Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

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Definitions & Abbreviations

AST	Administrative Support Team
AHV	Anchor handling tug
ALS	Accidental limit state
AUV	Autonomous underwater vehicle
DFF	Design fatigue factor
DLC	Design load case
DP	Dynamic positioning
FLS	Fatigue limit state
FOWT	Floating offshore wind turbine
LCA	Life Cycle Assessment
LCOE	Levelized cost of energy
MRL	manufacturing readiness level
MSV	Multi service vessel
MW	Megawatt
O&M	Operation and maintenance
OEM	Original equipment manufacturer
PC	Project Coordinator
PM	Project Manager
QTF	Quadratic transfer function
RAO	Response amplitude operator
RNA	Rotor Nacelle Assembly
ROV	Remotely operated vehicle
SPMT	Self-Propelled Modular Transporter
TLP	Tension leg platform
TLS	Tension leg system
TRL	Technology readiness level
ULS	Ultimate limit state
VIV	Vortex induced vibrations
WP	Work package
WPL	Work Package Leader
WTG	Wind turbine generator
AST	Administrative Support Team
AHV	Anchor handling tug

Executive Summary

The increasing relevance of industrialization capabilities of the available concepts for floating wind turbine platforms goes in line with the progress in the development of technology and manufacturing readiness. A key part of LIFES50+ effort is the development of industrialized processes which will allow for significant cost reduction through serial production, standardization, and optimized handling procedures along the lifecycle of the system. Complementarily, methods to determine the costs and risks of floating offshore wind turbine systems were developed in order to evaluate and rate the results.

This deliverable provides a comprehensive and generalized overview of the achievements of LIFES50+ with respect to industrialization of the FOWT technology.

In particular, this deliverable focusses on the following items:

(1) Platform selection
A list of parameters, which are needed to set up a decision making process, is defined and embedded into an optimization procedure by classifying the parameters into constraints, design parameters and performance indicators. This way, a transparent and systematic view on the selection and optimization procedure is given for finding the optimal concept for a given site.

(2) Station keeping
The mooring line design process is described, providing considerations during the design and listing relevant standards and load cases for catenary and taut mooring lines. Upscaling and risk considerations are also addressed.

(3) Installation and marine operations
Topics of marine operations and installation processes are covered, which constitute a large factor for cost reduction for floating offshore wind turbine projects. Common procedures are presented and differences between different concepts, constraints, challenges and risks are highlighted. A special focus is put on equipment to be used as well as on assembly methodologies.

The upcoming deliverable 7.10 on O&M, logistics, manufacturing and decommissioning can be regarded as a supplement to this document on topics of industrialization.

Contents

1 Introduction

With the increasing technology and manufacturing readiness level (TRL and MRL) of available substructures for floating offshore wind turbines (FOWT), the industrialization capabilities, which allow for low-cost mass production, become increasingly important in the design of advanced concepts. The main items required to achieve a high level of industrialization and to reduce costs have been named as standardised designs, optimised fabrication lines, easier assembly, transportation, installation, and decommissioning (James, 2015). With floating wind soon to arrive at a pre-commercial status, considerations of manufacturability, fabrication constraints, serial production, design complexity reduction, assembly, supply chain, installation, geotechnics, operation and maintenance (O&M) and risk are addressed as part of distinctive efforts in the LIFES50+ project. These aim at further increasing the TRL and MRL and developing an industrialized setting for future FOWT substructures.

To this point, substantial experience for industrialization was collected as part of the work performed in LIFES50+: In the design task in work package (WP) 1, the four different concepts were up-scaled to carry a 10MW turbine and withstand the loads from three representative sites of different environmental severity. Part of the work was also the consideration of fabrication, installation and O&M requirements. The designs were presented in (Sanchez, et al., 2017) and the relevant experiences for the up-scaling were collected in (Pérez, et al., 2017). The work provided insight into the different FOWT design philosophies present in the project and their performance at the different sites. The definition and application of a risk assessment methodology in WP6 as presented in (Hutton, et al., 2015) enabled the quantification and adequate addressing of critical items that could potentially lead, among other consequences, to failure of the structures. Based on efforts in WP2, it was made possible to compare the fundamentally different designs based on the definition of tools to assess the levelized cost of energy (LCOE), as well as the technical and environmental impact, which were presented in (Benveniste, et al., 2016). In the continuation of the project, the two selected designs are addressed in more detail and optimized designs are developed, a part of which is the incorporation of industrialization considerations. Topics focussing on industrialization are addressed in WP5, where a roadmap to an industrialized design process was presented in (Matha, et al., 2016) and procedures for numerical simulations in the mooring line design where investigated towards their application in an industrialized environment (Matha, et al., 2017).

As part of the work in WP7 and leading to this deliverable the abovementioned project results providing insight to industrialized design procedures for FOWT substructures were collected, scrutinized and summarized to provide a comprehensive and generalized overview on the achievements of LIFES50+ aiming at an industrialization of the FOWT community.

In particular, this deliverable focusses on the following items: platform selection, station keeping, and installation and marine operations as well as related risks and challenges to be expected in upscaling activities and the installation of large wind farms. The upcoming deliverable 7.10 on O&M, logistics, manufacturing and decommissioning can be regarded as a supplement to this document on topics of industrialization.

The deliverable is organized as follows:

Chapter 2 describes the selection procedure of substructure concepts for a given site. As this is a no straightforward task, it was decided to abstract and embed the connected evaluation of the boundary conditions into an optimization procedure. This provides a transparent view on the decision making procedure which is performed in the selection and optimization of site specific FOWT substructure concepts.

Chapter 3 describes the mooring line design process, providing considerations during the design and listing relevant standards and load cases for spread and tension mooring lines. Upscaling and risk considerations are also addressed.

Chapter 4 covers topics of marine operations and installation processes, which constitute a large factor for cost reduction for FOWT projects. Common procedures are presented and differences between different concepts, constraints, challenges and risks are highlighted. A special focus is put on equipment to be used as well as on assembly methodology.

