating offshore wind project feasibility because adverse working conditions would require O&M to be carried out by tow-to-port interventions, even for minor repairs or troubleshooting.

Workability is categorized by the ISO 2631-1(1997) [58] as health, comfort, perception, and motion sickness. These categorizations are divided into two motion-frequency-dependent groups:

- 0.5 hertz (Hz) to 80 Hz for health, comfort, and perception
- 0.1 Hz to 0.5 Hz for motion sickness.

Workability metrics are taken here to be in the form of accelerations and tilt angles, with acceleration being the driving metric. The values can vary considerably between different support structure designs. Kaptan et al. [59] studied the human exposure during maintenance onboard a spar and two semisubmersible floating wind turbines. A frequency-domain approach was adopted to study the dynamic response of three 5-MW floating wind turbines and criteria for human exposure were considered. It was found that the lateral accelerations of OC3-Hywind and CSC Semisubmersible are significantly larger at the nacelle level than at the platform level, whereas the opposite was observed for WindFloat.

Motion limits for different activity categories according to Nordforsk [60] are shown in Table 16, where the quantities are maximum permissible RMS values.

Table 16. Maximum RMS Motion Combination Values for Floating Wind Applications

Category	Vertical Acceleration	Lateral Acceleration	Roll
Light manual work	0.2 g	0.1 g	6°
Heavy manual work	0.15 g	0.07 g	4°
Intellectual work	0.10 g	0.05 g	3°
Transit passenger	0.05 g	0.04 g	2.5°
Cruise liner	0.02 g	0.03 g	2°

This means that the combined motion of 0.05-g vertical acceleration, 0.04-g lateral acceleration and maximum 2.5° roll amplitude are classified as a nonworkable condition.

A workability index can be defined as the ratio of workable time (the summed amount of time during which the workability thresholds are not exceeded) to the total time duration, based on simulation of the lifetime distribution of metocean conditions, following the methodology described in [61].

3.1.3 Accessibility

When modeling O&M strategies and costs for fixed-bottom offshore wind installations, accessibility is often computed based solely on the significant wave height limitations for vessel operations. The significant wave height limits are assumed to be 1.5–1.75 m for crew transfer vessels (CTVs) and 2.25–2.5 m for service operations vessels (SOVs). In addition, helicopter interventions are limited by the wind speed (the limit is assumed to be 22 m/s) and possibly by the sea state with respect to emergency ditching, which depends on the helicopter certification.

For FOWTs, it is imperative to consider the motions of the floating platform, which are affected by a larger set of parameters like wave height, wave period, wave heading, and swell, and their combined probability of occurrence. For vessel interventions, the vessel-platform multibody hydrodynamic interactions should be considered. For helicopter interventions, the nacelle motions need consideration to assess the feasibility of hoisting in different metocean conditions. These factors demonstrate the importance of considering more than just wave height limits when assessing the impact on availability.

In Task 49, the level of analysis when assessing workability will vary depending on the purpose of the analysis. Some baseline assumptions about vessel limits that can be used in such an analysis are given in Section 5.

3.2 Mooring System

The mooring system should be designed to limit the offset range of the platform and to survive the expected range of loading conditions over the design life. Mooring system designs can be refined to minimize cost while meeting the necessary requirements. Mooring system engineering requirements are driven mainly by strength, fatigue, performance, and installability (ability to be installed). Strength requirements ensure that the mooring system will survive expected extreme storms and the most demanding operating conditions with a specified safety factor. Fatigue requirements verify that the mooring system is capable of withstanding the fatigue damage from cyclic loading over the lifetime of the system. The effects of corrosion, marine growth, abrasion with the seabed, and damage from compressive forces can be important and require consideration. The inspectability (ability to be inspected) of components affects the safety factors required. Finally, performance requirements govern the intended platform motions and limitations to protect the power cable and overall system. The mooring system can be adjusted by changing the line material, line diameter, and profile or configuration to meet these requirements while lowering cost.

The anchors in a mooring system need to be suitable for the seabed soil characteristics and need to provide sufficient holding capacity to resist the loads from the mooring system. There is a variety of suitable anchor technologies, with variation in installation processes, suitability for different directions of loading, and compatibility with different soil types. Anchor selection and sizing must therefore be compatible with both the seabed conditions and the mooring system design. Regarding compatibility between anchors and mooring lines, the loading direction is a key factor. For example, drag embedment anchors have very limited vertical load capacity, so they are only suitable if the mooring loads are confirmed to be near-horizontal at all times. In the case of shared anchors between several platforms, anchors need to support multidirectional loads and, in the case of taut mooring lines, a larger vertical load component. Anchor selection and positioning are dependent on compatibility with the seabed and installation procedure. Installation procedures and anchor positioning accuracy and movability (e.g., anchor dragging) considerations can also affect spatial constraints for distances to other mooring system components or power cables.

For ultimate load analysis, a statistical fitting of the maximum tension values obtained from time-domain simulations with multiple seeds can be used to calculate the ultimate loads used in the various mooring system requirements discussed above. The general procedure is as follows:

1. Run the load case multiple times with different wind-wave realizations. The number of required realizations depends on convergence of the targeted statistical quantity (for example, the most probable maxima).
2. Extract the maximum tension, or the peak tensions, from each realization.
3. Fit a probability density function to the extracted maximum/peak tensions (e.g., a Gumbel, Frechet, or Weibull distribution depending on which fits the data best).
4. Select the design tension based on the empirical fitted distribution either as a function of the most probable maximum value from the fitted density function or as a higher fractile, based on the applicable standards.

For fatigue analysis, the loads need to be simulated across many cases that collectively represent the joint distribution of metocean conditions. Because mooring lines have specific headings, and metocean conditions often have a highly nonuniform directional distribution, the fatigue loads can vary strongly depending on mooring line heading. Wind and wave headings are therefore a crucial part of the metocean cases. In an array context, the wakes of upwind turbines can change the wind speed and increase the turbulence intensity felt by a given turbine. These factors can increase fatigue loads and should therefore be considered in the analysis. Methods for doing so are discussed in Section 6.4.2.

Mooring line fatigue can have a strong dependence on the line heading relative to the dominant wind direction, so adjusting the headings can provide potential for reducing the fatigue. Therefore, Task 49 will use turbine spacing assumptions that are mildly conservative at the component design stage. If small fatigue exceedances are found on certain mooring lines later in the design process, they can likely be mitigated by small heading adjustments during the layout design stage.

The assumed design life of the floating offshore wind system is used when accounting for fatigue and corrosion of the mooring system. Most standards specify a design life of at least 20 years, so the assumed 25-year design life is consistent with those standards.

There are a number of design standards that apply to the design of mooring systems for offshore wind turbines, mostly originating from the oil and gas industry. The mooring systems of the reference array designs should be developed such that they meet the most important criteria of an applicable standard, but we do not specify a certain standard that should be followed. A general description of the ULS design approach for mooring lines is provided, along with the specific requirements from the DNV and American Petroleum Institute (API) standards, as these standards are most commonly used by the contributors of WP2.

3.2.1 DNV Requirements

DNV-ST-0119 [55], Floating Wind Turbine Structures, gives requirements for mooring systems. It provides two consequence classes: Consequence Class 1 for failures that are unlikely to cause unacceptable consequences like loss of life, and Consequence Class 2 for failures that may lead to unacceptable consequences, such as loss of life. Unless otherwise specified, the FOWT structure and its stationkeeping system shall be designed to Consequence Class 1 with a target annual probability of failure threshold of 10^{-4}. This requirement reflects that the floating structure is unmanned during severe environmental loading conditions.

DNV-ST-0119 specifies that the design tension of a mooring line, T_d, is the sum of two factored characteristic tension components:

$$T_d = \gamma_{mean} \times T_{c,mean} + \gamma_{dyn} \times T_{c,dyn} \tag{1}$$

where $T_{c,mean}$ is the characteristic mean tension and $T_{c,dyn}$ is the characteristic dynamic tension. Coefficients γ_{mean} and γ_{dyn} are load factors for mean and dynamic tension, respectively.

DNV-ST-0119 Section 8.2.2.6 specifies load factors for mooring lines that depend on whether the analysis is for the ultimate, fatigue, or accidental limit state (ULS, FLS, and ALS, respectively). These load factors are summarized in Table 17.

Table 17. Load Factors Depending on Limit State and Safety Class From DNVGL-ST-0119 Section 8.2.2.6.

Limit State	Load Factor	Consequence Class	
		1	2
ULS	γ_{mean}	1.3	1.5
ULS	γ_{dyn}	1.75	2.2
ALS	γ_{mean}	1	1
ALS	γ_{dyn}	1.1	1.25

In the design of a mooring system, these limit states are used to ensure the survivability and safety of the system. For ALS purposes, T_d is computed under a damaged condition of the mooring system, meaning one mooring line is broken.

The ULS and ALS design criterion is

$$T_d < S_c \quad (2)$$

where S_c is the characteristic capacity of the mooring component. When statistics of the breaking strength of a component are not available, then the characteristic capacity of the body of the mooring line may be obtained from the minimum breaking strength, S_{mbs}, of new components as

$$S_c = 0.95 \times S_{mbs}. \quad (3)$$

DNV-ST-0119 [55] Section 9 provides design guidelines for anchors (as does DNV-OS-J103), including factors to be used for different anchor types, limit states, and consequence classes. The load on the anchor is taken as the tension at the interface of the mooring line and the anchor, computed following Equation (1). The anchor resistance is based on the anchor capacity considering site-specific soil characteristics. The characteristic anchor resistance can be estimated empirically or based on test data. The design anchor resistance, R_d, is calculated from the characteristic anchor resistance, R_c, as

$$R_d = \frac{R_c}{\gamma_m} \quad (4)$$

where γ_m is the material factor. The material factors for different types of anchors and for different consequence classes are summarized in Table 18.

Table 18. Anchor Soil Material Factors From DNV-ST-0119

Anchor Type	Consequence Class 1		Consequence Class 2	
	ULS	ALS	ULS	ALS
Pile anchors	1.3	1.0	1.3	1.0
Gravity anchors	1.3	1.0	1.3	1.0
Suction anchors	1.2	1.0	1.2	1.2
Free-fall anchors	1.3	1.0	1.3	1.0
Fluke anchors	1.3	1.0	1.3	1.3
Plate anchors	1.4	1.0	1.4	1.3

DNV-ST-0119 [55] notes that suction anchors may have coupling between the vertical and horizontal modes at failure, making the resulting resistance lower than the vector sum of uncoupled maximum horizontal and vertical resistances.

Fatigue should be considered for the mooring lines. For the FLS, the cumulative fatigue damage is accumulated for the mooring line components from repeated, cyclic loading. The fatigue damage should be calculated based on Miner's rule and by summing up the fatigue damages d_i from individual sea states:

$$d_c = \sum_{i=1}^{n} d_i. \quad (5)$$

The n environmental conditions should be chosen to appropriately discretize the long-term environment that the mooring system is subject to. Each environmental state should consist of heading angles, wind, wave, and current parameters, as well as the probability of occurrence of that environmental state.

The fatigue damage in each sea state is defined as the ratio of the number of stress cycles encountered in state i during the design life to the number of cycles to failure. DNV recommends that the number of cycles to failure is computed using an S-N curve, which follows the following equation:

$$n_c(s) = a_D s^{-m} \quad (6)$$

where n_c is the number of stress ranges to failure, s is the stress range in megapascals, a_D is the intercept parameter, and m is the slope of the S-N curve. The parameters a_D and m are specific to the material. The DNV-recommended fatigue curve parameters are shown in Table 19.

Table 19. S-N Curve Parameters for Different Mooring Materials

Mooring Material	a_D	m
Stud chain	1.2×10^{11}	3.0
Studless chain	6.0×10^{10}	3.0
Stranded rope	3.4×10^{14}	4.0
Spiral rope	1.7×10^{17}	4.8

The number of stress cycles in each environmental condition can be determined using time-domain or frequency-domain analysis. A time-domain approach means simulating the mooring system in each environmental condition and using rainflow counting techniques to count the number of stress cycles. A frequency-domain approach would instead compute damage using the standard deviation of the stress process for wave-frequency and low-frequency components, as well as the mean upcrossing rate. The frequency-domain approach is faster, but potentially less accurate. DNV-GL-OS-E301 section F 300 provides details for either approach.

Table 20 shows the design fatigue factors (DFFs) specified in DNV-ST-0119 Section 8.2.5.1.

Table 20. Design Fatigue Factors From DNV-ST-0119

Consequence Class	Design Fatigue Factor
1	5
2	10

DNV-OS-E301 states that if a mooring line is regularly inspected, then a safety factor of 3 is applicable. These safety factors are applied to the fatigue damage or fatigue life.

3.2.2 American Bureau of Shipping Requirements

The ABS gives guidelines for the design of mooring systems for floating wind turbines through its Guide for Building and Classing Floating Offshore Wind Turbines [56] and several other guidance documents. ABS requirements frequently refer to API standards for additional details and recommendations. Similar to the DNV standards, the ABS standards specify design conditions that pertain to ultimate loads and fatigue loads of the mooring system.

According to the ABS Guide for Building and Classing Floating Offshore Wind Turbines [56], the safety factors for normal (equivalent to ULS) and abnormal (equivalent to ALS) design conditions relate to the state of the structure (intact and damaged, respectively) and whether the mooring system has redundancy. The guidance assumes that the mooring systems are properly maintained and inspected, and that the mooring connecting hardware has equivalent or higher breaking strength than the mooring lines. Table 21 lists the recommended ABS guidelines for normal and abnormal safety factors. These safety factors are recommended for steel mooring lines. For simplicity, Task 49 suggests applying them for all line types. The safety factors align with API RP 2SK recommendations, with a 20% increase for nonredundant systems [62].

Table 21. ABS Strength Safety Factors for Normal and Abnormal Design Conditions

Loading Condition	Redundancy	Design Condition	Safety Factor
Design Load Cases	Redundant	Intact	1.67
		Damaged with one broken mooring line	1.05
		Transient with one broken mooring line	1.05
	Nonredundant	Intact	2.0
Survival Load Cases	Redundant or nonredundant	Intact	1.05

ABS guidelines for computing ultimate loads are different from the DNV approach. ABS does not specify separate load factors for mean and dynamic tensions. Instead, a safety factor is applied directly to the most probable maximum line tension. Additionally, ABS designs for the rated MBL of the components rather than the characteristic capacity.

ABS guidance for anchors uses a similar approach for safety factors as the guidance for mooring line components. The safety factors depend on the anchor type, loading condition (design or survival load case), the mooring system redundancy, and the design condition (intact or damaged). Table 22 lists anchor safety factors specified by ABS [56] and suction pile safety factors from API RP 2SK [62].

Table 22. Anchor Safety Factors From ABS and API

Loading Condition	Redundancy	Anchor Type	Design Condition	Safety Factor
Design load cases	Redundant	Drag anchor	Intact	1.5
			Damaged	1.0
		Vertical load anchor or plate anchor	Intact	2.0
			Damaged	1.5
		Suction piles	Intact	1.6 lateral 2.0 axial
			Damaged	1.2 lateral 1.5 axial
	Nonredundant	Any	Intact	20% increase in safety factor for redundant design
Survival load cases	Nonredundant or redundant	Any	Intact	1.05

These safety factors are meant to be applied when comparing the ultimate loads from the mooring lines on the anchors to the expected anchor holding capacities.

ABS specifies calculation of fatigue on mooring line components according to Miner's rule for linear damage accumulation, as discussed in the previous section. Instead of an S-N curve, ABS recommends that the resistance of the line to fatigue damage is modeled using a T-N curve, which gives the number of cycles to failure (*N*) as a function of normalized tension range (*T*). A T-N curve follows the equation

$$n(t) = k\left(\frac{T}{RBS}\right)^{-m} \tag{7}$$

where *N* is the number of cycles to failure, *T* is the tension range, and *RBS* is the reference breaking strength. The values *m* and *k* are constraints that are specific to the material or component. Table 23 lists *m* and *k* values for common mooring components.

Table 23. T-N Curve Parameters for Different Mooring Materials

Component	*m*	*k*
Common studlink	3.0	1,000
Common studless link	3.0	316
Baldt and Kenter connecting link	3.0	178
Multistrand wire rope	4.09	$10^{(3.2 - 2.79\ Lm)}$
Spiral-strand wire rope	5.05	$10^{(3.25 - 3.4\ Lm)}$

ABS specifies the same redundant/nonredundant DFFs as DNV for systems that cannot be inspected or repaired (but uses FDF instead of DFF). However, ABS also specifies a lower DFF if the mooring systems are inspectable and repairable, as shown in Table 24. In general, Task 49 will apply a DFF factor of 3 for nonredundant but inspectable and repairable designs.