2 Platform selection

2.1 Introduction

When searching the optimal site specific design solution of FOWT substructures, the aim is to find the best compromise between the system costs and the overall system performance. Significant work has been performed in the past on investigating the advantages and disadvantages of different platform concepts and on procedures to find optimal platforms for predefined site conditions. These are presented in section 2.3. The basic, functional requirements of FOWT substructures were summarized by (Henderson, et al., 2010):

1. *Maintain the turbine rotor sufficiently high above the sea*
2. *Maintain position within the range required for the power cable*
3. *Counteract the turbine's thrust, torque and yaw loads*
4. *Provide a sufficiently stable base for the wind turbine, i.e. to counteract the wave and sea-current loads*

The solutions to these objectives are typically linked to the fundamental static stability characteristic of a considered platform: barge (water plane area stabilized), spar (ballast stabilized) and tension leg (mooring line stabilized), which can be combined in the pitch restoring stiffness coefficient:

$$C_{55}^{total} = C_{55}^{water\,plane} + C_{55}^{ballast} + C_{55}^{mooring} \quad (1)$$

The selection of the platform or the stability classification can be seen as the first design step of FOWT substructure design. Once this is established, the determination of the many different parameters describing the platform is performed as highlighted e.g. in (Müller, et al., 2016), keeping in mind the abovementioned basic functional requirements. While this may lead to seemingly optimal solutions, satisfying only the functional requirements (which in itself is by no means is a simple task) is a strong reduction in the scope of the overall FOWT design procedure. It misses the various and complex influences, decisions and constraints that are part of the design and hence can only account for a fraction of what a designer has to deliver when defining an FOWT substructure concept.

The complexity of interactions within the overall FOWT system throughout its lifetime makes it difficult to determine the one best concept as it is not straight forward to pin down one indicator next to the LCOE (which only reveals itself once all design parameters are fixed) that could serve as a global performance measure for any platform. Rather, the concept selection is seen here as an optimization process for a given site, including different possible designs with competing characteristics that (once they are expressed in terms of cost) sum up to the LCOE. Even though this may shed some light on the compromises to be made, a simple definition or solution of the overall problem that applies for any designer on the market may not be possible, due to the numerical effort required for the suitability check of any given concept as well as the developer-dependent design constraints (e.g. availability of production units). Successful FOWT-designers will know their possibilities and limitations regarding different platforms, station keeping systems, installation methods, design tools, site conditions, etc. and will draw economically feasible conclusions in the form of compromises from them.

This chapter first introduces an approach for the problem definition for finding optimal design solutions. The approach is subsequently used in order to evaluate previous research on the topic. Building on the previous research as well as a questionnaire that was sent out to LIFE50+ partners, the problem description was defined for the platform selection.

2.2 Optimization problem description

It is the aim of this work to provide a list of parameters that are needed to set up a decision making process. These will give a more transparent and systematic view on the procedure which is part of selecting a concept for a given site. As done for shipbuilding (Papanikolaou, 2011), the decision making can be viewed as the solution of an optimization problem which is formulated around three key parameters:

Constraints
Constraints are the hard limits of the design and result from the environment of the considered design (e.g. site conditions, serviceability limits of the chosen turbine, water depth…). The design must be within these constraints, so the constraints define the limits of the design space.

Design parameters
Design parameters represent the different qualitative and quantitative decisions the designer has to make as part of each design realization (e.g. which platform type, which material to use, wall thickness, etc.). Design parameters can be chosen by a new decision making or optimization process (if sufficient information is available) or randomly (if sufficient information is not available).

Performance indicators
Performance indicators of a given design evaluate the different characteristics of the system (e.g. material weight, installation time, etc.). The different indicators are usually transformed into costs, weighted and result in the overall objective of the performed optimization (e.g. the LCOE).

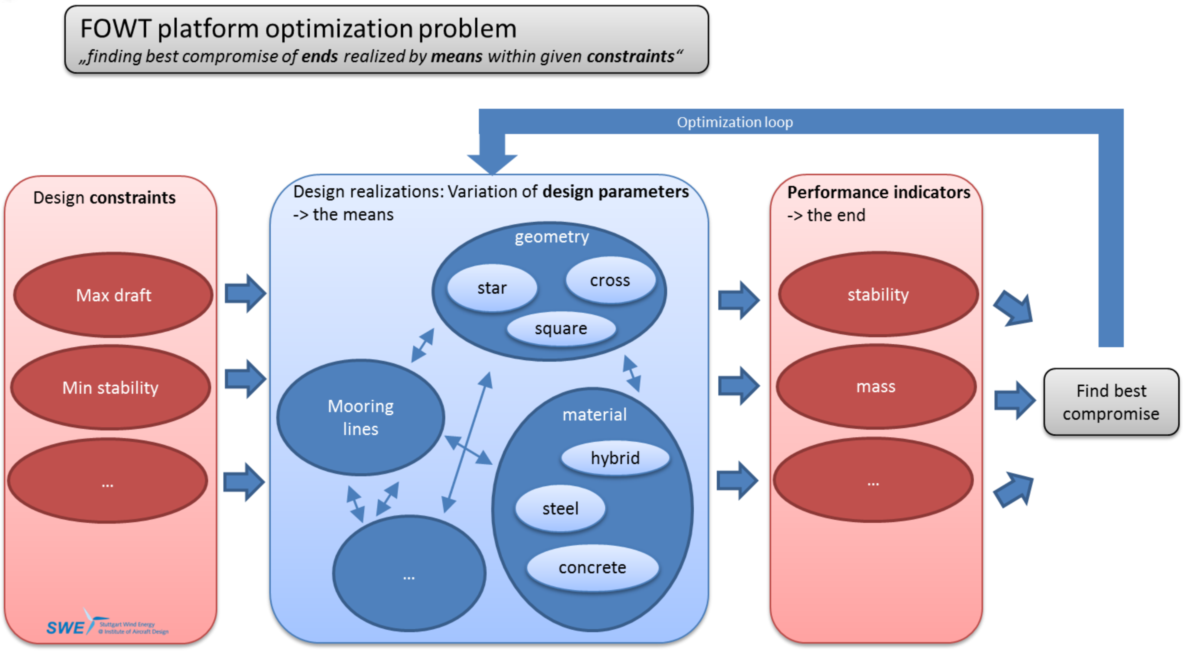

Figure 1: FOWT platform selection optimization problem

A sketch of the overall optimization procedure for FOWT is described in Figure 1. The description of the selection and optimization process is aiming at a high level overview and does not entirely go in line with industry procedures particularly due to the following items:

1. The mooring lines are considered as a design parameter of the platform optimization, which can be optimized separately, see chapter 3. It should be kept in mind that the mooring system significantly influences also the platform type (see Eq. (1)), but is seen at a lower importance, especially when focussing on mooring line characteristics such as material, additional elements and connectors. In this way, the decision on the platform type includes the definition of tension constraints for the mooring system.
2. In an industrial setting and as part of a typical tendering process, it is to be expected that the client contacts a number of (preselected) concept developers for a given site. As the developers typically focus on one design which is then optimized site specifically, the choice for a certain substructure geometry (and other parameters such as e.g. material, mooring lines, etc.) can be seen as preselection prior to the substructure optimization as described in Figure 1. For simplification and better overview, design parameters are taken as variables in this work, even though this likely is not the case in the industry, where certain parameters may be fixed for concept developers.

It is likely that a small number of criteria (such as water depth, draft, footprint and maximum motions) will drive the overall platform selection procedure for a given site, as some concepts may result in economically unfeasible designs. If in principle a concept can be used for a given site, the evaluation of which concept is likely to perform best at this site will be extremely difficult due to the many properties of a platform. Even if one concept may initially seem unfit for a given site, design specific assets (e.g. efficient installation procedure) may balance out other disadvantage for one particular design (e.g. higher manufacturing cost).

This complexity of the design when taking into account all life cycle stages of the system leads to the importance of the definition of performance indicators, which allow for a transparent view on the overall characteristic for a given system.

2.3 Previous research

Using the framework presented in the previous section, previous research focussing on optimization of designs and comparison between different concepts will now be analysed in order to describe the optimization problem.

- (Butterfield, et al., 2005), review
    - **Performance indicators**
      A differentiation of the advantages and disadvantages of different platform types, which are expected to influence the performance and cost of a floating platform, was provided and is shown in Table 1. These can be regarded as performance indicators for this work. It is worth mentioning that the impact on turbine stability classification is regarded as a separate item, to be evaluated independent of the platform performance.
- (Tracy, 2007), optimization
    - **Constraints**
      Stability during towing and operation, dynamic pitch, line tension, slamming height/ air gap
    - **Performance indicators**
      Nacelle acceleration, static plus three sigma tensions, displaced volume
- (Jonkman, et al., 2011), (Robertson, et al., 2011), (Matha, 2010), load comparison
    - **Performance indicators**
      Different load cases were evaluated and the sea to land ratio of different dynamic responses was used as a means of quantifying the impact of the platform on the turbine. Table 2 summarizes the performance of the different platform types.
- (de Boom, 2011), semi-submersible concept presentation
    - **Performance indicators**
        - Platform: access, lifting operations next to floating body within short time, disconnection and tow-away to harbor possible
        - Mooring lines: restoring force characteristics.
        - Figure 4 shows a mooring system providing a linear restoring behavior.
- (Fylling, et al., 2011), optimization
    - **Constraints**
        - Turbine: max tower inclination angle, max nacelle acceleration
        - Platform: max draft, heave/pitch period boundaries
        - Mooring lines: min/max tension, min fatigue life, max slope angle at anchor
    - **Design parameters**
        - Platform: cylinder and heave plate dimensions, vertical position of mooring line fairleads, submerged weight
        - Mooring lines: line orientation, pretension/distance to anchor, segmentation
    - **Performance indicators**
      combined costs of platform, cable and mooring lines
- (Bachynski, et al., 2012), TLP design study

- **Constraints**
  Survival under seismic loads, water depth, platform natural period such that the first-order wave excitation is avoided (e.g. surge and sway > 25s, heave, roll, pitch <3.5s), maximum mean offset to limit angle at tendon connectors, minimum displacement, minimum tendon cross sectional area to prevent failure.
- **Design parameters**
  Displaced volume, water plane area/inertia moment, center of buoyancy, center of gravity, number of mooring lines, mooring line angle, platform shape, mooring line material, anchor type, column diameter, pontoon radius, permanent ballast weight, natural periods, stiffness
- **Performance indicators**
  Structural loads on wind turbine and tendons, platform motions, power production, mooring line pretension, steel mass, displacement, load variation

- (Castro-Santos, et al., 2013), LCOE study
  - **Performance indicators**
    It was indicated that most of the costs are to be expected from the manufacturing (number of wind turbines, power of each wind turbine, mass of platform and wind turbine, cost of steel, direct labour, direct material and activities) and exploitation (cost for taxes, assurance exploitation management and O&M) life cycle phases, see Figure 2. A large number of cost items was established which could be helpful to determine more detailed cost drivers / performance indicators.
- (Myhr, et al., 2014), LCOE study
  - **Performance indicators**
    A substantially increased steel price sensitivity of LCOE for steel based structures was identified (and a consequent LCOE uncertainty of up to ca. 5%), and an influence of the water depth related to mooring system costs. No remarkable change of sensitivity between different platform concepts was found for farm size, distance to shore, project life span, load factor or discount rate. The results also show the contribution of different components to the overall substructure costs (see Figure 3).
- (Hall, et al., 2014), (Hall, et al., 2013), optimization
  - **Constraints**
    Static pitch angle, dynamic pitch angle, slackline events
  - **Design parameters**
    Several platform geometry variables (e.g. diameter and column spacing), mooring line configurations
  - **Performance indicators**
    Nacelle acceleration, support structure cost
- (Adam, et al., 2015), TLP load comparison (wave tank experiments)
  - **Performance indicators**
    Max accelerations
- (Strach-Sonsalla, et al., 2016), review
  - **Constraints**
    Natural frequency outside of 1P, 3P excitation, survival under extreme conditions and failure, air gap, sloshing, operational limits in inclination, acceleration and motion amplitudes, hydrodynamic stability during normal operation
- (Lemmer, et al., 2016), optimization
  - **Constraints**
    - Draft, hydrostatic pitch stiffness

- **Design parameters**
  - Platform radius, column spacing, heave plate thickness, ratio of heave plate radius and column radius
- **Performance indicators**
  - Cost (weight), standard deviation of tower top displacement, mass moment of inertia

Table 1: Design Challenge Tradeoffs for Stability Criteria (Butterfield, et al., 2005)

	Floating Platform Technical Challenges		
	Platform Stability Classifications		
Platform Design Challenge	Buoyancy (Barge)	Mooring Line (TLP)	Ballast (Spar)
Design Tools and Methods	-	+	-
Buoyancy Tank Cost/Complexity	-	+	-
Mooring Line System Cost/Complexity	-	+	-
Anchors Cost/Complexity	+	-	+
Load Out Cost/Complexity (potential)	+	-	
Onsite Installation Simplicity (potential)	+	-	+
Decommissioning & Maintainability	+	-	+
Corrosion Resistance	-	+	+
Depth Independence	+	-	-
Sensitivity to Bottom Condition	+	-	+
Minimum Footprint	-	+	-
Wave Sensitivity	-	+	+
Impact of Stability Class on Turbine Design			
Turbine Weight	+	-	-
Tower Top Motion	-	+	-
Controls Complexity	-	+	-
Maximum Healing Angle	-	+	-

Key: + = relative advantage
- = relative disadvantage
blank = neutral advantage

Table 2: Qualitative assessment of offshore wind turbine floating platform classes (Jonkman, et al., 2011)**, indicating relative advantage ('+') and disadvantage ('-').**