Table 24. Design Fatigue Factors From ABS

Redundancy	Inspectable and Repairable	Design Fatigue Factors
Redundant	Yes	2
	No	5
Nonredundant	Yes	3
	No	10

3.2.3 General Stationkeeping and Stability Requirements

Because the main purpose of the mooring system is to provide stationkeeping, its ability to limit the floating platform horizontal motions is the most fundamental performance requirement. This performance requirement can generally be expressed as a maximum permissible mean horizontal offset and extreme horizontal offset in any direction. This offset is sometimes referred to as the watch circle radius. The appropriate limit can be chosen as a percentage of the water depth (e.g., 10%), as a specific distance, or as a distance that depends on the limits of the dynamic power cable designs. For the reference array designs, this limit will be chosen based on the expected acceptable power cable ranges of motion.

The mooring system is the sole source of yaw stiffness to the floating wind turbine, and a minimum degree of yaw stiffness is necessary for turbine yaw stability. An additional consideration, especially for spar platforms, is that an instability from coupling between roll and yaw motions can develop if the roll and yaw natural frequencies are close to each other [63]. Therefore, the yaw natural frequency needs to be considered when designing the mooring system. The mooring system's yaw stiffness suitability can be assessed by checking the stability of time-domain simulations, particularly in misaligned wind-wave conditions.

3.2.4 Corrosion and Marine Growth

Corrosion can result in significant weight and strength reduction for metal mooring components. Corrosion rates are region-specific, but the absence of widespread corrosion data necessitates using more general recommendations. DNV-OS-E301 [64] specifies a corrosion allowance of 0.4 mm/year for bottom and splash zone areas, assuming that regular inspection is carried out by a remotely operated vehicle (ROV). This value represents a rate at which the nominal diameter is assumed to reduce. Larger corrosion allowances are recommended for the Norwegian continental shelf and tropical waters. To account for corrosion, the MBL of chain is adjusted as follows:

$$MBL_{corroded} = MBL\left(\frac{D_{corroded}}{D_{new}}\right)^2 \tag{8}$$

The corroded MBL should be accounted for in strength and fatigue evaluations of the mooring design.

Marine growth can result in an increase in mooring line weight and hydrodynamic loads. DNV-OS-E301 specifies values for marine growth thickness for two locations in the North Sea and Norwegian Sea, as shown in Table 25.

Table 25. Marine Growth Thickness Recommendations From DNV-OS-E301

Depth (m)	Marine Growth Thickness (mm)	
	Central and Northern North Sea	Norwegian Sea
-2 to 40	100	60
>40	50	30

The recommended thickness changes at a depth of 40 m to represent greater marine growth at lesser depths. Ideally, site-specific marine growth data should be applied because marine growth is known to vary significantly in different regions. However, when site-specific data are not available, the Central and Northern North Sea recommendations can be assumed as the more conservative options. The marine growth thickness should be considered by changing the weight and drag coefficients of the mooring line. The following equation can be used to calculate the mass of marine growth:

$$M_{growth} = \frac{\pi}{4}\left[(D_{nom})^2 - \left(2\Delta T_{growth}\right)^2\right]\rho_{growth}\,\mu \tag{9}$$

where D_{nom} is the nominal diameter, ΔT_{growth} is the marine growth surface thickness, ρ_{growth} is the density of marine growth, and μ is 2.0 for chain or 1.0 for rope. The marine growth density ρ_{growth} can be taken as 1,325 kg/m^3 if site-specific data are not available.

The drag coefficient (relative to the nominal diameter) can be increased according to

$$C_{D\,growth} = C_D \left[\frac{D_{nom} + 2\Delta T_{growth}}{D_{nom}}\right] \tag{10}$$

where C_D is the original drag coefficient.

In the absence of another well-defined approach, Task 49 will take the conservative approach of doing fatigue and extreme loads analyses at the end-of-life condition, when both marine growth and corrosion are expected to have the greatest detriment to the mooring system loads and strength.

3.2.5 *Redundancy Requirements*

Redundancy refers to whether a mooring system can withstand a component failure and is therefore an important criterion for the safety factors a mooring system requires. In general, a mooring system is redundant if the FOWT position criteria and mooring system strength criteria can be met even when one mooring line is broken. A mooring system is nonredundant if it cannot meet its strength requirements or the FOWT position requirements, or both, when a line is broken [56]. Multiple guidance documents, including ABS and DNV, prescribe that safety factors be increased by 20% for nonredundant morning systems [55], [56]. The 20% increase is already reflected in Table 21 for nonredundant mooring systems. Task 49 will begin with nonredundant mooring system designs, consistent with the three-line mooring systems that are most prevalent to date.

The consequences of a mooring line failure are not in the scope of analysis for the initial reference designs. However, these consequences—which can include platform structural damage near the attachment point, power cable damage due to excess motions, or, in the worst case, collision with other surface assets or vessels—are important considerations for future work.

3.3 Power Cables

Design requirements for power cables in the Task 49 reference designs focus on basic layout and power transmission requirements of the array cables and mechanic requirements of the dynamic cable portions. The array cable topology and cable sizing need to be adequate for the power production of the array. Cable routing should keep adequate clearances from other parts of the system. For the dynamic cables, there are many mechanical requirements related to accommodating motions and withstanding extreme and fatigue loads. Mechanical considerations with static cables, such as loads due to scour or certain seabed features and on-bottom stability analysis [65], are outside the scope of the reference designs.

3.3.1 *Array Cable Topology and Layout*

The topology of array cables is largely an electrical consideration involving losses, cable capacity, and potential need for redundancy or at least reducing the impacts of a cable failure. Cables need to be sized to keep losses and cable temperature to acceptable levels, which are associated with cable resistance and thermal constraints on the cables, especially for static cables that are buried in the seabed. These considerations are in the scope of the Task 49 reference designs and can be approximated by using cable sizes that have a rated power capacity that exceeds the amount of power they will be required to transmit. The tolerable level of electrical losses may be an economic trade-off alongside wake loss considerations.

The layout and routing of array cables over the seabed should avoid risks and challenging areas on the seabed. These include areas where ships lay anchor, fishing trawling areas, third-party infrastructure like pipelines, hazards like unexploded ordinance, environmentally protected areas, and seabed features such as steep slopes, deep channels, or areas prone to slope instability or seismic activity [66]. Many of these details will not be in scope for the basic reference designs, but some may arise for more advanced reference designs.

The layout of dynamic cables needs to consider the mooring system and the direction of power transmission. Dynamic cables should depart from the turbine at a heading such that they are well separated from any mooring lines to avoid the possibility of interference or clashing.

Export cables involve additional design considerations such as the number of cables, how they run to shore, various environmental and regulatory factors, and how system security and redundancy are assured [66]. Multiple export cables can be laid separately or may be bundled together from the platform to the shore. However, export cables are not in the Task 49 reference design scope.

Aside from ensuring appropriate cable sizing (per Table 13), the main consideration in the array cables of the reference designs will be avoiding interference issues, which is discussed more in Section 3.4.

3.3.2 Dynamic Cable Mechanical Constraints

The dynamic cable system connected to a floating wind turbine must be able to withstand the motions of the floating platform over its service life. The dynamic cable refers to the cable itself along with ancillary equipment attached to the cable, such as buoyancy modules, bend stiffeners, or abrasion protection sleeves. The dynamic cable will be exposed to repeating tension and bending loads during the service life, which need to be within the acceptable limits of the cable, including what the internal cable components can withstand. The entire dynamic cable configuration—including ancillary equipment such as bend stiffener, buoyancy modules, and protection at the hang-off point and touchdown point—needs to be designed to the motions and loads imposed by the site conditions and floating wind turbine and mooring system designs. It also must support the significant weight changes that can occur due to marine growth and must be compatible with potential disconnection and reconnection [67].

Dynamic cables can generally be evaluated in the same load cases used for evaluating mooring systems.

For ultimate load analysis of dynamic cables, the main requirement is that the dynamic cable designs are compatible with the extreme motions of the floating system. The two most critical aspects to check for the survivability of the dynamic cable itself are whether the tensions are within the minimum breaking load and whether the curvatures are above the minimum bending radius [32]. These parameters should be known for a given cable product, and appropriate safety factors are dictated by the standards. Additional requirements could relate to avoiding clashing or abrasion, such as ensuring that the buoyancy section and its buoyancy modules do not contact the seabed. For fatigue analysis of dynamic cables, bending fatigue tends to be more severe than axial tension fatigue, so special attention is paid to changes in the cable curvature [32], [50].

DNV and ABS (drawing from API and International Organization for Standardization [ISO] standards) discuss requirements for dynamic cables. While the scope of Task 49 may not permit full use of the requirements, it is worthwhile to review them and try to follow their general considerations.

DNV-ST-0119 discusses requirements for subsea power cables for floating wind turbine installations. It provides many general guidelines and a few specific requirements. Characteristic loads considering a 50-year exceedance probability should be used for permanent installations. For loads analysis, all relevant cyclic loads should be considered, including vortex-induced vibration if applicable. It refers to many other documents, including the following:

- ISO 13628-5 [68] provides additional detail on many considerations for dynamic cables and is based on API SPEC 17E "Specifications for subsea umbilicals."
- DNV-ST-0359 specifies requirements for subsea power cables during each project phase.
- DNV-RP-0360 [30] provides a risk-based approach for the subsea cable life cycle and the various limit states.
- DNV-RP-F401 [69] provides additional requirements for dynamic subsea power cables.

DNV-ST-0119 Section 16.7 discusses calculation of **load effects**, referencing other parts of the standard for specific factors. In general, these methods involve a combination of characteristic load effects, which are multiplied by load factors, depending on the limit case, and then summed to compute an overall "design load effect" for each limit case. Additional considerations are mentioned for load-bearing steel components and for lifting operations where safety concerns are higher. Given the complexity of this methodology, it is not summarized here.

DNV-ST-0119 Section 16.7.3 specifies **utilization factors** for load-bearing steel components (e.g., the armor wires), depending on the consequence class (as mentioned in Section 3.2.1) as shown in Table 26. These factors can be considered scalars of the allowable load to the yield strength of the armor (i.e., they are a reciprocal of the factors normally used by DNV). For steel accessories that are non-load-bearing, material factors are mentioned.

Table 26. Armor Utilization Factors DNV-ST-0119 Section 16.7.3

Condition	Utilization Factor
ULS - Normal operation (Consequence Class 1)	0.67
Installation (Consequence Class 1)[4]	0.67
ALS - Abnormal operation	1.00

Fatigue loads analysis should consider the fatigue due to bending as well as tension. DNV-RP-F401 Appendix A discusses the calculation of effective curvature for use in fatigue calculations and how it can be aggregated over multiple loading conditions. Examples of cable fatigue calculations can be found in the literature (e.g., [32], [51], [53]). Vibrations of dynamic cable will result in repeated variations in curvature along the cable configuration, which can contribute to the fatigue load on the cable. Standards generally recommend that these contributions to

[4] The installation value is different than in DNV-RP-F401 Section 3.8.1, which specifies 0.78.

fatigue be evaluated and included if significant. However, it should be noted that a dynamic cable's vortex-induced vibration response is complex because the bend stiffness is significantly nonlinear, which results in a hysteretic bending moment-curvature relationship.

According to DNV-ST-0119 and other standards cited by it, the design fatigue factor for steel components in dynamic cables should not be less than 10 unless otherwise stated. DNV-RP-F401 also specifies a minimum DFF of 10 for various internal components of the cable.

The ABS Guide for Building and Classing Floating Offshore Wind Turbines [56] Section 10.1.7 briefly mentions considerations for dynamic cables. They should be designed to accommodate the maximum excursions for the design load cases specified for the rest of the floating system design. They should have a fatigue life of at least 5 times the design life of the floating wind turbine installation (i.e., the DFF is 5), accounting for all phases and unplanned events such as partial recovery and reinstallation. The ABS guide references API Specification 17E for further detail; this is equivalent to ISO 13628-5 [68], which is referenced by the DNV standards.

Some of the above standards may be out of scope for the efforts in Task 49. At a minimum, the extreme tensions and curvature of the power cable should be evaluated. To be conservative, a safety factor of 2 can be applied to both tension and curvature, which aligns with typical mooring system safety factors. This is more conservative than the inverse of utilization factors shown above.

3.3.3 Marine Growth

Marine growth can significantly impact the dynamic cable profile and dynamic response and therefore needs to be accounted for when designing the dynamic cable configuration [45], [47]. Marine growth will result in an increase to the weight and cross-sectional area of the cable and ancillary equipment, as well as increased surface roughness. These changes can make the cable profile much lower in the water and can significantly increase hydrodynamic loads. As with the mooring system, the most challenging condition is expected to be at the end of life with maximum marine growth. For the sake of conservatism and with the lack of an alternative simple approach, the Task 49 reference designs will do extreme and fatigue loads analyses in this end-of-life marine growth state. The marine growth assumptions for cables can be the same as those for the mooring lines, which were discussed in Section 3.2.4.

3.3.4 Additional Dynamic Cable Considerations

The hang-off point is where loads are transferred between the dynamic cable and the FOWT, so it must be designed to withstand the loads without damaging the cable. It is the location generally most prone to fatigue damage. Whether a bend stiffener or I/J-tube is used at this location, it should be sufficient to prevent the cable from exceeding its minimum bend radius criterion over the motion envelope of the floating system and any profile angle that the cable might take. Additional considerations would consider the degree of localized fatigue damage, and how the design of the hang-off point protection device and the entire dynamic cable can keep that damage within limits. Design of the hang-off point protection device is outside the scope of Task 49, but a typical choice should be assumed to ensure that the overall dynamic cable design is reasonable.

Similar considerations are required for the touchdown location, where contact with the seabed can cause abrasion and high local curvatures. A cable protection is often attached around the cable at the touchdown location. Motions at the touchdown location can also be restricted using an anchored tether that is connected to the cable with a clamp and bend stiffener. Design of such components is outside the Task 49 scope, but a typical choice should be assumed to ensure the overall dynamic cable design is reasonable.

DNV-RP-F401 mentions that radial loads need to be considered to avoid crushing damage to the cable internals such as the semiconducting screen. Sources of radial load include hydrostatic pressure, clamping during installation, contact forces from chutes, clamping from anchors and buoyancy modules, and contact forces with midwater arches. The radial load capacity of a cable may constrain the attachment of cable protection components and may constrain installation processes. However, evaluating these loads is outside the scope of Task 49.

Torsional forces on a dynamic cable should be considered, as they can generate clamping forces and alternative wind/unwind forces on the armor wires. Guidance in industry standards is limited in this respect, and evaluating these loads is outside the scope of Task 49.

3.4 Layout

Layout in the context of the Task 49 reference designs refers to the positions of the FOWTs and their mooring lines and dynamic cables, as well as the routing of static power cables. The primary concerns with layout are to minimize wake losses, which are based on the turbine positions, and to respect spatial constraints related to the lease area boundaries and margins between mooring systems and power cables.

A regular and repeated pattern for turbine positions is preferred for navigation purposes, although many studies have considered irregular layouts to optimize energy production for a site-specific wind resource and project area. The layout regularity will be determined according to the scoping in Section 1.4. For floating wind arrays, the floating platforms experience dynamic motions due to wind and wave loads. The accuracy of existing wake models to estimate power under these dynamic motions is an area of research. Another factor is the significant mean offsets that can occur due to the mooring system compliance. The range of these offsets, or the watch circle radius, may cause a large enough alteration to the relative wind turbine positions that it affects the wake losses. These questions may be considered when selecting the modeling and design methods to use during the layout design process.

3.4.1 Turbine Spacing

Wind turbine spacing will be determined during the design process based on cost and energy production factors. Spacing from the wind farm area boundary (i.e., the lease area boundary) will be determined so that the mooring lines and anchors completely fit within the boundary. Installation processes must also be considered so that the anchor drag distance is included within the lease area boundary.

3.4.2 Clearances

Contact between FOWTs, mooring lines, array cables, and other installations should be avoided using adequate clearances. According to API RP 2SK [62], a minimum horizontal clearance of

10 m should be maintained between the mooring lines of separate moored units. When a mooring line crosses another mooring line in the vertical plane, a minimum vertical clearance of 10 m is required if one of the mooring lines is along the seabed. If both lines are suspended at this location, the vertical clearance should be increased to 20 m. These general values can be considered absolute minimums; choosing larger margins that are proportional to the magnitudes of motions may be warranted during the development of each design.

It is common practice to demonstrate clearances under all load cases between items such as mooring lines, cables, bend stiffeners, platform substructures, and any other components. If assuring these clearances is not possible, then the modes of contact and their consequences should be assessed. For example, two cables may cross and have contact with a low impact energy, which may be permissible, whereas contact between a mooring line and a cable's buoyancy modules is unacceptable because of the high likelihood of buoyancy module damage.