	TLP	Spar buoy	Barge
Pitch stability	Mooring	Ballast	Buoyancy
Natural periods	+	0	−
Coupled motion	+	0	−
Wave sensitivity	0	+	−
Turbine weight	0	−	+
Moorings	+	−	−
Anchors	−	+	+
Construction	−	−	+
O&M	+	0	−

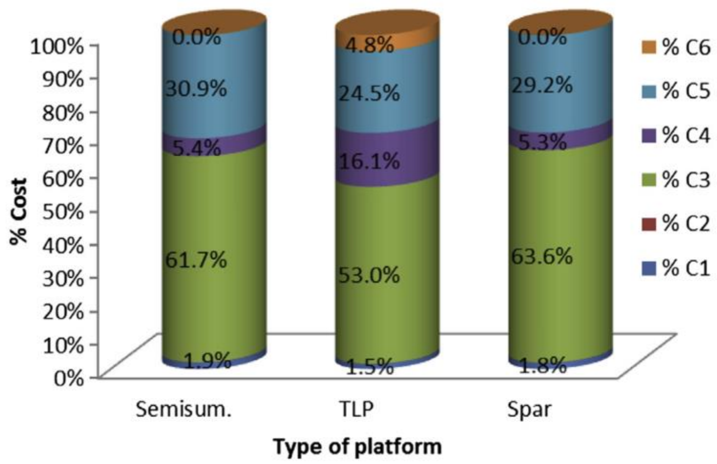

Figure 2: Percentage of the costs for different floating platform models. C1: Definition cost, C2: Design cost, C3: Manufacturing cost, C4: Installation cost, C5: Exploitation cost, C6: Dismantling cost (Castro-Santos, et al., 2013)

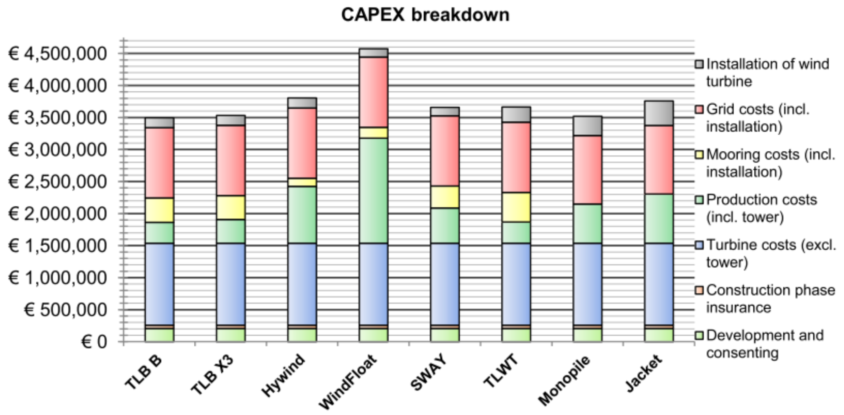

Figure 3: CAPEX quantification per MW for different concepts (water depth: 200m) (Myhr, et al., 2014)

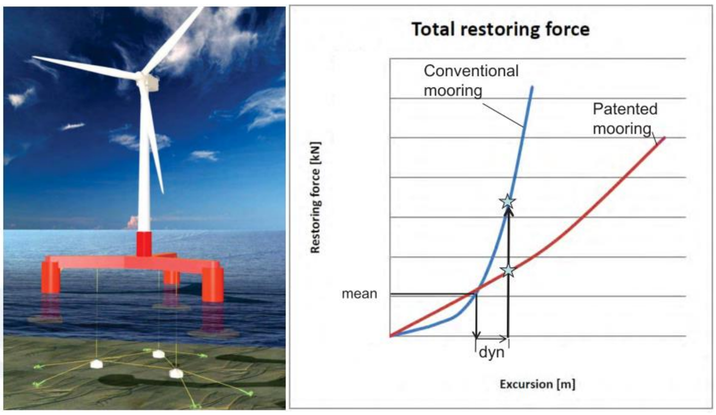

Figure 4: GustoMSC mooring connection with advanced restoring characteristics (de Boom, 2011)

2.4 Optimization problem for concept selection

Based on the previous research listed above and on a questionnaire filled out by the LIFES50+ participants the constraints, design parameters and performance indicators describing the search for optimal floating wind turbine substructures is assessed and provided below. Note that all items provided here are resulting from the authors' evaluation of different sources of input and thus may not represent the opinion of all LIFES50+ consortium members to the last detail. Also, the provided lists may not be complete and could be subject to change in the future.

2.4.1 Constraints

In general, a site specific platform is considered to be designed in accordance with the applicable guidelines (applied for the given site conditions). This typically means ensuring that the environmental loads can be endured by the designed system over the full life time. More restrictions from other life cycle stages are present, however, these might be more dependent on the individual designer or local government but also need to be taken into account (e.g. maximum sizes of components from a logistics point of view).

In this section, relevant constraints are presented in Table 3. They are classified according to a related life cycle category and described in more detail below. An alternative view to categorize the design constraints may be a division between environmental and logistical parameters, which is not done here, but could, potentially, better separate the items for different stages in the design.

Additional constraints regarding installation and assembly are also given in section 4.2.5.

Table 3: Constraints in the decision making of FOWT support structure selection

Life cycle category	Constraint
D	Numerical / design effort
D	Mooring line footprint
D	Site conditions
ML	Component dimensions / weights
ML	Material
IA	Stability during transport
IA	System dimensions
IA	Weight
IA	Minimum weather window
OM	Stability, motions & accelerations (SLS)
OM	Frequency constraints
OM	Load constraints (ULS, FLS, ALS)
DC	Decommissioning constraints

D – Design
ML – Manufacturing & Logistics
IA – Installation & Assembly
OM – Operation & Maintenance
DC– Decommissioning

Numerical /design effort: The numerical/design effort required to design a FOWT system within guideline requirements might be excessively large, if the structure or parts is too complex or too little information exists on the behavior of the structure. While the design of both substructures and wind turbines is well known in the adjacent industries, the challenge meant here is resulting from the effects of the coupled systems (aerodynamic, hydrodynamic, controller domains), which need to be taken into consideration.

Mooring line footprint: The site-specific design may require a maximum footprint per installed unit to be fulfilled in order to meet designated distance between turbines / area requirements.