Additional clearance constraints may be warranted for specific components. For example, drag embedment anchors may require additional margins to accommodate possible additional drag. Guidance for anchor clearance from assets and subsea infrastructure is given in industry-standard guidelines (e.g., ISO 19901-7 recommends a minimum clearance for drag embedment anchors of 300 m in the drag direction and 100 m in other directions from other installations). For long-term moorings, it may be a requirement for systems to be monitored for anchor drag. These anchor-specific factors should be considered in addition to the general layout spacing margin of 10 m mentioned previously.

For the reference design work in Task 49, clearances will be checked using the nominal positions of the turbines and mooring lines, at a minimum. Checking this constraint in all conditions and dynamic simulations will depend on the time and analysis methods available. If such checks cannot be done, safety factors will be added to the results from nominal analyses to compensate. It is likely that larger clearances will be more appropriate for the scale of the reference array designs, which may be decided on a case-by-case basis, depending on factors such as water depth and watch circle radius.

4 Site Conditions

Floating wind array design is highly site-specific. The wind resource affects the appropriate turbine class and the system loads, as well as the AEP and wake losses, which are factors for the array layout. Wave and current conditions play a large role in the floating system loads and are therefore a major influence on the design of the floating support structure. The water depth through the area affects the mooring design and dynamic cables, and the seabed soil characteristics affect the anchor design and array cable layout and installation. All these site characteristics need to be considered when developing a floating wind array design.

In addition to environmental conditions, which often relate directly to technical engineering constraints on a design, factors related to local infrastructure and supply chain, grid connection, ecosystem characteristics, other ocean users, and socioeconomic context play an important role. Fishing, tourism navigation, shipping, and recreational activities are unlikely to be permitted inside a wind farm area, making socioeconomic impacts especially relevant in regions where these activities play a large role in the local economy or culture.

Certain aspects of site conditions are used for each stage of a floating offshore wind project's development. Following is a summary of some of the prominent aspects:

- During **site assessment**, wind resource data are used to assess the possible energy yield. Initially, these data can be in the form of wind atlases; later, they can be from more site-specific wind resource studies, including studies that incorporate new measurements. In the offshore environment, the seabed conditions and oceanographic climate have a large bearing on the required support structures and hence the project LCOE.
- During **layout design**, which deals with the positions of the wind turbines and the placement of mooring lines, anchors, and power cables, more detailed data about the wind resource, metocean conditions, and seabed are required. Key drivers of the layout are power production (as affected by wake losses and electrical losses), space needs for the mooring systems, and the routing of array cables. The joint distribution of metocean conditions plays a role in the turbine positions to minimize wake losses and the mooring line orientations to reduce fatigue loads. Seabed conditions also affect the mooring system and array cable placement and associated constraints and costs, which can be factored into the layout design.
- During **support structure design**, which involves loads analysis of the coupled response of a floating wind turbine, simulations spanning a wide range of operational and nonoperational load conditions (wind and wave load, controller action, and fault scenarios) need to be run. These cases include extreme cases and fatigue analysis over many cases that collectively represent the joint distribution of environmental conditions expected over the system lifetime. The seabed information is necessary as a boundary condition for these loads analyses. The metocean conditions need to include the extreme values associated with specific return periods (e.g., 50 years) and, for fatigue assessment, the joint distribution of metocean parameters (e.g., mean wind speed, significant wave height, spectral peak period).
- When planning **marine operations**, which are subject to the hazards of the marine environment, hourly metocean conditions, general site characteristics, and the availability of specialized equipment all need to be considered. Metocean conditions need to be

considered on an hourly basis to identify sufficiently long weather windows during which marine operations can be safely performed. Some operations are particularly sensitive; for example, wind speed, wave height, wave period, and wind-wave misalignment are particularly critical for installing a wind turbine rotor blade. A response-based derivation of the operational limits requires detailed simulations of the system. Distance to port and availability of required vessels are also key variables that affect the required length and timing of weather windows.

The following subsections note the reference site conditions developed in Task 49 and discuss the specific site condition needs for developing the reference array designs.

4.1 Reference Site Conditions From Work Package 1

In Task 49, WP1 developed a broad collection of reference site conditions, forming a set of baseline site condition information within what is possible for a general effort that does not specialize to a specific region. The WP1 report, *Reference Site Conditions for Floating Wind Arrays,*[5] presents the characteristics of the reference sites, which will be used to inform the design of the reference floating wind arrays.

WP1 surveyed the environmental characteristics of 49 sites of expected floating wind development around the world, which represent the global floating wind pipeline. This effort involved analyzing wind and wave time series for these sites from the ERA5 reanalysis dataset (hourly data from 1979 to 2021) to determine a core set of representative reference site characteristics and trends between different parameters (e.g., water depth, wind resource, wave severity). A number of “severity” categories were identified to select a number of sites that would represent the overall global pipeline.

WP1 then compiled more detailed information for 11 selected reference sites. The reference site information focuses mainly on metocean conditions and seabed characteristics (where available). The intent is to provide realistic technical site condition datasets for a variety of site types (variety in water depths, wind resource, wave climate, etc.). While the intent is to have representative rather than location-specific reference site data, using data from specific locations ensures the realism of the datasets. Table 27 lists these sites.

[5] The WP1 report *Reference Site Conditions for Floating Wind Arrays* will be published and available on the Task 49 website at https://iea-wind.org/task49/

Table 27. Reference Sites Developed by WP1

Synthetic Case No.	Wind Condition Severity	Wave Condition Severity	Site	Water Depth (m)
1	Mild	Mild	Oahu (Hawaii/U.S.)	567
2	Lower-Moderate	Mild	Sicily (Italy/Mediterranean)	353
3	Lower-Moderate	Lower-Moderate	Humboldt (U.S.)	707
4	Severe	Severe	Ulsan (South Korea)	188
5	Upper-Moderate	Severe	MoneyPoint One (Ireland)	102
6	Severe	Severe	Havbredey (UK)	91
7	Severe	Severe	Fukushima (Japan)	120
8	Upper-Moderate	Upper-Moderate	Utsira Nord (Norway)	273
9	Lower-Moderate	Upper-Moderate	Gulf of Maine (U.S.)	148
10	Severe	Upper-Moderate	Geomundo (South Korea)	70
11	Severe	Upper-Moderate	Sud de la Bretagne (France)	94

Additional site condition information can be found in the WP1 report and associated published datasets.

WP1 has also provided assumptions related to site-specific infrastructure, environmental impact constraints, and socioeconomic factors. However, these factors are more difficult to generalize; therefore, they are considered a starting point from which to consider such aspects in the reference design effort, with recognition that future work on such aspects would need to be more site-specific.

4.2 Metocean Conditions

Metocean conditions—mainly focused on wind, wave, and current—are the key data from which DLCs can be determined for assessing that a design can withstand all expected environmental loadings at a site. DLCs comprise both worst-case conditions (for checking ultimate loads) and the lifetime distribution of loading (for checking fatigue life). In addition, the lifetime distribution of metocean conditions is relevant when determining the energy production of a design, and the weather windows during which conditions are mild enough for marine operations.

Metocean data may need to be in the form of statistical measures of worst-case conditions, such as the largest wind speed expected in a 50-year period. Others require joint probability distributions that capture the lifetime characteristics of the wind farm. Still others require hourly time series.

Regardless, similar measures describing wind, wave, or current conditions are used:

- **Wind** conditions are usually described by a wind velocity (speed and direction) at the hub height (and also at the surface for marine operations). The wind shear exponent and turbulence intensity are also needed for loads analysis. Gust speed is sometimes also included for marine operations. At initial site assessment stages, a wind resource map with the wind speed probability distribution may be sufficient. For layout optimization and AEP calculation, a speed and direction distribution in the form of a wind rose can be used.

- **Wave** conditions are usually described by a wave spectrum such as the Joint North Sea Wave Project (JONSWAP) or the Pierson-Moskowitz spectra and the associated spectral parameters: significant wave height, peak spectral period, and a peak enhancement factor. The wave directionality needs to be considered, too. Directional distribution or wave spreading is often neglected to limit the number of parameters required. Real sea states are often combinations of more than one wave system, such as a wind sea system and a swell sea system, and this can have a significant impact on the operability of floating offshore structures. It is important to consider the wind sea and swell sea components separately for sea-state-sensitive marine operations so that the time spans of availability for offshore work can be accurately calculated during installation and maintenance analyses.
- **Current** conditions are usually described by current speed and direction at the surface and at multiple points in the water column. Currents can be a combination of wind-generated currents near the surface and tidal or other marine currents distributed through the water column. Currents near the surface are most widely measured and are also most significant for floating wind support structure design because the floating platform is near the surface and provides the greatest frontal area for current drag forces. Therefore, for preliminary design it can be justified to use surface current velocity measurements and then apply a standard current profile (such as provided in IEC 61400-3-1 Section 6.3.3.3 or ISO 19901) for estimating the currents through the water column.

Considering the variety of forms that metocean conditions are needed in, the natural first step is gathering data in time series format. Time series are the form that most raw site data are available in, and they can be used directly in analyses of AEP and marine operations.

Based on the time series, the joint probability distribution of the various metocean parameters can be constructed in several ways. The most straightforward is a gridded approach, where the metocean parameter space is divided into a rectangular grid. IEC 61400 3-1 [70] specifies the recommended maximum bin widths to use for analyzing joint probability distributions as follows:

- Wind speed: 2 m/s
- Significant wave height: 0.5 m
- Wave period: 0.5 s
- Direction: 30°.

The rectangular-grid approach results in a very large number of bins, which would be too many to simulate for fatigue loads analysis for the purposes of the reference designs. However, the gridding approach can be useful for fitting probability distributions to the data that capture the correlations in the data. Conditional probability distributions can be fit, such as the distribution of significant wave height for a specific wind speed band. Joint probability distributions can also be fit, which allow for plotting of contour lines and the direct computation of conditional probabilities. Cheynet et al. demonstrate this approach [71]. The joint probability models can be used to predict the extreme conditions for ULS analysis, to generate contour lines and contour surfaces, and to be applied in fatigue analysis and power production estimation for the wind farm. They are also used to determine weather windows for different operations (installation, O&M, and decommissioning), for logistics analysis and power production estimates.

All the approaches are more tractable when there are fewer parameters, so it is common to seek out a minimal set of parameters that are needed for the joint distribution analysis. Wind speed, significant wave height, and peak spectral period are the three most common parameters when computing joint probabilities. However, loading direction is also important. From a wind turbine point of view, the misalignment angle between wind and waves may cause increased dynamic responses of the tower in the side-side direction due to less damping compared to the fore-aft direction. Studies have reported that neglecting the wind-wave misalignment will underestimate the tower base bending moment, the fatigue damage, and other structural responses [72]. To account for this effect, a joint distribution of the mean wind speed and the misalignment angle between the mean wind direction and the wave direction can be established from the metocean dataset and used as input for the response analysis. However, the approach of ignoring absolute wind direction and instead considering wind-wave misalignment angle is not suitable for analyzing floating support structure loads because, unlike the turbine, the support structure does not align itself with the wind. Therefore, Task 49 design efforts will consider both the wind and wave directions in absolute terms when developing the reference designs. Current speed and direction can also play a significant role on the mooring system loads and therefore need to be considered.

Extreme metocean values representing worst-case conditions at different probability levels are needed for assessing the ultimate loads on a floating wind array. The extreme values are generally considered in terms of certain return periods that relate to the intended design life. A return period indicates the time span in which a certain extreme value is expected to occur; for example, a 50-year wave height is the most likely wave height expected to occur in 50 years, which is equivalent to a probability of occurrence of 0.02 in any given year. Standards for floating wind generally recommend the largest return period to be 50 years [54], [70], but some standards specify 100 years or even 500 years to account for extreme events such as hurricanes [70], [73], [74], [75]. In general, using longer return periods may better capture the many probabilistic factors that affect the extreme wave conditions for a floating wind array, such as when there may be combined wind-driven and swell sea states.

Typhoon, hurricane, and tropical cyclone conditions can present environmental loading conditions that do not fit the typical assumptions and distributions discussed previously. Extreme change in wind velocity is a dominant consideration, and return periods or safety factors may need to be adjusted to compensate. Analysis of these extreme conditions is often approached with Monte Carlo simulations. These conditions are not considered in the initial reference designs, but the designs can form a baseline from which a variant could be developed for typhoon conditions.

At the array scale, spatial variations in wind, wave, and current conditions across the array could be non-negligible. These spatial variations could influence the loadings encountered by individual floating turbines in an array [71]. For practicality, spatial variation of metocean conditions is left outside of the scope for the Task 49 reference designs, but it is an important topic for future research.

An important array-level phenomenon is the effect of the turbine wakes on inflow conditions of each turbine. The reduction in wind speed and increase in turbulence can affect power production, extreme loads, and fatigue loads. The same cannot be said for hydrodynamic couplings; wave or current interaction effects between turbines are generally negligible. The changes from the ambient wind conditions deserve consideration and are discussed further in Section 6.4.2.

4.3 Seabed Characteristics

Seabed properties and considerations affect the design of mooring systems, intra-array cables, and the export cables. Therefore, realistic assumptions of seabed properties are needed to ensure the practicality of the array designs developed in Task 49. The following subsections discuss water depth and bathymetry, geotechnical, and seismic considerations.

4.3.1 Water Depth and Bathymetry

Floating offshore wind has potential in a wide range of water depths, ranging from approximately 50 m to more than 1,500 m. The selected water depth for the array designs will greatly influence the specific choice of mooring system, from catenary to taut to semi-taut, and will also influence the dynamic cable design. Some areas of potential floating offshore wind development feature high gradients in seabed depth, raising concerns on the impacts of seabed bathymetry on array designs. Seabed bathymetry creates mooring systems where the anchors are at different water depths, which requires design adjustments of individual mooring lines and may result in asymmetric system dynamics. Bathymetry information is often available in a rectangular grid of depth measurements, and these can be used when site-specific bathymetry is needed.

4.3.2 Geophysical and Geotechnical Conditions

The seabed geophysical and geotechnical conditions in terms of soil/sediment and rock characteristics have a large role in anchor selection. Shallow or outcropping bedrock, or an otherwise hard seabed (e.g., glacial till) may require drilled or gravity-based anchors, whereas areas with thick silt, clay, or sand deposits would allow the use of drag embedment anchors, suction caissons, plate anchors, and so on—depending also on the loading direction from the mooring system. Suction pile anchors may be required in finer-grained sediments with a low shear strength, which may be common in deeper, low-relief basins. Subsurface heterogeneity is also an important consideration—subsurface layers can impact the integrity of any anchor emplaced above it through differential settling or failure. Thickness of sediments must be assessed using sub-bottom profiler or seismic reflection data to determine the best anchor choice.

In the spirit of the reference designs planned thus far, seabed variations will be relatively limited or simplified, so detailed methods for handling seabed variations are not required. The main detail required will be to specify sets of soil properties across the extent of a reference array site. WP1 developed reference soil characteristics that can be applied for use in the reference designs. Because the anchor selection has little effect on the rest of the design, the soil characteristics may be selected for different reference array variants.

4.3.3 Seismic Hazards and Geohazards

Seismic hazards are mostly relevant in highly seismic areas such as the Pacific Rim. These hazards will mainly be secondary in nature, such as earthquake-induced slumping that could cause movement of anchors and breakage of mooring lines; ground shaking (with minimal impact for catenary moorings but potentially severe loads for tension-leg platforms); liquefaction and fault movement, which could damage export cable routes; and tsunamis, which could impact tension-leg platforms or any floating structures close to shore. Deeper slopes and basins can frequently host strong currents (either larger-scale oceanographic currents or localized density/turbidity-driven currents) that have the potential for destabilizing anchor and mooring systems. Postglacial muds (finer-grained sediments that typically occupy deeper basins) often host large volumes of interstitial gas, biogenic or otherwise, that may pose an engineering challenge. These factors are not considered in the currently planned reference array designs but may be added in future variations.

4.4 Local Infrastructure

Local infrastructure can have a large effect on floating wind array design decisions. Port capabilities may limit which support structure types are feasible or economical, and distances to construction and maintenance ports can affect costs as well as O&M strategy choices. The distance to a construction port could affect the choice of platform type. For example, if a suitable deep-water port or facility is not near to the site, spars may not be practical. The distance to a maintenance port will affect the choice of maintenance delivery system, such as the design choice of a helipad on a platform or atop a turbine tower; this would also affect the size of the helipad (larger helicopter vs. smaller). The use of maintenance vessels in place of or in combination with helicopter transport could affect the optimal design of the platform, and considering the parameters of extreme metocean conditions (wave height, period, etc.) will inform the design of boat landing equipment. Distance to the transmission grid will affect the electrical export system design, including the choice of an AC versus DC electrical system. While these factors are outside the reference array design scope, they can affect costs and installation and maintenance requirements.

To balance the site-specificity of these considerations with the goal of providing broadly representative reference array designs and design approaches, we adopt a single generic set of infrastructure and logistical assumptions when developing the reference designs. They are described in Section 5, along with a discussion of considerations about marine infrastructure constraints, requirements for installation and O&M ports, vessel requirements, and associated costs. Exploring site-specific variations to these assumptions is an area for future work, for which the reference array designs could provide a valuable baseline.

4.5 Environmental and Ocean Use Considerations

Considerations related to environmental impacts and other ocean users have a large bearing on floating wind farm development. Because these considerations can be very location-specific, the Task 49 reference designs will not directly account for them. However, the reference designs are intended to provide baselines that could be used for future studies, including studies that relate to environmental and ocean use considerations. Therefore, they are worth noting at this stage.

The environmental impacts of floating wind arrays are most notable on pelagic life and include entanglement risks (especially when combined with derelict fishing gear), habitat displacement, spill risks, and noise impacts [76]. Floating wind support structures can also attract marine life, acting as fish aggregation devices or providing surfaces for marine growth, creating artificial reefs. The artificial reef effect can be a factor in end-of-life decisions.

Decommissioning of floating wind arrays is an open topic that could have significant impacts on total costs and environmental impacts. If the system is fully removed, the decommission steps can be most simply approximated as the reversal of the installation steps. However, in some cases, leaving components such as anchors in place may cause less environmental impact than removing them by avoiding the disruption to the seabed area and the marine growth on the structures. There is also potential for component recycling or reuse, ranging from reusing anchors in place to recycling steel and copper, or using wind turbine blades as aggregate for new composite structures.

A newer area of environmental concern is related to the mooring system materials, since floating wind arrays are expected to involve larger quantities of fiber rope than previously deployed. Recent research [77] describes the release of microplastics from the abrasion of marine ropes and suggests that marine ropes may have been underestimated as a source of microplastics in previous work. These findings were related to ropes used for hauling, but there may be similar implications for mooring ropes, which have been less studied. Current regulations on microplastics do not apply to mooring ropes, but microplastics are a growing concern. Due diligence is warranted to understand if there are implications for floating wind mooring systems.

Spatial overlap with fishing activities is a common area of concern, where loss of access to fishing grounds would negatively impact fishers and put increased pressure on other areas to which fishing activities could be displaced. Many open questions exist regarding how floating wind arrays and fishing activities can deconflict or even coexist, such as through dedicated fishing lanes and well-defined boundaries.

The other main concern with ocean users is shipping and navigation disruptions or hazards, including the potential need for shipping routes to be altered and for techniques to be developed to mitigate the risk of collision.

The considerations mentioned above are not within the scope of the initial reference array designs. However, they are relevant considerations for floating wind arrays and topics of future study for which the reference array designs can be used when generating a baseline.

5 Costs and Logistics

A floating wind project will incur a wide range of costs during its lifetime. These costs are collectively defined as life cycle costs and are broadly subdivided into development and consenting, production and acquisition, installation and commissioning, operations and maintenance, and decommissioning and disposal costs. The scope of each category is defined as follows:

- **Development and consenting** costs are related to the planning and development of the project, from the beginning until project completion. These include spent contingency and construction insurance costs.
- **Production and acquisition** costs are capital expenditures related to the procurement and manufacturing of the components of the wind farm.
- **Installation and commissioning** costs are related to transportation to the site, construction, and verification of the performance of each wind farm component.
- **Operations and maintenance** costs are expenses incurred during the operational lifetime of the project to ensure the reliable operation and management of the floating wind power plant, as well as any applicable lease price for the wind farm development area.
- **Decommissioning and disposal** costs relate to the end of life of the floating wind project and returning the area to pre-wind-farm conditions.

To support the reference array designs with cost and logistical details, Task 49 gathered information and selected assumptions for each of these cost categories. Many of the factors in these cost categories can vary significantly depending on location and the technology and temporal changes in prices and market conditions. Where data from a specific published source are used, reference to the source is made; however, many of the presented values are generic estimates sourced by Task 49 participants based on their engineering expertise and experience. Ranges are provided where considerable differences in estimates occurred. This is to be expected, given the nascent nature of the floating wind sector and the lack of real-world data and experience. The aim is to provide solid, peer-reviewed figures as a general starting point for use with the reference designs. It should also be noted that given the diverse range of technologies that could be selected for a floating wind farm (platform, mooring system, and array design), this document provides an overview of the information gathered and the approach WP2 will take in costing the reference farm array designs. The task will provide detailed cost figures for each of the reference farm designs in future reports.

5.1 General Assumptions

The LCOE will be calculated for each reference farm to assist in the optimization process. Equation (11) is used to calculate LCOE, with the inputs outlined in Table 28. The financial assumptions used to calculate the discount rate are outlined in Table 29. The discount rate is the weighted-average cost of capital (WACC). These assumptions were specified, based on the financial criteria in NREL's "2022 Cost of Wind Energy Review" for a floating wind farm [57]; however, this calculation will not consider tax in order to remove the influence of different national regulations from the reference farms. While the WACC is still very site- and project-dependent, a common WACC has been selected so that the different site locations can be compared.

$$LCoE = \frac{I + \sum_{k=1}^{n} \frac{LP}{(1+r)^k} + \sum_{k=1}^{n} \frac{INT}{(1+r)^k} + \sum_{k=1}^{n} \frac{A^k}{(1+r)^k} + \sum_{d=n+1}^{f} \frac{(D^d - S^d)}{(1+r)^d}}{\sum_{k=1}^{n} \frac{E^k}{(1+r)^k}} \quad (11)$$

Table 28. Equation (11) Abbreviations

Abbreviation	Financial Assumption
LCOE	levelized cost of energy
I	investment costs
n	project lifetime
k	year in project lifetime
LP	loan payment
r	discount rate
INT	interest payment
A	annual costs
d	year in post-project decommissioning
D	decommissioning costs
S	salvage revenue
E	energy produced

Table 29. Financial Assumptions

Parameter	Percentage
Nominal pretax WACC	7.14%
Real pretax WACC	4.53%
Inflation rate	2.5%
Debt interest rate	5.9%
Debt fraction	60%
Return on equity	9%

The site conditions (e.g., site metocean conditions and bathymetry) are discussed in Section 4. The general reference farm assumptions relevant for economic analysis are outlined in Table 30. The reference array will be approximately 1 GW in size and assumed to be operational for 25 years, beginning in 2028.

Table 30. Common Project Assumptions

Parameter	Value
Year of final investment decision	2025
First year of operation	2028
Project lifetime	25 years
Turbine rating	15 MW
Number of turbines	67

The costs of a given part of the system can be divided into two components: component/material costs and logistics costs:

- **Component costs** reflect the cost of acquiring components of the array and having them delivered to the port or staging area. These costs will typically be characterized on a per-unit, per-mass, or per-size basis.
- **Logistics costs** reflect the cost involved in installation, maintenance operations, and decommissioning. The majority of associated expenses are related to equipment use (i.e., vessels or port facilities), the personnel/labor costs, and maintenance/replacement component costs.

The level of detail in modeling the costs related to different components depends on whether the component will be designed within the task, or if it will be taken as fixed/given. Simple assumptions or fixed costs will be adopted for those elements whose design is outside of the scope of the task. Instead, the fidelity level to model the costs of those components that will be designed within the task needs to be detailed enough to capture the sensitivities to changes in the array design. For example, two alternative mooring system designs may have different component costs (due to different component types, sizes, or quantities) and different installation requirements (requiring different installation steps, equipment, or time durations). These differences should be captured in the cost assumptions.

Modeling costs related to different logistical processes will be based on those methods that have already been tested at pilot farm scale or are widely considered to be promising solutions. Installation and maintenance practices for floating wind farms are still in the early development stage. Methodologies are evolving quickly, and there is no convergence on best practices. Thus, the installation and maintenance practices reported in this section are only representative of the different installation and maintenance approaches that can be applied to floating wind farms. Reference farm designs will specify the assumptions used to model logistics and their respective costs using open-access tools where possible (see Appendix A.3). It is important to note that the reference site selected for a farm design will have a significant impact on logistics costs. For example, weather windows will impact site accessibility and how long operations may take, thereby increasing/decreasing costs and power production. However, the purpose of the reference farm designs is not to determine costs for a single farm, but to provide reasonable assumptions that users can take and apply to other sites and with different modeling tools.

The numbers reported in Sections 5.2 to 5.6 are not an exhaustive collection of all the inputs necessary to model the wind farm components and logistics cost. Instead, these numbers are representative of the approach that will be adopted to model the component and logistics costs of the reference array designs. These figures were compiled considering an extensive survey within Task 49 as well as a review of existing literature to fill the gaps. Therefore, while they have not been validated, these are based on discussions with industry and researchers with considerable engineering expertise. The final set of inputs will depend on the configuration of the reference arrays. These will be compiled and verified by Task 49 contributors for each reference array.

5.2 Development and Consenting

Development and consenting costs are costs incurred to bring forward floating wind projects, until the completion of the construction works, including:

- Permitting costs to secure the lease area and obtain all the necessary authorizations to initiate the operation of the wind farm
- Survey costs (preconstruction and during construction), incurred to collect data and characterize the wind farm site
- Engineering costs from initial technical feasibility to detailed engineering
- Tendering and contracting costs to procure the necessary components from the suppliers
- Project management, legal, administrative, and other activity costs supporting the development process of the wind farm
- Contingency and construction insurance.

Development and consenting costs are generally dependent on the number of turbines installed in the wind farm, with larger wind farms incurring higher development costs. However, less technical aspects, such as the regulatory environment surrounding the project, have a significant impact on the development costs. In the task, fixed costs will be taken for each wind farm size evaluated. As a baseline value, 9.7% of the total capital cost can be assumed for the development, contingency, and construction insurance costs for a large-scale wind farm.

5.3 Component Production and Acquisition Cost

Production and acquisition costs include the manufacturing and procurement costs related to the components of the wind farm, as well as those costs incurred to deliver the components to the marshaling port or staging area. From a design point of view, it is useful to express the production and acquisition costs as a function of the physical properties of the component, so that the cost of several possible designs can be compared. Where possible, this approach will be adopted to determine the production and acquisition cost of the components designed within the task.

5.3.1 Floating Wind Turbine Unit

Both the wind turbine and the floating platform are considered as fixed within the scope of the task. As these components will not be subject to modification, a fixed price could be attributed to both the wind turbine and the floating platform. Alternatively, the cost of the platform can be subdivided into materials and manufacturing cost. In a simplified cost-modeling approach, the materials costs can be assumed proportional to the mass of structural material for the platform, while the manufacturing costs are proportional to a manufacturing complexity factor (MCF):

$$P\&A_{floater} = Cost_{structural-material}\, Mass_{structural-material}(1 + MCF) \quad (12)$$

where $P\&A_{floater}$ is the production and acquisition cost of the FOWT unit. The MCF expresses the complexity of the fabrication process for different platform concepts. Typical values are given in Table 31.

Table 31. Typical MCF for Different Platform Concepts [78] [79] [80]

Platform Concept	MCF	MCF	MCF	MCF, average
Semisubmersible, steel	2	1.81	3	2.3
Spar buoy, steel	1.2	1.31	2	1.5

The fixed-cost approach is adopted for costing the turbine, while the MCF-based approach is adopted for the floating platform, to allow for costing different platform concepts.

5.3.2 Mooring System

The stationkeeping system cost is expressed as a function of key physical properties, depending on the mooring line composition. For chain and wire rope, this implies per-mass costing, while for polyester and nylon, a per-length per-MBL approach is adopted. Representative values are reported in Table 32. Where applicable, buoys and connectors will be priced separately (possibly as a per unit base). Anchor costs are expressed on a per-mass basis in Table 33. Due to the high variability in soils and loading angle, the anchor costs are approximate and should be reviewed for specific designs.

Table 32. Mooring Lines Cost Coefficients

Material	Cost Coefficient
Chain ($/kg)	2.54–6.34 (grade dependent)
Wire rope ($/kg)	5.39
Polyester ($/m/MN)	16.5
Nylon ($/m/MN)	43

Table 33. Anchor Cost Coefficients per Kilogram Mass

Anchor	Cost Coefficient
Drag embedment ($/kg)	5.07–6.34
Suction pile or driven pile ($/kg)	3.8–5.07
Gravity anchor ($/kg)	1.27–2.54

5.3.3 Array Cables

Similar to the stationkeeping costs, the cost of the array cables is expressed as a function of key physical properties, cable length, cable capacity, and voltage. Cost coefficients as per-meter for dynamic and static cables with different capacities are reported in Table 34 for 66-kV cables. The representative cost of cable accessories, including buoyancy modules, stiffeners, and connectors are provided in Table 34 for the reference 70-m water depth case presented in [38]. The cost of submarine joints when both dynamic cables and static cables are installed is also reported. Additional cost coefficients may be needed to accurately model the costs of cables with different capacities, cables in different water depths, or other cable configurations.

Table 34. 66-kV Cable Cost Coefficients for Dynamic and Static Cables

	Cross section (mm²)					
Cable Components	**95**	**150**	**300**	**400**	**630**	**800**
Dynamic cable cost 66kV ($/m)	282	382	539	606	713	885
Static cable cost 66kV ($/m)	259	355	500	561	655	815
Buoyancy modules (per single cable) ($k)	70	75	96	106	149	188
Stiffeners and connectors (per single cable) ($k)	160	172	203	225	273	310
Submarine joints ($k/turbine)	237					

5.3.4 Power Export

The solution adopted for power export depends principally on the capacity of the wind farm and on the distance from the onshore connection point. Offshore substations are necessary for high capacities and distances from shore, with further distances from interconnection requiring more expensive high-voltage DC solutions. The cost of the floating substation is driven by the cost of the topside (structure, electrical equipment, backup generators, logistics equipment) and the cost of the platform. For floating wind applications, both fixed and floating substations are under consideration, with water depth driving the pivoting point. As the design of the substation is beyond the scope of this task, the cost of the substation will be fixed as a proportion, e.g., $187,000/MW.

The export cable cost can be modeled as the array cables, as a function of voltage, capacity, and cable length. Within the task, the power export procurement costs will be modeled as a fixed cost for each wind farm size considered.

5.4 Installation and Commissioning

Installation and commissioning costs include all the costs incurred during the construction phase of the wind farm. This typically involves the following activities:

- Anchors installation and pre-lay of mooring lines
- Pre-lay of array cables
- Laydown of export cables
- Transporting the platforms from the construction site to the marshaling/assembly port
- Assembling the wind turbines on the platforms
- Transporting the floating units to site
- Mooring lines hookup
- Dynamic cables pull-in and hookup
- Installation of the substation(s) (if considered)
- Final commissioning for all the components.

This list of activities and the details of each process are highly dependent on the nature of the components installed in the wind farm.

The costs incurred during the installation and commissioning phase are mostly related to the equipment hired for the operations (vessels, cranes, self-propelled modular transporters, dry docks), the personnel involved in the activities, and vessel fuel consumptions. The costs related to the equipment are usually subdivided into:

- Costs associated with reaching/leaving the operative location and preparing/dismantling the equipment for the assigned activities (mobilization/demobilization).
- Costs associated with carrying out the assigned activities. These costs are a function of the costs incurred to hire the equipment (usually expressed in day rates) and the time required to carry out the activities. This operational time is itself a function of the capacity required for the task, the specific capacity of the equipment mobilized, its operational limits, and the metocean conditions.

Many installation activities (and maintenance activities in Section 5.5) can only be carried out in relatively calm metocean conditions. These constraints are approximated by maximum values of significant wave height (H_S) and wind speed (WS) for specific activities, where applicable.

Because the floating offshore wind industry is evolving quickly, methods for floating wind farm installation are not converged to one single established method. Therefore, the following sequence of activities only represents one of the possible installation strategies. This representative strategy is applicable to semisubmersible platforms and involves the pre-lay of the moorings and cables while the wind turbine is assembled on the semisubmersible at the quayside. Subsequently, the floating assembly is towed to the wind farm site, where the moorings and then the dynamic cable are connected to the floating unit. Finally, the floating unit is commissioned. The principle equipment estimated to be necessary for each installation activity is also reported. It is assumed that the selected port has sufficient depth and quayside space to assemble the wind turbine(s) on the semisubmersible(s) and that the quayside crane has enough reach and capacity.

5.4.1 Activities

Installation will require an assembly/integration port with enough depth and quayside space, as well as crawler cranes or ring cranes with sufficient reach to assemble the wind turbines. The WP1 report Section 6 outlines specific port requirements and constraints for floating offshore wind.

Anchors installation and pre-lay of mooring lines: The activities and duration will depend on the anchor and mooring line design. Literature suggests that the installation of drag anchors and moorings can be carried out up to a significant wave height of 2.5 m by anchor handling tug support vessels (AHTS) [81]. Two AHTS in tandem pull might be needed to embed anchors for large wind turbines. For suction piles, a heavy-lift vessel (HLV) may be employed to preinstall the anchors, with the moorings connected in a second step by an AHTS equipped with an ROV.