Site conditions: Site conditions may prohibit the use of certain platform types. In particular, the water depth may disqualify concepts with increased draft (e.g. spar) or certain mooring systems (e.g. catenary) and hence the platforms relying on them. The maximum drift allowed from the dynamic cable perspective (10-20% of water depth) will impose stiffness constraints on the system that might be impossible to realize. If occurrence of ice loads is likely, this needs to be considered in the design. Geotechnical and –physical site conditions may prohibit the use of certain anchoring systems that define a given concept. The occurrence possibility of extreme events such as typhoons or cyclones can also constrain the use of certain concepts.

Component dimensions / weights: Dimensions / weights of components and materials have to be kept within limits in order to stay within the limits of the logistic chain or manufacturing yards. E.g. max component weight 2,000 tons for use of SPMTs; if large components need to be manufactured, storage places must be available at the harbor so the parts can be stored during manufacturing, assembly or O&M operations.

Material: As a desired material might not be feasible for given site (supply chain limitations, fabrication…), the use of a certain material may not be possible. Being restricted to use a certain material (e.g. concrete) could however lead to the inclusion of local content, which may be an advantage for the concept.

Stability during transport: A minimum stability during transport is required in order to ensure a safe installation of the system. This is in particular a challenge for concepts with small water plane area, especially for TLP, where the excess of buoyancy needs to be taken into account during transport (e.g. by use of additional weights).

System dimensions: Dimensions of the assembled system have to be kept within limits, in order to allow towing operations to site of operation. This also includes the draft, as depending on the designated harbor, a maximum draft may exist which cannot be exceeded in order to allow installation of the platform.

Weight: A limitation on the system weight may exist due to harbor operations or vessels to be used for towing and installation

Minimum weather window: A minimum required weather window for the installation of a given platform may be in conflict with the one available at a given site. The assembly location will influence the minimum weather window (i.e. is the system assembled in a dry dock, or are some operations necessary on site?). Towing and O&M procedures may also be restricted by the weather window at the considered site.

Stability, motions & accelerations (SLS): A minimum stability of the turbine/overall system may be required in order to ensure a safe operation of the system. Excessive motions and/or accelerations may not be allowed due to serviceability limit states (SLS) imposed by the design requirements of the used wind turbine and platform.

Frequency constraints: It needs to be ensured that the systems' and components' natural frequencies are not within the range of excitation frequencies coming from the wind turbine generator (e.g. 1P, 3P, especially for the tower), or the environment (e.g. wave periods, especially for the floater and the mooring system). If swell occurrence is likely, this should also be considered. It is mentioned that the platform pitching eigenfrequency is usually a bandwidth limitor of standard blade-pitch controllers of the WTG. This means that a very low platform pitch eigenfrequency might limit the controller performance. This depends, however, on the specific platform as well as the controller.

Load constraints (ULS, FLS, ALS): Site-specific load conditions need to be endured by the system. The applied guidelines can be used for definition of the relevant load cases. Clearances (air gap, sloshing) also need to be ensured.

Decommissioning constraints: The concept must allow meeting decommissioning requirements from local government (i.e. allowance for leaving behind anchors or mooring lines, using certain materials, etc.).

2.4.2 Design parameters

In this section, relevant design parameters in the platform design are listed in Table 4 and are described below. Each design parameter requires a decision for one or another alternative and thus can also be the base for a new optimization problem. In this work this is presented in more detail for the mooring lines in section 3.5.

Table 4: Relevant design parameters in the platform design

Design parameters
Platform type
Geometric shape
Weight distribution
Articulation
Mooring system
Material
Compartmentation
Ship impact resistance
Risk profile

Platform type: Different platform types exist as mentioned in the introduction of this chapter. The source of hydrostatic stability defines these as TLP, spar buoy, barge or hybrid forms (such as semi-submersible). As described in section 2.2 in a usual tender process, the decision on a certain platform type is typically not part of the optimization procedure, but closely linked to the concept developer's portfolio.

Geometric shape: Different geometric shapes are possible: star, triangle, square, moon pool, application of heave plates, etc. The shape significantly influences the platform hydrostatic (i.e. displaced volume, water plane area/inertia moment, center of buoyancy) and hydrodynamic properties and thus influences other design parameters as well. Generally, the smaller the cross-sectional area is at the water line (CSA) the smaller the platform excitation to wave inputs is to be expected. Also smaller CSA is an advantage in terms of numerical simulations (if $\frac{member\ diameter}{wave\ length} > 0.2$, wave diffraction becomes relevant). The geometric shape and the resulting dimensions will also influence the choice of vessels used for installation. A triangle design has been proven to be effective in terms of stability/mass ratio. As described in section 2.4 in a usual tender process, the decision on a certain geometric shape is typically not part of the optimization procedure, but closely linked to the concept developer's portfolio.

Weight distribution: The distribution of platform weight (including ballast) will define the center of mass and thus influence the dynamic behavior of the platform , hence also influencing the platform stability. By taking active ballasting into account, the weight distribution becomes an adjustable variable for different conditions.

Articulation: Including joints to the substructure provides the possibility to add means of active and passive control on the dynamic behavior of the floating wind turbine (e.g. additional swivels to allow control of yaw positioning.)

Mooring system: Depending on the soil conditions and the water depth at the site, the selection and design of the mooring system (consisting of mooring lines, anchors and auxiliary equipment) may be of high influence on the overall costs.

Material: The ratio of different materials used in the design has some influence of the overall weight and cost of the structure, as well as the sensitivity towards FLS or ULS conditions. Some platform types may not be feasible with a certain material (e.g. TLP shouldn't be made of concrete due to high bending load amplitudes). In principle, either steel or steel reinforced concrete is normally chosen, for which the advantages and disadvantages are the following:

- Steel:
    - Advantage: experience of working with steel in the offshore industry, recycling, steel yard availability and efficiency, lighter structure, logistics
    - Disadvantage: welding cost, price per ton, corrosion protection
- Concrete:
    - Advantage: low price and price uncertainty per ton, low fatigue sensitivity, robust/durable, flexible geometries, low maintenance, low carbon content, construction local to offshore site (i.e. local content)
    - Disadvantage: required thickness, mass, size, handling weight on land, recycling/environmental footprint, logistics

It has been noted that concrete seems to be more cost-efficient when the turbine size increases. In addition, the disadvantage regarding recycling characteristics of concrete may be diminished when it is used as aggregate. The future may also see towers and substructures made (partially) from composite materials as they promise lighter solutions.

Compartmentation: The designer may decide on a separation of the platform into different compartments that can be flooded without drowning the whole unit.

Ship impact resistance: The designer needs to decide how resistant the platform will be to hull breach due to collision. Compartmentation could be an item to address this issue,

Risk profile: The designer might choose not to accept the design or any part that score above some threshold in terms of risk.