Table 35. Installation Assumptions for Preinstallation of Anchors and Moorings

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Preinstallation anchors and moorings	8–12 h, depends on soil conditions and water depth	1–2 AHTS with ROV or 1 HLV and 1 AHTS with ROV	2.5	11–13 for crane operations with HLV

Pre-lay of array cables, laydown of export cables: These activities involve the pre-lay of array cables and the laydown of export cables. These activities are usually performed by cable laying vessels (CLV). For array cables, a wet-storage approach is adopted for the dynamic cables. Typically, the cable is laid before the installation of the floating units and fitted with buoyancy modules and riggings to allow for recovery for the pull-in, once the floating units reach the site. It is also possible to install the cables after the floating units, such as might be necessary for fully suspended dynamic cables, which do not touch the seabed.

Table 36. Installation Assumptions for Pre-Laying Cables

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Pre-lay cables	Depends on installation rate (e.g., 0.2–0.3 km/h for simultaneous lay/burial)	CLV	2–3	Not applicable (NA)

Activities can be split and modeled in much greater detail as described in [82].

Transport the platforms from the construction site to the assembly/integration port: This activity involves the transportation of the substructure from the construction site to the assembly/integration site for the installation of the wind turbine. The procedure described in Table 37 consists of the float-out of the substructure at the construction site, followed by the wet-tow and berthing of the substructure at the assembly/integration port. An alternative approach involves the dry transportation of the substructure to the assembly/integration site, followed by float-out and positioning at the quayside. The float-out can be performed with the aid of self-propelled modular transporters and semisubmersible floodable barges, or in a dry dock where available. Three to four tugboats are mobilized to support berthing operations.

Table 37. Installation Assumptions for Transportation of Platforms

Activity	Duration (h)	H_S Limit (m)	WS Limit (m/s)
Vessels-semisubmersible coupling	4	Activity carried out at port	NA
Float-out from construction/launching site	Depends on float-out method	Activity carried out at port	NA
(If needed) ballast to towing draft	6	2.5	NA
Tow semisubmersible to location for wind turbine assembly	Depends on distance and vessel speed	2.2	30
(If needed) De-ballast to enter assembly port	6	2.5	NA
Position semisubmersible at quayside	6	Activity carried out at port	NA
(If needed) Ballast down for heavy-lift operations	6	Activity carried out at port	NA
Towing vessels return to construction/launching site	Depends on distance and vessel speed	3.2	30

Assemble the wind turbines on the platforms, followed by precommissioning: This activity involves a crawler crane assembling the wind turbine on the semisubmersible. Precommissioning is carried out at the quayside to save time offshore.

Table 38. Installation Assumptions for Assembly of Platforms

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Assemble turbine on semisubmersible at quayside, followed by precommissioning	5–10 days	Quayside crane	Activity carried out at port/shipyard	12 for crane operations

Tow the floating units to site and moorings hookup: This activity involves towing the preassembled floating units to the wind farm site, followed by mooring lines hookup. (De)ballasting operations are also involved, to reach the required draft for the different operations. One AHTS equipped with ROV, one large tugboat for tow-out, and a second supporting tugboat perform the moorings hookup at the wind farm site, while 2 or 3 supporting tugboats assist the operations at port.

Table 39. Installation Assumptions for Towing and Hookup of Floating Units

Activity	Duration (h)	H_S Limit (m)	WS Limit (m/s)
Vessels-floating unit coupling	4	Activity carried out at port	NA
(If needed) de-ballast to exit assembly port	6	Activity carried out at port	NA
(If needed) ballast to towing draft	6	2.5	NA
Tow floating unit to site	Depends on distance and vessel speed	2.2	18
Position the floating unit at site	6	2.5	NA
Ballast to operational draft	6	2.5	NA
Mooring lines retrieval and connection	For 3 pre-laid, all-chain moorings: 30–48	1.5	10–12
Towing vessels return to assembly/integration port	Depends on distance and vessel speed	3.2	30

Pull-in infield cable, followed by commissioning: This activity involves the pull-in of the pre-laid infield cables, followed by the final commissioning of the floating unit at site. An SOV with ROV and walk-to-work gangway is mobilized to assist the operations.

Table 40. Installation Assumptions for Assembly of Pre-Laid Dynamic Cables

Activity	Duration (h)	H_S Limit (m)	WS Limit (m/s)
Dynamic cables retrieval and connection	36–48	1.5	NA
Commissioning	24–48	3–3.5	NA

5.5 Operations and Maintenance

Operations and maintenance costs are incurred during the lifetime of the wind farm, and relate, respectively, to the management and integrity of the asset.

Operational costs are incurred for the monitoring and management of the wind farm and related assets, including:

1. Leases for the offshore area
2. Leases and management of onshore facilities, such as workshops, warehouses, control rooms, offices, quayside, and berths at the O&M port
3. Marine management
4. Wind farm and offshore operation monitoring
5. Transmission charges
6. Operational insurances
7. Administrative and professional services.

These costs are highly project-dependent. In Task 49, fixed costs will be taken for each wind farm size evaluated. The fixed annual operating costs can be taken as approximately $31,000/MW/year, which is per MW of installed capacity, adapted from [83]. This is a reference value and it excludes country-specific offshore area lease costs.

Maintenance costs are incurred to maintain the integrity of all the components of the wind farm. Similar to installation costs, maintenance costs are driven by vessel rates, consumables (fuel, spare parts), personnel (long-term or fixed contracts) and port equipment. Furthermore, the failure rates of the wind turbine components and the frequency of services are necessary inputs for computing costs related to corrective and preventive maintenance activities, respectively.

As for installation, there still needs to be convergence on what will be the established practices for the maintenance of floating wind farms. Options include the tow-to-port strategy where major service operations occur onshore; an offshore strategy where all maintenance occurs offshore; or a mixture of onshore and offshore maintenance operations. To represent the options, the following section represents the sequence of activities for:

- An onshore/tow-to-port strategy for major wind turbine repairs/replacements or major service operations
- On-site (offshore) minor maintenance/service operations
- On-site (offshore) major maintenance/service operations.

5.5.1 Activities

A port with suitable requirements in terms of accessibility, space, and proximity to the wind farm is usually selected as a base for managing and operating the wind farm. Section 6 in the WP1 report outlines specific port requirements and constraints for floating wind farms.

Table 41 reports a representative sequence of activities for a tow-to-port maintenance strategy for major wind turbine repairs/component replacements or scheduled services, e.g., overhauls. Similar to the installation procedure, it is assumed that the selected port has sufficient depth and quayside space to perform the replacement at the quayside and that the crawler crane has enough reach. The sequence of events include:

- The floating wind unit is disconnected from the dynamic cable and moorings, following a sequence of activities reversed to the installation.
- The floating unit is then towed to the port used as a maintenance base, where the major component repair/replacement occurs at the quayside employing a crawler crane.
- The floating unit is then towed to the site and reinstalled.

An SOV with ROV and walk-to-work gangway is mobilized to assist the cable disconnection and reconnection, and subsequent recommissioning of the floating wind turbine. One AHTS equipped with ROV, one large tugboat for tow-out, and a second supporting tugboat perform the moorings connection and disconnection at the wind farm site, and 2 or 3 tugboats support the berthing and unberthing operations in port.

The time required for mooring lines and dynamic cables connection and disconnection activities depends on the number of moorings and cables to be connected, the water depth, and the connector type. Thus, the activity durations reported in Table 41 are only indicative, whereas the actual value to be used within the logistic model will depend on the reference wind farm configurations.

Table 41. Major Components Repair/Replacement (Turbine, Platform, Moorings, Anchors): Onshore/Port

Activity	Duration (h)	H_S Limit (m)	WS Limit (m/s)
SOV transits to site	Depends on distance and vessel speed	5	30
Dynamic cables disconnection	36–48	1.5	NA
Towing vessels and AHTS transit to site	Depends on distance and vessel speed	3.2	30
Vessels-floating unit coupling	4	2.5	NA
Mooring lines disconnection	30–48	1.5	NA
De-ballast to towing draft	6	2.5	NA
Tow floating unit from site to port	Depends on distance and vessel speed	2.2	18

Activity	Duration (h)	H_S Limit (m)	WS Limit (m/s)
(If needed), de-ballast to enter port	6	2.5	NA
Position floating unit at quayside	6	Activity carried out at port	NA
(If needed) ballast down for heavy-lift operations	6	Activity carried out at port	NA
(If needed) towing vessel transit to site to tow the following unit	Depends on distance and vessel speed	3.2	30
Major component replacement/ repair/servicing overhaul	Depends on operation	Activity carried out at port	12
Vessels-floating unit coupling	4	Activity carried out at port	NA
(If needed) de-ballast to exit from port	6	2.5	NA
(If needed) de-ballast to towing draft	6	2.5	NA
Tow floating unit to site	Depends on distance and vessel speed	2.2	18
Ballast to operational draft	6	2.5	NA
Mooring lines connection	For 3 all-chain moorings, 30–48	1.5	NA
(If needed) towing vessels return to port to tow following unit	Depends on distance and vessel speed	3.2	30
Dynamic cables connection	36–48	1.5	NA
Recommissioning	24–48	3–3.5	NA

Table 42 reports a representative sequence of activities for an on-site, HLV-based maintenance strategy, where it is assumed that the HLV is capable of performing the floating-to-floating major component repair/replacement or service overhaul. The whole procedure involves the mobilization of one HLV vessel. Floating-to-floating overhaul has not yet been performed in floating wind farms; thus, the durations and limits presented in Table 42 are representative of those adopted in the academic literature, rather than based on real-life operations. It is assumed that the HLV has sufficient reach to perform the floating-to-floating replacement.

Table 42. Major Components Replacement (Turbine, Platform): On-Site

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Load component on HLV	12	1 HLV	Activity carried out at port/shipyard	12
HLV transits to site	Depends on distance and vessel speed	1 HLV	4	30
Vessel positioning	2	1 HLV	2	15
Major component replacement/repair/ servicing overhaul	Depends on operation	1 HLV	1.5	12
Vessel depositioning	2	1 HLV	2	15
HLV transits to port	Depends on distance and vessel speed	1 HLV	4	30
Recommissioning	24–48	1 SOV with ROV	3–3.5	NA

Table 43 and Table 44 report representative activities for on-site major repairs/replacements for cabling, moorings, and anchors.

Table 43. Major Repairs/Replacements (Cabling): On-Site

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Load technicians/ equipment on CLV	12	CLV	Activity carried out at port/shipyard	NA
CLV transits to site	Depends on distance and vessel speed	CLV	4	30
Major repair/replacements	Depends on activity	CLV	2	NA
CLV transits to port	Depends on operation	CLV	4	30

Table 44. Major Repairs/Replacements (Moorings, Anchors): On-Site

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Load technicians/ equipment on AHTS	12	AHTS with ROV	Activity carried out at port/shipyard	NA
AHTS transits to site	Depends on distance and vessel speed	AHTS with ROV	4	30
Major repair/ replacements	Depends on activity	AHTS with ROV	2	NA
AHTS transits to port	Depends on operation	AHTS with ROV	4	30

Table 45 reports a representative sequence of activities for an on-site, minor inspection or repair maintenance strategy, where it is assumed that a CTV or SOV transfers personnel and their equipment to the floating turbine to undertake the operation offshore. The latter will be more expensive but could include using a motion-compensated gangway to transfer personnel at a higher Hs limit. An advantage of an SOV is that the vessel can stay on-site for 1–2 weeks, significantly reducing time spent traveling.

Table 45. Minor Repairs/Inspections (Turbine, Platform): On-Site

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Load technicians/ equipment on CTV/SOV	4	1 CTV/SOV	Activity carried out at port/shipyard	NA
CTV/SOV transits to site	Depends on distance and vessel speed	1 CTV/SOV	3 for CTV; 4 for SOV	30
Technicians transferred to turbine	2 for CTV; 0.5 for SOV	1 CTV/SOV	2 for CTV; 3 for SOV	15
Minor repair/inspection	Depends on operation	1 CTV/SOV	3	18
Technicians transferred to vessel	2 for CTV; 0.5 for SOV	1 CTV/SOV	2 for CTV; 3 for SOV	15
CTV/SOV transits to port	Depends on distance and vessel speed	1 CTV/SOV	3 for CTV; 4 for SOV	30
Recommissioning	6	NA	NA	NA

Table 46 reports the on-site activities for minor inspection and maintenance of cabling, moorings and anchors using CTVs and divers.

Table 46. Minor Repairs/Inspections (Cabling, Moorings, and Anchors): On-Site

Activity	Duration (h)	Equipment	H_S Limit (m)	WS Limit (m/s)
Load technicians/ equipment on CTV	4	1 CTV and divers	Activity carried out at port/shipyard	NA
CTV transits to site	Depends on distance and vessel speed	1 CTV and divers	3	30
Minor repair/inspection	Depends on activity	1 CTV and divers	1.5	NA
CTV transits to port	Depends on operation	1 CTV and divers	3	30

5.5.2 Failure Rates

Table 47 reports existing reference failure rates for wind turbines from two sources.

Table 47. Unscheduled Maintenance Data – Turbine [84] [85]

	Minor Repairs		Major Repairs		Major Replacements	
	[84]	[85]	[84]	[85]	[84]	[85]
Failure rate (failures/ turbine/year)	6.81	3	1.17	0.31	0.29	0.08
Repair time (h)	6.67	7.5	17.64	24	116.19	52
Crew members	2.61	2	3.44	3.5	9.14	5
Cost of spare parts/repairs ($)[a]	178	1,270	2,190	58,400	52,000	425,000

[a]The reported cost is converted from British Pounds Sterling to U.S. Dollars assuming £1 = $1.27.

More failure rate information is available in [86], with separate failure rates for geared and direct-drive turbines and listing of different percentile values. For the 50th percentile, it specifies annual failure rates of 0.059 for direct-drive turbines and 0.119 for geared turbines.

Table 48 reports failure rates for balance-of-systems components.

Table 48. Unscheduled Maintenance Data – Balance of Systems [87]

Component	Failure/Component/Year
Moorings, chain	0.0025–0.00378/km
Moorings, polyester	0.0017/km
Anchors, drag embedment	0.00012
Static cable	0.003/km
Dynamic cables	0.003

Static cable rates are per distance while dynamic cable rates are per cable.

Another source reports an annual failure rate for array cables of floating wind farms as 0.0094/km [38].

Because reliability information for floating wind farms is extremely limited, the listed failure rates for wind turbines are generally derived from either fixed-bottom offshore wind turbines or expert elicitations. The main source of failure rates for balance of system components is experience from other offshore industries. Additional information about failure rates may be obtained through the efforts of Task 49 WP3.

5.5.3 Scheduled Maintenance

It can generally be assumed that each wind turbine will require an annual service/inspection. Other parts of the system—such as the floating platform, the mooring lines, and the dynamic cables—will generally need to be inspected at regular frequencies as well. Annual inspections could initially be assumed, but the timing is uncertain with little real-world experience. More accurate frequencies could be determined based on specific designs and the economic trade-offs between inspectability, inspection frequency, monitoring systems, and safety factors.

5.6 Vessels and Ports

Table 49 and Table 50 report some typical values for day rates and mobilization/demobilization costs for vessels, cranes, and port charges.

Table 49. Vessels and Cranes Rates

Item	Daily Rate ($k/day)	Mob./Demob. ($k)	Transit Speed (km/h)	Towing/Operation Speed (km/h)
Small tugboat (bollard pull < 80 t)	5	2–3 day rates	19	6–8
Large tugboat	30	2–3 day rates	19	6–8
Large AHTS with ROV	80	3–4 day rates	22	
Cable laying vessel	128	5 day rates	17	200–300 m/h
HLV with > 5,000-t crane	500	5 day rates	19	
CTV	2.3	In day rate	35	
SOV (long-term contract)	$11 million/year		18–20	
SOV with ROV	30	3–4 day rates	18–20	
Crawler crane	20	2–3 day rates		
Ring crane	50	$1 million each		

Table 50. Port Rates and Charges

Item	Rate
Open working/storage space	1.5 $/($m^2$ week)
Quayside working/storage space	1.7 $/($m^2$ week)
Lay-up anchorages (based on rates for oil and gas rigs)	360 $/(unit day)
Berthing rates (based on rates for oil and gas rigs)	2300 $/(unit day)
Installation/O&M vessels within port limits	0.1 $/(unit gross-tonnage day)

5.7 Weather Constraints

The successful completion of all offshore operations is dependent on weather limits. The assessment of weather constraints is a large topic that has significant uncertainty. The constraints listed in the previous sections are dependent on the exact operation being conducted, the operation duration, wave direction relative to the vessel, and vessel type. Those mentioned above are general values or ranges because specific values can vary considerably between sites, technologies, operations, etc.

Weather conditions limit the operations that can be conducted during installation and maintenance. Delays due to weather will significantly impact costs and the production potential of a floating offshore wind farm. For example, weather conditions are generally more favorable in the summer and more prohibitive in the winter. The installation start date could therefore influence the overall time and cost. Even if planned for the summer, delays could push operations into the winter months and costs could rapidly escalate. Alternatively, the installation can be suspended until the following year, which can entail a large demobilization-mobilization cost and further delay project commissioning, energy production, and revenue.

For maintenance, it is necessary to access a site to undertake operations when unexpected failures occur to maximize energy production and revenue. Particularly at sites farther offshore in deeper water, dynamic site conditions could pose additional challenges in terms of accessibility and limited weather windows to complete operations.

With little real-world experience in maintaining floating offshore wind farms, it is difficult to accurately estimate the weather constraints associated with different operations. Such constraints are particularly difficult to determine for major maintenance and replacements, given the lack of consensus on how major maintenance will be undertaken. Currently, platforms are towed to shore for major maintenance operations; however, research is ongoing to find feasible ways to undertake major maintenance operations offshore. If the required lifts can be undertaken at the water depths of floating wind farms, performing maintenance offshore could be more efficient and could make better use of available weather windows than current tow-to-shore maintenance practices.

To approximate the impact of weather conditions on floating array costs, Task 49 will incorporate the above wave and wind constraints into the installation and maintenance modeling. Follow-on work with the reference array designs could consider alternative installation and maintenance strategies, their respective risk and cost implications, the maintainability of floating wind array systems, and the effect of O&M equipment choices on weather constraints.

6 Design Methods and Conventions

Designing the reference arrays will involve applying the information and concepts outlined in the previous sections while also coming up with specific solutions to solve the challenges of each reference design. This section discusses the approaches and conventions that will be used in developing the reference designs and summarizes some of the key next steps in the design process.

6.1 Floating Wind Array Design Description

Establishing a common method for describing a floating wind farm design is essential for ensuring that the reference designs can be communicated and transferred between parties. IEA Wind Task 37 developed a framework for describing a floating wind turbine's design parameters for use in multidisciplinary design analysis and optimization (MDAO). This framework, referred to as the WindIO ontology, uses a hierarchical structure to organize the various components of a floating wind turbine design.[6] Within the hierarchy, there are fields dedicated to describing each part of the design.

WindIO currently has two separate ontologies. The turbine ontology provides a relatively detailed description of a turbine, including a limited description of the floating support structure. Many reference wind turbine designs, including the IEA Wind 15-MW reference wind turbine and VolturnUS-S support structure, already have definition input files following the WindIO ontology. The farm ontology provides a lower-fidelity description of a wind farm, with very basic turbine information (e.g., power curves) and without information yet for floating support structures.

The plan for IEA Wind Task 49 is to expand on the WindIO farm ontology to provide support for floating wind support structures and offshore wind site parameters such as seabed conditions.

An ontology in this context is a way of recording information that describes a floating wind farm project, including both site condition information and design information. The goal of the ontology is to provide a standardized format for recording and exchanging a description of a floating wind farm design. This capability is aligned with the work of IEA Wind Task 49, which focuses on integrated design of floating wind arrays. The ontology proposed here draws on elements from two established ontologies developed under a previous IEA Wind task. Task 37 developed plant-level and turbine-level ontologies. The current floating array ontology has a number of additions and differences that better suit the scope and emphasis of floating wind arrays. This ontology is in a draft form and will continue to be revised based on feedback from prospective users and collaborating projects.

The Task 49 Floating Wind Array Ontology is available on GitHub,[7] and a summary of its contents is as follows:

[6] https://github.com/IEAWindTask37/windIO
[7] https://github.com/IEAWindTask49/Ontology

- Site
    - Seabed bathymetry and soil type over a grid
    - Boundary and exclusion areas
    - Metocean parameters (for key DLCs and fatigue bins)
    - Wind resource data (wind rose)
    - Marine growth and corrosion parameters specific to the site (if available).
- Design
    - FOWT positions
    - Anchor positions and mooring line attachments
    - Array cable routes and attachments
    - Wind turbine
    - Floating platform
    - Mooring system designs
    - Mooring line section property descriptions
    - Anchor property descriptions
    - Dynamic cable profile designs
    - Cable section property descriptions.

The site section describes all the site information needed for a design, while being agnostic to any specific design. It combines elements from the WindIO ontologies with additional details about the seabed and fatigue cases that are crucial for floating wind applications.

The design section describes the floating wind array that would be installed at a site. It is roughly aligned with the WindIO plant ontology but adds significantly more detail about the design so that floating systems can be comprehensively described and loads analyses can be done.

The wind turbine and platform sections are intended to align where possible with the WindIO ontologies. However, the fidelity level for array design necessitates a different level of detail than previous ontologies.

The subsea components (mooring lines, power cables, anchors) are provided with more detail than in previous ontologies. Mooring line and power cable descriptions are divided into two parts: the list of mooring line (or cable) sections and their lengths and attachments, and a list of the mechanical properties of each section. Adding the attachment locations gives a complete mid-fidelity description of each mooring line. The anchors are also described with dimensional information such that a separate analysis could be done to estimate their holding capacity in given soil conditions.

This ontology is expected to evolve over the course of Task 49 and in potential coordination with other efforts such as in Task 55. The initial applications of the ontology for the reference designs will inevitably not address particular scenarios that may be of interest later, such as single-point mooring systems. The ontology should therefore be considered an evolving framework; rather than providing a fixed description here, readers are referred to the GitHub repository for the latest version.

6.2 Units and Coordinate System Conventions

To ensure clear communication, the reference designs will follow a set of conventions for the units and coordinate systems. The ISO International System of Units (SI) will be used. Angles will be referred to in the 360-degree system.

In general, the global *x*-direction will be aligned with geographic east, and the global *y*-direction will be aligned with geographic north. The *z*-direction is defined positive-up, measured from the mean sea level (e.g., a depth of 100 m corresponds to $z = -100$ m). The global coordinate system for any given array, unless specified otherwise, will have its origin located at the centroid of the array as determined based on the turbines' undisplaced locations. Floating wind turbine locations can be specified based on the *x*- and *y*-coordinates of the turbine reference point, which is defined as the intersection of the tower centerline (in undisplaced unloaded equilibrium) and the mean sea level. Figure 8 illustrates the coordinate system conventions.

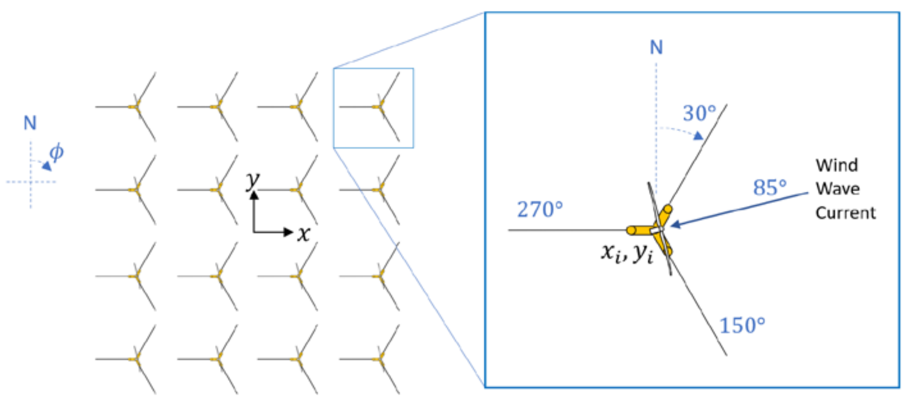


Figure 8. Coordinate system for array

At the array level, headings will be defined in accordance with compass headings where 0° points to geographic north and 90° is to the east. To avoid ambiguity, the heading of wind, wave, and current will refer to the direction from which the wind/current velocity or wave propagation vector is coming (opposite of the compass heading of the vector). Turbine heading is taken as the heading that the turbine front is facing, such that in aligned wind conditions the turbine heading and wind heading are the same number. The heading of mooring lines and dynamic power cables are the headings at which they extend away from the platform.

Many arrays, including the initial reference designs, use a regular grid layout (with turbines aligned in two directions and mooring lines having common orientations). To facilitate comparison of regular layouts, we can define a system of geometrical parameters to characterize such a layout. The parameters are:

- Rotation angle (α): a clockwise rotation to the rectangular orientation, resulting in x' and y' axes that define the rows and columns of the grid
- Row spacing ($D_{x'}$): distance between turbines along the x' direction
- Column spacing ($D_{y'}$): distance between turbines along the y' direction
- Skew angle (β): a further rotation that applies a shear to the layout such that turbine positions are shifted in the y' direction in proportion to their x' coordinate; this does not affect the row or column spacings
- Reference platform/mooring heading (γ): a rotation that describes the orientation of the platform and mooring arrangement relative to the y' direction; this is used to adjust the fit of mooring lines within a layout.

Figure 9 illustrates these variables for a sample array that includes both rotation and skew.

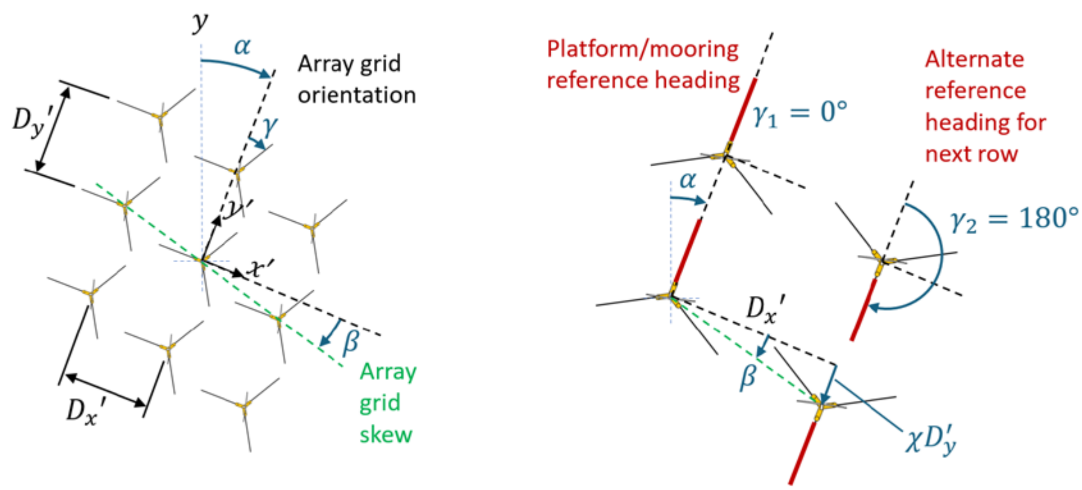


Figure 9. Regular grid array layout parameters

The skew can also be described by a skew factor χ such that each turbine's shift in the y'direction is

$$\Delta y_i' = \chi \, x_i' \frac{D_{y'}}{D_{x'}}, \tag{13}$$

where $x_i'$is the turbine's location along that axis. The conversion between skew rotation and skew factor is

$$\chi \frac{D_{y'}}{D_{x'}} = -\tan\beta. \tag{14}$$

This parameterization for regular grid layouts is a starting point for comparing layout options. Other types of layouts will require different parameters.

It is understood that various modeling tools could have different coordinate systems, and designers may use other local coordinate systems when looking at specific aspects of the design problem. Dynamics models often measure floating wind turbine motions relative to their undisplaced positions in terms of surge, sway, heave, roll, pitch, and yaw. If the *x*-axis is aligned with the dominant loading direction, then surge, sway, and heave are aligned with the *x*, *y*, and *z* axes, respectively, and roll, pitch, and yaw are the respective rotations about those axes following the right-hand rule. In this case, wind and wave directions are often defined about the *z*-axis, measuring counterclockwise from the positive *x*-axis when viewed from above; this implies a reversal and an offset of 90° from the compass headings used at the array-level coordinate system, so care must be taken. In general, alternative coordinate systems for certain design aspects can be used in the reference design effort, but array-level results should be presented in the defined global coordinate system, which is also how the array ontology is set up.

6.3 Design Process

Task 49 is not intended to prescribe or propose a design process but rather to facilitate reasonable design processes for developing the reference arrays. This design basis lays out the general scope, considerations, requirements, and assumptions; then, individual design efforts can develop their approaches using these resources. In that spirit, this subsection offers general guidance for steps that should be part of the design process and the order they might most naturally follow.

Various types of analyses are needed during the design process, and a variety of modeling tools exist for these purposes. Task 49 encourages interoperability so that designers can use any tools that have sufficient capabilities. Different tools may be used for different parts of the same design, or even to check the same parts of a design. A partial list of relevant tools for component design, farm design, optimization, and cost modeling is provided in Appendix A. The ontology discussion in Section 6.1 is intended to facilitate information exchange between different tools.

As discussed in Section 1.5, the reference design process was envisioned to have two main phases: (1) developing designs for the components or subsystems (such as mooring lines and dynamic cables) for the site conditions and (2) integrating the components into a full array and adjusting the layout and component designs to create a good array-level design.

Following is a rough outline of the steps that could be taken to develop a reference array design.

Component design:

- Gather site conditions (these should be time series or joint probability functions/contours of wind, wave, and current conditions, as discussed in Section 4.2).
- Process metocean conditions to provide the inputs to the necessary design load cases, including fatigue bins (see discussion in Section 6.4).
- Design the mooring system to suit the floating wind turbine and site conditions such that it can pass the DLCs for various mooring headings, including with initial assumptions about the array layout to account for wake effects (see discussion of design requirements in Section 3.2).
- Size the anchors to withstand the combined horizontal and vertical loads of the mooring designs in the DLCs.
- Design the dynamic cables such that they survive the DLCs, accounting for various headings of cables and mooring lines (see design requirements in Section 3.3).

- Consider subsystem-level interactions, such as how the power cables must be able to accommodate the watch circle determined by the mooring system, while the cables also exert forces on the platform and therefore can affect the watch circle.

Array design:

- Define the site boundary and select and parameterize a layout to position the floating wind turbines and their mooring systems within the boundary.
- Process metocean data for energy production calculations (considering wind speed and direction distribution as well as severe sea states that could require turbine shutdown).
- Evaluate the AEP of the reference wind farm for fixed turbine positions and potentially consider floating turbine positions. Steady-state motion models, such as surrogate models based on aero-hydro-servo-elastic simulations, may be used for the floating version to account for the movements of FOWTs and their impacts on flow field and power production.
- Optimize or tune the layout and mooring/cable orientations while considering AEP and/or cost factors subject to layout constraints (such as boundary, spacing, and clearances as discussed in Section 3.4) as well as any other design factors such as heading-dependent load considerations on mooring lines or dynamic cables.
- Select the location of the substation.
- Design the routing of the internal cable network (the static part) that connects all the FOWTs to the substation.
- Confirm performance through coupled simulations of the array or a subset of the array that is repeated throughout. The integration process should check that the requirements and constraints appropriate for each subcomponent are still adhered to.

In the end, the full floating wind array design, including the wind turbine locations, mooring line configurations, anchor positions, dynamic cable configurations, substation location, and electrical cable routings, should be specified to the level of detail defined by the ontology, which will allow the designs to be replicated and used in various modeling tools.

6.4 Load Cases

Selecting load cases for evaluating the strength of the designs is the most demanding part of the design process because it relates to survivability requirements, which are much more critical than other objectives related to cost reduction or optimization. Therefore, this section provides details and justification regarding the choice of load cases for Task 49.

Current design standards for FOWTs, such as IEC-61400-3 [70], specify DLCs that span a wide range of operational and nonoperational load conditions and include checks for ultimate loads and fatigue loads, including in fault cases. Ideally, all IEC load cases would be evaluated in the design of a floating array. However, due to constraints on time and the breadth of the design effort, Task 49 down-selected a smaller subset of load cases to evaluate. The following load cases are the most critical and limiting for the design of floating arrays:

- DLC 1.6: severe sea state at rated wind speed
- DLC 6.1: 50-year storm parked case
- DLC 1.2: fatigue analysis.

DLC 1.6 and 6.1 are common load cases that are evaluated for the survivability of the system in extreme operating and nonoperating conditions. DLC 1.6 is rated wind speed—thus, the maximum aerodynamic thrust force—coupled with severe waves. DLC 6.1 is a 50-year storm case where the turbine is parked.

Table 51 summarizes the return period of the wind, waves, and current used in the ultimate load cases. DLC 1.6 is notable for using 50-year wave parameters for the given wind speed based on joint probabilities rather than using the unconditional 50-year wind speed. For DLC 6.1, unconditional 50-year wind, waves and current are used to check the designs in an extreme storm condition. The unconditional waves and current values are used because the conditional distributions do not have enough data points at extreme wind speeds. Additional considerations for the extreme loads analysis are outlined in Section 6.4.1.