2.4.3 Performance indicators

In this section, relevant performance indicators in the platform design are listed and described. Because not all of the indicators can be expressed as cost directly, the evaluation of a platform remains a multi-objective problem, which includes the relevance-weighting of the different performance indicators. As for the constraints, a classification of the indicators with respect to different life cycles is performed. The platforms mentioned in the description are used in a high-level sense and are in no way linked to the concepts participating in LIFES50+. As already mentioned in section 2.4.1, the intention here is to shed light on the complex interactions of compromises that need to be decided on as part of the design process rather than to indicate which platform performs best overall. Also, none of the below indicators is to be taken as the most important one. The design is always a compromise between different goals. In this section we are also focussing on an evaluation of the platform types only – hence the mooring line design and the turbine are not part of the evaluation.

Table 5: Performance indicators for platform designs

Life cycle category	Performance indicator	Description
D	Mass	Amount of material used
D	Physical complexity	Simpler structures allow simpler models
D	Platform motions	Negative combinations of platform characteristics with wave excitation characteristics
D	Technology readiness	Reduced effort and uncertainties in design
D	Redundancy	Reduced risk
D	Scalability	Simplified upscaling
D	LCA	Small environmental footprint
ML	Serial production	Modularity, component number, fabrication time, fabrication flexibility
IA	Installation	Fast, simple and cost efficient installation
OM	Operation and maintenance	Accessibility of wind turbine tower/nacelle, ease of inspection & maintenance of mooring system, ease of health assessment/monitoring, ease of major repairs
OM	Power curve	Performance characteristics for the specific site conditions
D, ML, IA	Robustness towards changing adjacent components	Robust design
D, ML, IA	Robustness towards changing environmental conditions	Robust design
D, ML, IA	Robustness towards local markets	Robust design
DC	Platform value at end of lifetime	Lifetime extension, recyclable components

D – Design
ML – Manufacturing & Logistics
IA – Installation & Assembly
OM – Operation & Maintenance
DC– Decommissioning

Mass: This relates to the total mass of the substructure, not including ballast. A reduced mass of the platform may indicate less material used and thus reduced incurred cost in the production. It should be noted that simply reducing the mass can have a critical influence on the substructure performance, see e.g. TLP (reducing the mass requires redesign of the mooring system). Typically barge-type platforms tend to have larger mass compared to the other platforms when using the same material configuration. Also, concrete-material platforms typically tend to have a larger mass.

Physical complexity: Physically simple structures will enable simpler modelling, resulting in faster and less conservative designs with lower uncertainty (e.g. the geometry of a spar allows the use of simpler models than other concepts (e.g. star-shaped platforms)).

Platform motions: While platform motions in different degrees of freedom may reduce the loading on the system, it is likely to have a negative influence on the system performance. Typically, the interplay between the physical properties of the structures and the waves effect the platform performance, i.e. platform natural frequencies or other wave excitation peaks in the wave spectrum likely lead to increased motions. Making use of e.g. the wave cancellation effect may be beneficial to mitigate negative consequences. Different degrees of freedom should be considered.
For the **platform pitch,** small platform motions will result in small variances of the tower top motions and thus in the power performance. A large pitch stiffness leads to an increased platform stability and hence reduces tower top motions. However, high stiffness should not be regarded as an absolute beneficial factor, e.g. having the pitch period in the frequency range of the waves can increase fatigue loads. For the **platform surge,** large motions may negatively impact the loads on mooring lines and the dynamic cable. Typically, barge platforms tend to show larger horizontal displacements than other platforms, while TLPs or platforms with taut mooring systems tend to show small displacements. For the **platform yaw,** platforms with small yaw stiffness due to the geometric setup or eccentricity of the rotor blades may lead to increased motions.
Potentially, some of the induced loads may be reduced by active or passive load mitigation systems which will enhance the power performance and reduce the loading of the system (e.g. unit positioning at a predefined angle, individual pitch control, etc.). This will come at some cost, as the applied systems may need to be maintained. Also, if a component failure of the load mitigation system is a critical issue, redundancy or sufficient safety levels need to be considered in the design. At this point in time load mitigation systems are not typically implemented in FOWTs, but could be more common in future designs.

Technology readiness: The technology readiness level (TRL) of a given platform helps to reduce the design effort and risks as well as the uncertainty of the costs and investors' confidence. There are different ways to derive the TRL. A means for indication of the TRL could be the number of installed platforms of this system in the form of prototypes and pre-commercial farms. To this point full-scale FOWT systems based on spar and semi-submersible platforms have been deployed.

Redundancy (station keeping system): A redundant station keeping system reduces the risk level of the system (and thus insurance costs) and allows the station keeping system to be designed for a normal safety class. Without a redundant station keeping system, the consequences of failures need to be considered in the design. These can be critical, if the considered platform is not self-stable (typically TLP substructures for floating wind applications).

Scalability: The same concept may have to be adapted for different wind turbines sizes. In that case, considerations for different parameters may be important and have to be evaluated case-specifically. For example, if the concept's dimension is generally large and the dimension is a relevant factor due to constraints in the production, concepts with smaller overall dimensions have an advantage (e.g. TLP substructures). On the other hand, larger structures may not require a significant redesign of the substructure, but simple upscaling by means of enlarging the dimensions, which results in a reduced upscaling effort.

LCA: The life cycle assessment (LCA) can be used as a measure of how "green" the platform is. The environmental footprint of concrete platforms and synthetic mooring lines may be less beneficial, when looking at recycling capabilities.

Serial production: If a large number of units is to be produced, several specific items become important:

- **Modularity:** A high ratio of modular components of a structure indicates enhanced manufacturing capabilities (flexibility towards supply chain, manufacturing yard, i.e. industrialized manufacturing) as well as simpler transportation and, consequently, reduced costs. While in general all platform concepts can be modularized, it tends to be easier to realize this with steel structures. Large concrete structures tend to be more difficult to design in a modular manner.
- **Component number:** A small number of components/parts and thus joints/connections requires less time for manufacturing (e.g. welds, connecting flanges) and reduces expected maintenance costs (e.g. inspection). This is comparable to the selection of jacket substructures and monopiles, where both platforms are highly modular, but monopiles have an advantage with respect to the number of components due to the reduced number (and complexity) of welding connections.
- **Fabrication time:** A smaller fabrication time means a higher flexibility of the overall production and faster project delivery. To reach this, the platform design needs to allow a high level of automation and use of assembly lines during the production.
- **Fabrication flexibility:** A platform that can be fabricated at different sites and is not limited to a certain harbour, workshop etc. will have a relative advantage, because it is less dependent on given local conditions and possibly increased transportation cost. Additionally, simultaneous manufacturing at multiple facilities is possible.