Table 51. Return Periods of Metocean Parameters for Strength DLCs

	DLC 1.6	DLC 6.1
Wind	Rated	50-year
Waves	Joint 50-year	50-year
Current	1-year	50-year

The final required load case, DLC 1.2, represents the expected range of metocean conditions that contribute to fatigue damage over the lifetime of the system. For this reason, evaluating the fatigue loads of DLC 1.2 requires a large number of simulations that reflect the lifetime loading of the system. Section 6.4.2 describes in more detail how the metocean conditions for this load case are determined.

The specific wind, wave, and current parameters for an array design can be determined based on available metocean data for the site. In general in Task 49, the wind speed and direction will be taken from hourly metocean data sources, while the wind shear can be assumed from design standards, and the turbulence intensity comes from site-specific data that defines turbulence intensity at each wind speed. The wave heights, periods, and direction come from hourly metocean data sources while the wave spectra and shape factor are assumed from standards. The current speeds and direction come from metocean data sources, and the current profile can be assumed from standards. As noted in Section 4.2, spatial variations in ambient metocean conditions are not considered in the Task 49 scope. However, wake effects can have a significant effect on loads and should be considered. Of the array aspects being designed within Task 49, the mooring system is the most sensitive to wind inflow conditions. An existing design effort in Task 49 has indicated that the overall effect of wakes on mooring system ultimate loads is not prominent, but both wake-added turbulence and wake velocity deficits have a significant effect on mooring system fatigue loads. Therefore, methods for accounting for wake effects in the fatigue analysis are discussed in Section 6.4.2.

6.4.1 Extreme Conditions

The extreme design conditions can be found by reading values from extreme value distributions or environmental probability distribution contours at the points that correspond to the desired return period. The most important metocean parameters to get extreme values for are wind speed, significant wave height, wave peak period, and current speed. The most probable directions corresponding to these extreme values should also be identified. Wind, wave and current extreme values are typically uncorrelated and can be computed independently. However, the wave height and period are closely related, so their extreme values should not be computed separately. One approach is to construct a joint probability distribution of wave height and period, then pick points on the probability contour of the desired return period. The choice of which height-period point to use along a contour can be made based on knowledge of which is the most severe load for the design in question, or multiple values can be used in a loads analysis. For example, the peak period can be chosen to coincide with the natural periods of the floating system, which is likely to cause the greatest motion and loading. An alternative approach is to focus solely on the extreme value of wave height, then use the most probable wave peak period that corresponds to the extreme wave height. For simplicity and to avoid choices about wave height-period trade-offs, we use the latter approach.

When setting up extreme load cases, there are choices about how to handle directionality. The simplest and most conservative approach is to assume aligned wind, waves, and currents. Because the mooring system and dynamic cables also have associated directions, a simple solution is to evaluate each extreme case at two opposite headings; typically, one heading will result in the largest mooring system loads while the opposite heading will result in the largest platform offsets. However, as mentioned earlier, misalignment of wind, waves, and current can cause increased motions and loads in some cases. There are also some load cases specifically designed to handle misaligned conditions or transient conditions where the wind direction changes. Each reference design effort may make a different choice about its extreme load cases based on the specifics of the design and site conditions.

6.4.2 Fatigue Bins

For evaluating fatigue loads of floating systems, a set of metocean conditions must be defined that represents the joint probability distribution of the metocean conditions at the site. This set of metocean conditions, often called fatigue bins, can then be used to run a set of simulations that model the fatigue damage that occurs under each metocean condition. The lifetime fatigue damage can be found by summing the damage in each case, weighted by the probability of occurrence of that metocean condition.

To represent the distribution of metocean conditions in a discrete and concise way that lends itself to a small number of fatigue simulations, clustering approaches can be used. The full set of metocean parameter data points is grouped into clusters, and each cluster is reduced to a single representative point at its centroid. The clusters are determined based on the proximity between data points and do not need to follow a rectangular pattern, allowing for much more efficient coverage of the data distribution, as shown by Kanner et al. [88]. Clustering provides a practical approach for coming up with a manageable number of fatigue bins that can be simulated for analyzing fatigue loads during the reference array design effort.

Initial fatigue analyses done for the reference designs indicated that the presence of currents did not have a significant effect on the aggregate fatigue damage. Therefore, the reference designs may exclude current from the fatigue analyses and use only five metocean parameters: wind speed, wind direction, significant wave height, peak spectral period, and wave direction.

The impact of wake effects on downwind turbines is important to consider in the fatigue analysis of the mooring system. Wake effects decrease the mean wind speed for downwind turbines, which can increase the aerodynamic thrust force for above-rated wind speed. Additionally, wake effects increase the turbulence intensity through wake-added turbulence, which may significantly increase fatigue damage for components.

To incorporate these array-level considerations in the mooring design, the fatigue analysis should consider an increased turbulence intensity and velocity deficit due to wakes. IEC 61400-3-1 provides detailed equations for calculating an increased turbulence intensity due to wake effects that depends on the number of neighboring turbines and the Wöhler exponent [54]. Alternatively, Frandsen et al. provide a simpler equation [89]:

$$TI = \sqrt{\frac{1.2C_T}{s^2} + {I_0}^2}, \tag{15}$$

where C_T is the thrust coefficient, s is turbine spacing normalized by rotor diameter, and I_0 is the ambient turbulence intensity.

In either case, the spacing between turbines must be assumed as an input. To determine the velocity deficit, there are a number of different wake models that can be used. Archer et al. review several of them [90], including the Jensen model, which represents the velocity deficit as follows:

$$1 - \frac{v}{u} = \frac{1 - \sqrt{1 - C_T}}{(1 + 2ks)^2}, \tag{16}$$

where C_T is the thrust coefficient, s is turbine spacing normalized by rotor diameter, v is the downstream wind speed, u is the ambient wind speed, and k is a wake decay coefficient recommended to be taken as 0.04 for offshore conditions in [90].

The turbine spacing used in these equations should consider the distances between turbines in the array layout along different wind headings, with an emphasis on the wind headings that are most prevalent. For example, in the case of a site with one dominant wind direction, the distance between turbines near that direction could be taken as the s value. At the component design stage, an initial array layout evaluation can be performed, or a conservative turbine spacing may be assumed. Mooring line fatigue can have a strong dependence on the line heading relative to the dominant wind direction, so adjusting the headings can provide potential for reducing the fatigue. Therefore, Task 49 will use turbine spacing assumptions that are mildly conservative at the component design stage, with the assumption that small fatigue exceedances on certain mooring lines could be mitigated by small heading adjustments during the layout design stage.

6.4.3 Optional Load Cases and Other Considerations

There are many more involved considerations when selecting load cases that are not central to the scope of Task 49 but deserve mention and consideration in future work. In particular, we identified several additional load cases that may be impactful in the design of floating arrays but that were considered less critical than the above extreme and fatigue cases:

- Survival load case with 500-year conditions and reduced safety factors

- DLC 9.1/9.2/10.1/10.2
- DLC 2.3.

Survival load cases apply metocean conditions with a very large return period—for example, 500-year storm conditions—with significantly reduced safety factors and check the survivability of the system. However, survival load cases are owner-specific and are considered optional in Task 49. Additionally, damage and subsequent loss of a mooring line can be important drivers in the design of floating wind systems. DLC 9.1 and 10.1 analyze the transient situation after a mooring line failure. DLC 9.2 and 10.2 then model the situation after the mooring line has broken and the system has reached a new equilibrium position. These load cases are considered optional in Task 49 because IEC standards specify that these cases can be neglected for nonredundant mooring systems, where a larger safety factor has been applied. In practice, it may be beneficial to check these failure load cases even with nonredundant mooring systems to ensure that cascading failures do not occur.

DLC 2.3 refers to an accidental load case where grid loss may occur at any time during the course of a gust. The most unfavorable combinations shall be considered. The following three combinations of grid loss and extreme operating gust shall be examined, at a minimum, for each wind speed:

- The grid loss occurs at the time of the lowest wind speed.
- The grid loss occurs at the time of the highest gust acceleration.
- The grid loss occurs at the maximum wind speed.

Additionally, misaligned metocean conditions can cause challenges for the floating wind turbine response, including reduced aerodynamic damping to wave-induced motions and potential yaw excursions and stability challenges. Designs with single-point mooring systems that weathervane may face additional challenges in misaligned conditions when the ideal direction of the structure cannot be aligned with the environmental conditions. There may also be related control challenges and trade-offs in such conditions. We note these as considerations in potential future work.

Typhoon, hurricane, and tropical cyclone conditions can present environmental loading conditions that do not fit the typical assumptions. Extreme change in wind velocity is a dominant consideration and return periods or safety factors may need to be adjusted, such as increasing the safety factor for DLC 6.1 when the coefficient of variance is high. There can also be additional need for redundancy, such as the presence of a backup yaw battery. These considerations could be important in future design variants that include typhoon conditions.

The discussion here is focused on simplifying the extensive list of design load cases to focus on critical considerations for the reference array designs. Standards such as IEC 61400-3 should be referred to for a more complete listing of the site-specific factors affecting the engineering and safety requirements of a floating wind array.

6.5 Next Steps for Developing the Reference Designs

The reference arrays are intended to be representative and diverse designs that will provide the basis for future research in offshore wind. The reference designs variants are summarized in Table 52, which is repeated from Section 1. The primary focus of the Task 49 effort is to completely design and define the variant 1 design for three cases: shallow, intermediate, and deep. The variant 1 design is intended to be the simplest, where the follow-on variants address various challenges and innovations.

Each reference design will begin with a regular layout on a uniform seabed with the IEA Wind 15-MW reference wind turbine and the VolturnUS-S semisubmersible floating platform. The shallow-water design is planned for a 60-m water depth with a semi-taut mooring system. The shallow-water design uses Sørlige Nordsjø II metocean conditions, which is a site in the Norwegian North Sea. The dynamic cables will follow a conventional lazy-wave shape.

The intermediate water design is at a 300-m water depth and uses metocean conditions for the Utsira Nord wind energy area, off the southwest coast of Norway. This site was chosen because of its generally representative wave conditions (in contrast with the limited-fetch Mediterranean Sea) and because it has similar water depths to the proposed reference site (Utsira Nord has a depth of 260 m, while the reference site is chosen to have a depth of 300 m). The intermediate design will be a catenary mooring system and a lazy-wave dynamic cable.

Finally, the deep-water design is at an 800 m water depth. The deep-water design used metocean conditions for the Humboldt wind energy area, off the coast of California. This site was chosen because of the deep water depths, which range from 550 m to 1000 m. Due to the deep water depth, the mooring system will be taut synthetic and the power cables will be fully suspended.

Table 52. Planned Reference Array Designs (Repeated From Section 1)

Scenario	Shallow	Intermediate	Deep
Key features	Shallow-water mooring/cabling design challenges and innovations	Seabed feature constraints on anchor positions, and innovations on anchoring	Deep-water constraints on mooring layout and turbine spacing, use of W-shaped cables and deep-water mooring innovations
Design variants (sequential)	V1: uniform *Secondary options*: V2: depth gradient with adapted mooring designs V3: spring option	V1: uniform *Secondary options*: V2: complex seabed, adapted layout and anchor positions V3: shared anchor option V4: cable layout designs	V1: uniform *Secondary options*: V2: depth gradient with adapted layout, moorings, cables V3: shared mooring option V4: TLP option
Metocean	Sørlige Nordsjø II	Utsira Nord	Humboldt
Depth	60 meters (m) *Secondary option*: sloped 40–120 m	300 m *Secondary option*: irregular 200–400 m	800 m *Secondary option*: irregular 600–1,000 m
Seabed	Generic	Generic *Secondary option*: irregular with bedrock/ridges	Generic
Array layout	Rectangular	Rectangular *Secondary option*: varied	Rectangular *Secondary option*: varied
Platform type	Semi	Semi or Spar *Secondary option*: TLP	Semi or Spar *Secondary option*: TLP
Mooring configuration	Semi-taut shallow water	Catenary chain (+wire?) *Secondary option*: semi-taut intermediate water	Taut synthetic *Secondary options*: shared taut, TLP
Mooring layout	Regular	Regular *Secondary option*: varied	Regular
Anchors	Drag embedment *Secondary option*: suction pile	Drag embedment *Secondary option*: shared suction pile	Suction pile *Secondary option*: drag embedment
Cable configuration	Lazy wave	Lazy wave	Fully suspended
Cabling layout	Regular	Regular or irregular if seabed constraints	Regular

The design variants provide progressively increasing need for new or more heavily adapted designs. These adapted designs will tackle real-world challenges in the design of floating offshore wind arrays, such as varying water depth and seabed features. Task 49 may not have time to design these variants, but they are described here for completeness. These variants may be considered in a follow-along IEA task.

All design variants will make use of reference designs for the turbine and platform. In particular, the VolturnUS-S semisubmersible platform and the IEA Wind 15-MW reference wind turbine will likely be used.

Design 1.1: The first design exercise will be a shallow-water design for an 80-m water depth. The mooring system will be a semi-taut configuration with drag embedment anchors, potentially adapted from existing NREL and University of Maine mooring designs. The array layout will be rectangular.

Design 1.2: This design variant will alter the shallow-water semi-taut design from Design 1.1 for a sloped bathymetry seabed. The seabed will have a linear slope, varying from a 40-m depth to a 120-m depth. The mooring design, including line lengths and anchor placement, will need to be modified to account for the varying depth while continuing to meet constraints on platform offset, power cable clearances, and more. The array layout will be held constant.

Design 1.3: This design variant will explore peak load mitigation techniques for shallow-water mooring designs. Beginning with the 80-m constant depth from Design 1.1, this design variant will add springs or other load mitigation devices to understand the potential benefits in limiting shallow-water snap loads.

Design 2.1: The second design exercise will develop a catenary mooring system for an intermediate water depth of 300 m. This design will consider both chain and wire line composition for the catenary mooring system with drag embedment anchors. As a starting point, the VolturnUS-S catenary chain mooring system may be used. The array layout will be rectangular.

Design 2.2: This design variant will consider the effects of seafloor features on array design. Beginning with the intermediate depth catenary design developed in Design 2.1, this variant will adapt the mooring and cable design for a varied seabed composition that limits the anchor choice, cable design, and subsea burial strategy. The array layout will also be varied to handle infeasible regions of the farm area.

Design 2.3: This design variant will evaluate the potential benefits of shared anchors. Starting with the intermediate catenary mooring system from Design 2.1, the array layout and mooring system orientations will be adjusted to allow for shared suction pile anchors.

Design 3.1: The third design exercise will focus on deep-water mooring challenges and innovations. This design will be a taut synthetic mooring system for a water depth of 800 m. The initial array layout will be rectangular and use suction pile anchors. Deep-water power cabling techniques will be applied with fully suspended designs.

Design 3.2: This design variant will consider the effects of varied bathymetry on deep-water moorings, cables, and array layout. Building on the learnings from Design 1.2, this exercise will alter the mooring system for a depth gradient from 600 to 1,000 m. The power cable design and array layout may also be adjusted for the varied water depth.

Design 3.3: This design variant will evaluate the benefits and challenges of shared moorings in the deep-water taut configuration. Using the mooring design from Design 3.1, the layout and mooring systems will be adjusted to best benefit from shared moorings connecting adjacent turbines. Multiple shared mooring array layouts should be considered.

Design 3.4: This variant focuses on featuring a TLP configuration. It will require identifying/adapting a suitable TLP design and designing tendons that are suitable for the range of depths.

7 Conclusion

Work Package 2 of IEA Wind Task 49 has created a design basis that gives guidance for creating floating wind reference array designs. This design basis is the culmination of extensive discussions among the task participants, literature review of guidance in published literature, data and recommendations contributed by participants, and pragmatic design strategies settled on by the reference design teams.

Through a broad survey of participants and facilitated small-group discussions, Task 49 defined the scope of the reference array designs to focus on designing the array layout, mooring systems, and array cabling systems while using existing floating wind turbine designs. The scope ends at the location of the substation to maintain focus on the array-level issues.

Design considerations, existing design information, and design requirements have been gathered and summarized for each aspect of the reference array design scope. The choice of requirements to use for the reference designs was refined through experience of the initial stages of the reference array design efforts. As a result, the listed requirements strike an ideal balance between following existing recommended practices and having a pragmatic array-level design pathway.

Drawing from the site conditions developed by Work Package 1, the design basis summarizes the necessary site information required for the reference array designs. The main design-driving load cases for the reference designs are identified, as are additional cases that deserve consideration. In particular, a clustering approach for fatigue analysis is identified, and the inclusion of wake effects when computing the mooring fatigue is strongly recommended.

For cost and logistics analysis, a comprehensive set of cost coefficients and logistics parameters was created based on literature review and expert estimates from participants. These values provide a baseline of assumptions that can be used with the reference array designs.

A system for describing the reference array designs is laid out, along with an array-level coordinate system to ensure consistent definitions. A rough outline of the overall reference array design process is presented as a nonprescriptive example for how the many considerations and requirements in the design basis can be woven together.

Three initial reference designs are under way—with water depths of 60 m, 300 m, and 800 m—based on the VolturnUS-S semisubmersible and IEA Wind 15-MW reference floating wind turbine. A selection of additional variants on these designs are proposed as future efforts to provide a greater variety of site conditions, support structure types, and design challenges.

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Appendix A. Relevant Design Tools

This section provides a summary of some existing software tools and methods that are relevant to help with floating wind array design. The lists represent examples of tools being considered by task participants and they are not exhaustive.

A.1 Component Design

DeepLines Wind[8] is a comprehensive software designed specifically to assess the dynamic response of floating and fixed-bottom wind turbines submitted to offshore environmental loadings. DeepLines Wind allows to perform fully coupled dynamic finite-element analysis simulations of all offshore wind turbine components. These simulations provide understanding of the dynamic response of the wind turbines, the floating platform, the dynamic mooring lines, and the power cable. DeepLines Wind offers a broad range of options to model the combined effects of the aerodynamic loads on the blades, active blades pitch control, hydrostatic and hydrodynamic loads on the floating platform, and dynamic mooring loads.

HAWC2[9] is a multibody aeroelastic code model for calculating wind turbine responses in the time domain. HAWC2 consists of different submodules to model the wind turbine. The blades and tower are modeled as Timoshenko beam elements, which allows HAWC2 to capture nonlinear deformations of the blades. The aerodynamics are calculated using blade element momentum theory, for the wind field different turbulence models can be used such as the wind fields generated using the Mann box. For the controller, a DLL file format of the wind turbine controller is required. Different turbine components are modeled as different bodies and are connected to each other using constraint functions. The external forces such as the aerodynamic, hydrodynamic, and servo forces are applied to each body separately.

MoorPy[10] is a quasi-static mooring model and a suite of associated functions for mooring system analysis. The core model supports quasi-static analysis of moored floating systems, including any arrangement of mooring lines and floating platforms. It solves the distributed position and tension of each mooring line segment using standard catenary equations. MoorPy automatically computes a floating system's equilibrium state and can be queried to identify a mooring system's nonlinear force-displacement relationships. MoorPy can be used directly from Python scripts to perform mooring design and analysis tasks, or it can be coupled with other tools to compute quasi-static mooring reactions as part of a larger simulation.

MoWiT[11] (Modelica library for Wind Turbines) is a computational model for modeling state-of-the-art onshore or offshore wind turbine systems and subsequent fully coupled time-domain simulation and load calculations in Dymola. The component-based library is based on the object-oriented and equation-based open-source modeling language Modelica. The hierarchical structure of programing in Modelica, as well as the multibody approach adopted in Modelica, benefit the modeling of such a complex system as a wind turbine. Hence, the wind turbine system is broken down into single components (main and subcomponents), which are modeled

[8] https://www.principia-group.com/blog/product/deeplines-wind/
[9] https://www.hawc2.dk/
[10] https://github.com/NREL/MoorPy
[11] http://mowit.info/

separately and interconnected to represent correct couplings and interactions between them. This structure also allows fast and easy exchange of single components to model different wind turbine technologies, turbine or support structure designs, control strategies, or site and environmental conditions. Furthermore, as MoWiT is under development by the Fraunhofer Institute for Wind Energy Systems, code modifications, optimizations, and enhancements are always possible. Finally, MoWiT is available free of charge for academic use and is currently being prepared to be offered open source.

OpenFAST[12] is a widely used open-source coupled dynamics model for floating wind turbines. The OpenFAST solver is made of different submodules to solve the multidisciplinary forces acting on the wind turbine. ElastoDyn deals with the inertia forces of the wind turbine and communicates with all other submodules inside OpenFAST. However, ElastoDyn is not capable of capturing the nonlinear deformations of the blade. For nonlinear blade deformation, the BeamDyn module should be used, but it is more computationally expensive. AeroDyn solves the blades' aerodynamics using the blade element momentum theory. ServoDyn is responsible for the wind turbine controller, and HydroDyn is responsible for the hydrodynamic forces on the platform. Within OpenFAST, MoorDyn provides dynamic modeling of mooring lines and power cables using a lumped mass approach. MoorDyn includes support for nonlinear elasticity, bending stiffness, and variable seabed bathymetry. MoorDyn can also be used independently for isolated simulation of a mooring line or dynamic power cable.

OrcaFlex[13] is a coupled time-domain simulation solution commercial tool for the dynamic response of offshore wind turbines. The aerodynamics are modeled using blade element momentum theory and the blades are considered to be flexible with six degrees of freedom. The platform is modeled as a rigid body, and the mooring lines are modeled using either finite-element representation or a lumped mass model. Moreover, OrcaFlex can be coupled to OpenFAST and be used for mooring system load calculation.

SIMA (SIMO/RIFLEX)[14] is a commercial tool for coupled time-domain dynamic analysis of several wind turbines. SIMO describes the rigid body motion of floating objects, and RIFLEX describes the dynamic response of flexible elements. The code has been widely tested by academic studies and the industry. Moreover, other products from Det Norske Veritas (DNV) (Sesam package) are well supported to be connected with SIMA. However, SIMA uses the same wind input for multiple wind turbines.

Simpack[15] is a commercial multibody system tool, which is application-independent. The user can define degrees of freedom at any location in the model. The use for wind turbine modeling is well established, including a model database of the public research wind turbines (the National Renewable Energy Laboratory [NREL] 5-MW and International Energy Agency Wind Technology Collaboration Programme [IEA Wind] 15-MW [in preparation] reference wind turbines) provided by Simpack. The wind turbine modeling requires aerodynamic and hydrodynamic solvers in addition to the multibody solver. Therefore, Simpack has standardized

[12] https://github.com/OpenFAST/openfast
[13] https://www.orcina.com/orcaflex/
[14] https://sima.sintef.no/
[15] https://www.3ds.com/products/simulia/simpack

interfaces to AeroDyn and HydroDyn, for example. Moreover, user-defined forces can be included through the user routine capability. The possibility to define degrees of freedom where needed in combination with the ability to couple in additional excitation forces through user routines adds flexibility to Simpack, which can be used to investigate the effect of different design parameters on the middle-fidelity level.

SLOW is a simplified low-order wind turbine model developed by the University of Stuttgart [91]. SLOW consists of a structural model and several submodels for the aerodynamics, hydrodynamics, and mooring system. The rotor is represented with a rigid actuator disk with a lookup table of the torque and thrust coefficients for each blade pitch angle and rotor tip-speed ratio. The frequency-dependent wave excitation coefficients are obtained from a panel code tool. Finally, the catenary mooring lines tensions are represented using a lookup table according to the platform's displacements. SLOW is flexible, and the different submodules can be updated according to the use case. SLOW represents a trade-off between calculation efficiency and including the important system degrees of freedom as needed by the user.

UiS Wind is an Open-Modelica-based fully coupled time-domain simulation tool for single-rotor or multirotor floating wind turbines. The aerodynamics are modeled using blade element momentum theory. The platform can be modeled as rigid or flexible bodies.

A.2 Farm Design

FAST.Farm is an extension of OpenFAST for predicting the performance and loads of wind turbines within a wind farm. FAST.Farm uses OpenFAST to solve the aero-hydro-servo-elastic dynamics of each turbine but considers additional physics for array-wide ambient wind, array-level control, and wake behavior through a dynamic wake meandering model. Through the possibility of a single MoorDyn instance, FAST.Farm supports bathymetry variations across the array as well as dynamic couplings from inter-turbine (shared) mooring lines or dynamic cables.

FarmShadow is a wind farm flow solver, based on analytical wake models. It relies on single wind turbine models for the velocity deficit, the wake-added-turbulence (WAT), and the wake deflection, that are further combined together. The use of WAT models allows the estimation of the local turbulence intensity at every rotor plane, which is then used as an input to by the velocity deficit models. Several models are implemented, including the Gaussian and super-Gaussian velocity deficit models, and the Tian WAT model. The wake superposition models include state-of-the-art approaches, including the momentum-conserving method of Bastankhah et al. [92].The model can be used in steady-state mode but also in dynamic mode given an unsteady inflow; passive tracers are advected through the domain to account for the meandering phenomenon. FarmShadow is used as a black box for wind farm layout optimization and power production maximization through wake steering approaches. A chaining between FarmShadow, DeepLines Wind, and TurbSim (developed by NREL) is now being considered to take into account the dynamic wake effects within a farm in the fully coupled aero-hydro-servo-elastic simulations of floating wind turbines.

FLORIS[16] is an open-source Python-based tool developed by NREL. The tool can be used for wind plant optimization and supervisory controller design. Moreover, FLORIS can be used to calculate the power production and the annual energy production (AEP) of the wind farm at steady state using different wake models.

FOXES[17] is a modular wind farm simulation and wake modeling toolbox that is based on engineering wake models. Its applications include wind farm optimization (e.g., layout optimization or wake steering), wind farm postconstruction analysis, wake model studies, and wind farm simulations invoking complex model chains. FOXES is built on many years of experience with wake model code development at the Fraunhofer Institute for Wind Energy Systems, starting with the C++ based in-house code "flapFOAM" (2011–2019) and the Python-based direct predecessor "flappy" (2019–2022).

MoorPy can be used to simulate multiple floating platforms along with interconnections between them in the form of shared mooring lines or dynamic cables. Floating platforms are represented with linear hydrostatic characteristics. By applying wind thrust forces on the floating platforms, MoorPy can then be used to estimate the offsets and restore characteristics of a floating wind turbines array.

PyWake[18] is an open-source Python-based tool developed by the Technical University of Denmark (DTU). PyWake is capable of calculating the farm flow field and the power production of the wind farm at steady-state conditions. It models the wake propagation inside the wind farm and the aerodynamic interactions between the wind turbines. The tool includes different wake models that can be used for wake calculation.

SIMA (SIMO/RIFLEX)[19] is a commercial tool for coupled time-domain dynamic analysis of several wind turbines. SIMO describes the rigid body motion of floating objects, and RIFLEX describes the dynamic response of flexible elements. The code has been widely tested by academic studies and the industry. Moreover, other products from DNV (Sesam package) are well supported to be connected with SIMA. However, SIMA uses the same wind input for multiple wind turbines.

TOPFARM[20] is a Python-based package developed by DTU for wind farm optimization. TOPFARM uses the OpenMDAO package for optimization and PyWake for AEP calculation. Using PyWake gives access to all the wake models implemented within the package while calculating energy production. Moreover, TOPFARM calculate the internal rate of return as well as the net present value of the wind farm. Since it is using PyWake no dynamic wind farm simulations can be done using TOPFARM.

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[16] https://github.com/NREL/floris
[17] https://fraunhoferiwes.github.io/foxes.docs/index.html
[18] https://github.com/DTUWindEnergy/PyWake
[19] https://sima.sintef.no/
[20] https://topfarm.pages.windenergy.dtu.dk/TopFarm2/

UiS Wind is an Open-Modelica-based fully coupled time-domain simulation tool for single-rotor or multirotor floating wind turbines. The aerodynamics are modeled using blade element momentum theory. The platform can be modeled as rigid or flexible bodies.

A.3 Cost/Logistics Models

There are a number of different cost and logistics (installation and O&M) models for offshore renewable energy technologies (wind, wave, and tidal). It is important to note tools designed for floating wave and/or tidal converters may also be useful for floating wind turbines. Summaries of existing models can be found in [93] [94] [95] [96] [97]. However, most of these are commercial software or services and are not open access. This section summarizes the known open-access tools available for cost estimation and logistics simulation.

COAST (Comprehensive Offshore Analysis and Simulation Tool) is a software tool developed by Fraunhofer IWES for making the weather a calculable factor already during the planning phase. COAST is designed to simplify the weather data-based planning, validation, and assessment of offshore work processes in the installation and operation phases. Incorporation of the analyses into the day-to-day workflows is quick and easy thanks to compatibility with Microsoft Project and an intuitive user interface. If delays have occurred in the implementation of a project, the COAST software enables project acceleration measures to be realistically estimated. On completion of the construction phase, the influence of weather risks can be validated, compensation claims asserted or rejected, and lessons learned documented for the future. The COAST software makes it possible to compare between different workflow planning concepts and variants in terms of the weather risks. Project plans can be optimized using sensitivity and scenario analyses. The results render weaknesses and bottlenecks in specific phases/activities clearly visible.

DTOceanPlus[21] software is an open-source suite of design tools for ocean energy projects. The Logistics and Marine Operations module is one of seven tools and is responsible for designing and planning the project life cycle phases (i.e., installation, maintenance, and decommissioning). The aim is to support selecting vessels, ports, equipment, and operation plans. Purpose-built databases of offshore operations, vessels, ports, and equipment were generated to support the main functionalities of the tool and are also freely available. The module proposes optimal logistic solutions that minimize total project costs, guiding project design and strategic investment decisions. Further detail is found in [98].

MoorPy includes functions and data for calculating mooring system component costs based on coefficients for each mooring line type and each anchor type. This is one option for automatically summing up a mooring system's component costs as a function of its design parameters.

ORBIT[22] (Offshore Renewables Balance-of-System and Installation Tool) is NREL's model for estimating the balance of system (BOS) costs of an offshore wind power plant. The BOS costs encompass all expenses required to construct a project other than the capital expenditures of the

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[21] https://github.com/DTOcean
[22] https://github.com/WISDEM/ORBIT

turbine. ORBIT is a process-based, bottom-up cost model and simulation tool. ORBIT includes many different modules that can be used to model phases within the BOS process, split into design and installation. The model is highly flexible, allowing the user to define phases specific to their project.

Robust O&M is an open-access tool developed by the University of Strathclyde [99]. It can estimate the availability of a given wind farm, simulating different reliability parameters, vessel specifications, number of technicians, etc. The purpose is to optimize a wind farm maintenance strategy.

The **SELKIE Logistics and O&M tool**[23] is an open-access decision-support tool developed in C++. It can simulate the logistics for installing a device (wind, wave, or tidal technology) offshore and the O&M over a project lifetime, based on user inputs for operation durations, weather limits, etc. It uses Monte Carlo simulation, varying the metocean data and failures per iteration, to consider the stochastic nature and uncertainty of these elements. The model uses an hourly time series of metocean data, applying a bootstrap method to vary the project lifetime time series per Monte Carlo iteration. Outputs include yearly breakdowns of costs and power production. The O&M tool will enable users to optimize the logistics required for the installation and O&M phase, e.g., the selection of ports, offshore vessel fleet, schedule activity, and operational strategy. While the tool was developed for wave and tidal technology, it can be used for offshore wind (fixed of floating), facilitating consideration of a tow-to-port strategy. This is a prerequisite functionality for an O&M tool simulating O&M for floating wind.

TopFarm[24] (Python package) was developed by DTU Wind Energy and is a wind farm optimizer for both onshore and offshore wind farms. It uses the OpenMDAO package for optimization and wraps the PyWake package for easy computation of a wind farm's AEP. Users can also include financial factors, e.g., foundation costs, electrical costs, fatigue degradation of turbine components, and O&M costs. The software calculates the wind farm interactions through PyWake, i.e., wake losses and power production, and the optimization objective function is evaluated through the cost model component, either by power production or financial goals. The base code is open-source and available on GitLab.

Wave Energy Scotland O&M Simulation model[25] is a Microsoft Excel-based O&M tool. It uses the Monte Carlo method to simulate the occurrence of faults on each device in a wave energy array by utilizing failure rate data. The user can choose whether a repair occurs offshore or if it is towed to an onshore base for maintenance. The model can also consider routine servicing. The user defines repair times and costs as well as metocean limits for marine operations. The model uses a time series of weather conditions to assess accessibility and calculate power production. The model simulates the array lifetime as realistically as possible by enforcing logistical constraints, including technician availability and quayside access. A full breakdown (per device and per year) of outputs, including availability, revenue, and operational expenditures, is presented, as is a table attributing costs to each fault category.

[23] https://www.selkie-project.eu/logistics-and-operation-and-maintenance-om-decision-support-tool/
[24] https://topfarm.pages.windenergy.dtu.dk/TopFarm2/index.html
[25] https://library.waveenergyscotland.co.uk/other-activities/design-tools-and-information/tools/om-simulation-tool/

WOMBAT[26] (Windfarm Operations and Maintenance cost-Benefit Analysis Tool) is NREL's tool for modeling the operations and maintenance of a wind power plant. The model calculates both direct and indirect O&M costs, along with power production, safety, and efficiency of operations. WOMBAT is a medium-fidelity tool with a flexible code base that allows for customizations to account for project-specific variations such as technological innovations, maintenance strategies, and site conditions.

[26] https://github.com/WISDEM/WOMBAT