Installation: The aim for a cost effective installation is that it all procedures can be performed fast, are simple and inexpensive. Items that may have a significant influence on the installation performance of a substructure are:

- **Stability during transport:** Stability during transport operations allows a more stable transport and hence cost-effective transport of the platform. To achieve this, a lower centre of gravity or a large second moment of water plane area is beneficial.
- **Installation time:** An efficient installation due to optimized connection solutions or parallelized installation procedures will enable a fast installation and early power production.
- **Required Infrastructure at harbour:** A concept that can be assembled at any harbour can freely choose the assembly harbour, which will reduce the time of installation. Also, cost are reduced due to availability of more options to choose from. Items that come into play for the assembly harbour are potentially platform draft, wind turbine assembly procedure, modularity, launching mechanism, storage requirements, and maximum weights & dimensions of components (i.e. lifting requirements).
- Also, the requirements regarding installation vessels, as well as the mooring and anchoring system may be of importance.

Operation and maintenance: During the system life, efficient execution of inspection, maintenance and repair operation is desired. This overall goal can be divided into the following items:

- **Accessibility of wind turbine tower/nacelle:** A good accessibility of the tower and rotor-nacelle assembly (RNA) enables quick and efficient maintenance manoeuvres. This can be realized by smaller platform motions due to improved dynamic behaviour and large deck areas.

- **Ease of inspection and maintenance of mooring system:** A good accessibility of the mooring lines enables quick and efficient maintenance manoeuvres (e.g. tow back to harbour). Above water mooring connection and access from deck support accessibility and maintenance. Smaller mooring line lengths allow faster inspections. Adjustments to allow simple re-tensioning procedures, sensors for condition monitoring are of advantage. Overall very specific point to the design and not related to a specific platform type.
- **Ease of health assessment/monitoring:** If it is possible to easily track the structural health of the system, the effort of scheduling and performing O&M tasks is reduced. The same applies to on-site health monitoring. Overall very specific point to the design and not related to a specific platform type.
- **Major repairs (e.g. change of blades)**
  Strategy for major repairs (on-site, tow in). Ease of disconnection process, vessel requirements. Challenging to find suitable heavy-lift crane vessels to allow on-site change of major turbine components (especially for 10MW units), so tow-in is likely necessary, which may be problematic for deep-draft structures.

Power curve: A good match of the mean measured and OEM performance characteristics for the specific site conditions is desired. For this, platforms with less motion tend to have less fluctuation in the produced power. Smaller mean inclination of the platform also yield less cosine-losses in the power output. The key to ensuring that the turbine characteristics are maintained is an adequately designed controller.

Robustness towards changing components: A system that performs well with different wind turbines / station keeping systems / electrical setups does not require a redesign and hence reduces uncertainty.

Robustness towards changing environmental conditions: This is regarded as one of the key items for a FOWT design. A system that performs well in different environmental conditions does not require a substantial redesign and hence reduces the uncertainty (e.g. with respect to expected loads and motions). Robustness towards the following items can be considered of importance:

- **Geotechnical considerations (including geophysics and bathymetry)**: Due to site specific locations it may be necessary to select different anchoring systems. Also, the water depth may vary for different turbines within a wind farm or even the same turbine but different anchors.
- **Metocean conditions**
  - ***Wind***: In addition to different maximum wind speeds, different classes of turbulence may have to be expected for different sites or locations within a wind farm. Also, more than one wind directions may be dominant, so that an ideal orientation of the platform may not be possible. Wind farm effects have not been considered in detail for FOWTs up to this point but can be expected to be an important consideration in the future.
  - ***Waves***: Different wave heights and especially wave period ranges (or even swell waves) may be present. As wind and waves may not come from one dominant direction, but vary in directionality, this could lead to a large range of wind-wave misalignments.
  - ***Currents***: Wind driven and tidal currents may be present at a site. Different current profiles, with varying directions, are possible. Vortex-induced-vibrations may also have to be considered.

  - *Tidal ranges*: Tides lead to site specific temporary changes in the water depth with varying magnitude for different locations. This could have some impact on the pretension of TLPs and thus have a larger effect on this platform type.
- **Extreme weather events:** Hurricanes, typhoons, ice, earthquakes, etc. may be present at the chosen site.
- **Marine growth:** For different locations, varying depth ranges and different compositions of marine growth are possible.
- **Weather window:** A large variety of available time for installation as well as O&M procedures is to be expected for different areas of deployment.
- **Climate**: For different locations, a change in the climate (in addition to the abovementioned parameters) may lead to the necessity of redesigning specific components, e.g. due to increased temperatures.

Robustness towards local markets: Local regulations (on materials, damage stabilites, etc.), supply chain, vessel availability, subsidies for local content, local economy (e.g. fisheries), environmental concerns, may also impact the decision making for the site specific design.

Platform value at end of lifetime: Platforms that are likely to be of value after their designated lifetime may be more desirable. This can be achieved by e.g. lifetime extension. Platforms that can potentially be used beyond their designed lifetime are to be higher valued. This may be due to more conservative design, application of advanced design methods or materials, etc. Other options to achieve a value after the design lifetime is the use of recyclable materials as well as accounting for measures that allow simple decommissioning procedures.

2.5 10 MW specific issues

A part of this work is the investigation of the influence of increasing size of wind turbines (and hence the platform size) on the concept selection. In order to do this, the same questionnaire as mentioned in section 2.4 was evaluated to determine relevant items which could change with increasing system size. Next to this, key results of the upscaling workshop as part of the LIFES50+ deliverable 1.6 (Pérez, et al., 2017) are included in this report to provide an overview of items to be considered when upscaling a system. Finally, as part of this work, a simulation study was performed to analyse the loading of different substructures with 10 MW systems. This was compared with a previous study performed with 5 MW systems and evaluated for differences.

2.5.1 Upscaling considerations and challenges for large wind turbines

New challenges for floating substructures due to increasing size of wind turbines are summarized here based on results of the above mentioned questionnaire and the LIFES50+ WP1 workshop as documented in (Pérez, et al., 2017).

From WP1 design experiences, the tower design and wind turbine control can be seen as the main challenges for the design. For the tower, upscaling could possibly increase 3P excitation. Thus, concept designers will likely need to adopt different solutions in order to avoid an overlap with this frequency in the design of the system. Both soft-stiff and stiff-stiff designs can be considered as was done in this project. For large wind turbines, the tower design should be addressed in close collaboration with the WTG manufacturer, taking into consideration the control algorithm to be used for the system.

From LIFES50+ experience, the same design procedures and modelling used for smaller wind turbines are also valid for larger ones. The concern is that the nonlinear scaling of diffraction effects and the mooring line loads may be a critical item as mentioned in (Strach-Sonsalla, et al., 2016), was not reflected by the LIFES50+ experience. The scaling of physical properties did not have detrimental effects on the overall concept design and the design procedures. Also, for the LIFES50+ designs, the design driving load cases remained the same as those for the floaters designed for smaller turbines. However, some load cases may need to be addressed in more detail, which might require a higher quality of the environmental data for a given site.

Logistics for serial production is regarded as a potential bottleneck as WTGs continue to increase in size. Modularization of the floating structure is considered a key factor in the path for the industrialization (including serial manufacturing) of large floating wind turbines and for large wind farms. The increased component sizes may make it impossible to fabricate and/or assembly them in certain shipyards/harbours. The final assembly of the platform, with the inclusion of the WT and tower erection, is also detected as a possible bottleneck for large scale wind turbines, due to the limited availability of lifting devices which can handle the required weights up to the required heights.

More related to the different concepts, the turbine spacing is increased with a larger rotor diameter which means that upscaling eases footprint restrictions for a given concept (e.g. catenary systems). However, concrete structures may at some point become excessively large.

Aspects not considered in detail in LIFES50+, like wind farm layout, turbulence modelling and power production can also significantly influence the floater and mooring line design and should be considered more closely when facing detailed design stages. In general, larger systems result in larger platforms and turbines relative to waves, wind and ice, which generally increases the number of potential deployment sites.

2.5.2 Load specific evaluation of platform types

A simulation study was performed in order to investigate the wind turbine loading for a given site using two different substructures. Simulation of an onshore wind turbine were used as a means for normalization. The floating DTU 10 MW reference turbine (Borg, et al., 2015) was positioned on top of the DTU TLP (made available for this work by DTU and presented in (Bredmose, et al., 2015), (Pegalajar Jurado, et al., 2016), (Heilskov, et al., 2016)) and the Stuttgart Wind Energy (SWE) TripleSpar (Lemmer, et al., 2016). In order to simplify the comparison, the same tower and controller was used for both platforms. While a different tower geometry may reduce the loads, it also complicates a direct comparison, when an onshore turbine is to be used as a reference. A new controller was established and used for both floating substructures. Using the same controller for both systems facilitates a direct comparison and was possible in this study because the pitch natural frequency of the SWE TripleSpar is similar to the surge natural frequency of the DTU TLP. This way, the FOWT controller for both platforms required the filtering of the same frequency range. The considered site was Site A - Golf de Fos (most realistic for development of FOWT wind farms) for which the design load cases (DLCs) 1.2, 1.4, 1.6, 6.1 were evaluated as described in (Krieger, et al., 2015). Preparatory simulations were also performed in order to determine the platform specific orientation at the site, worst case direction for wind and wave loading and wind speed dependent steady state conditions that were used as initial conditions for the simulations. The results of the different load cases are discussed in the following paragraphs, concluding with a global evaluation.

The following abbreviations were defined and used for the evaluated positions (mostly adopted from FAST):

- TwrBsM: resulting tower base bending moment
- TwrBsYawM: tower base yaw moment
- TTBrMxn: tower top fore-aft bending moment

- TTBrMyn: tower top side-side bending moment
- TTBrMzn: tower top yaw bending moment
- RootFlapM: blade root flapwise bending moment
- RootEdgeM: blade root edgewise bending moment
- PtfmSurge: Surge displacement of platform
- PtfmSway: Sway displacement of platform
- PtfmHeave: Heave displacement of platform
- PtfmRoll: Roll displacement of platform
- PtfmPitch: Pitch displacement of platform
- PtfmYaw: Yaw displacement of platform

Note that no load evaluation is performed for any location below the tower base as the loads on the onshore wind turbine were always considered as the reference values. Due to the fundamental differences of the investigated substructure concepts, a comparison of the platform or mooring line loads would not lead to any practical conclusions. Also, it is highlighted that the same wind environment was considered for both the onshore and offshore calculations. For the DLC1.6 reference case this implies the same loading as for DLC 1.2 for onshore calculations (similar to the onshore DLC1.1).

The loads are normalized using onshore reference simulations, as has been done previously in (Jonkman, et al., 2011).

DLC 1.2: Figure 5 shows the results of DLC1.2 calculations for different wind speeds. The same wind distribution (i.e. according to Gulf de Fos design basis) has been used for the onshore and floating conditions. Damage equivalent loads (DELs) were calculated using rainflow counting and a SN-curve slope of $m = 4$. The fatigue load case with the 10 MW shows similar results as has been presented in previous studies for smaller systems, e.g. (Matha, 2010), (Robertson, et al., 2011). For wind speeds with significant damage contribution (i.e. around rated wind speed and higher) the tower fatigue loads show a significant increase compared to the onshore system. This underlines that a site-specific design of the tower is needed also for floating wind turbines. The fatigue loading of the rotor shows no significant increase in the loading (<10% for relevant wind speeds), when the turbine is positioned on any of the two considered floating structures.

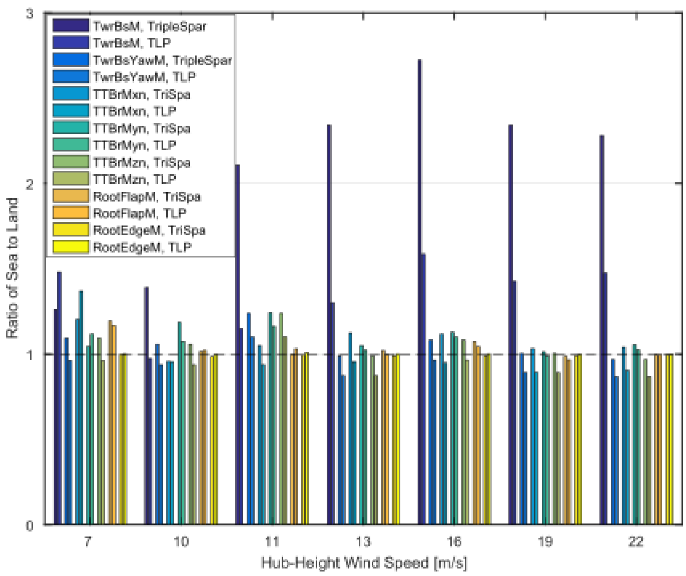

Figure 5: Mean sea-to-land DEL ratios from DLC 1.2 over wind speed

Figure 6 shows the comparison of DLC 1.2 across all wind speeds.

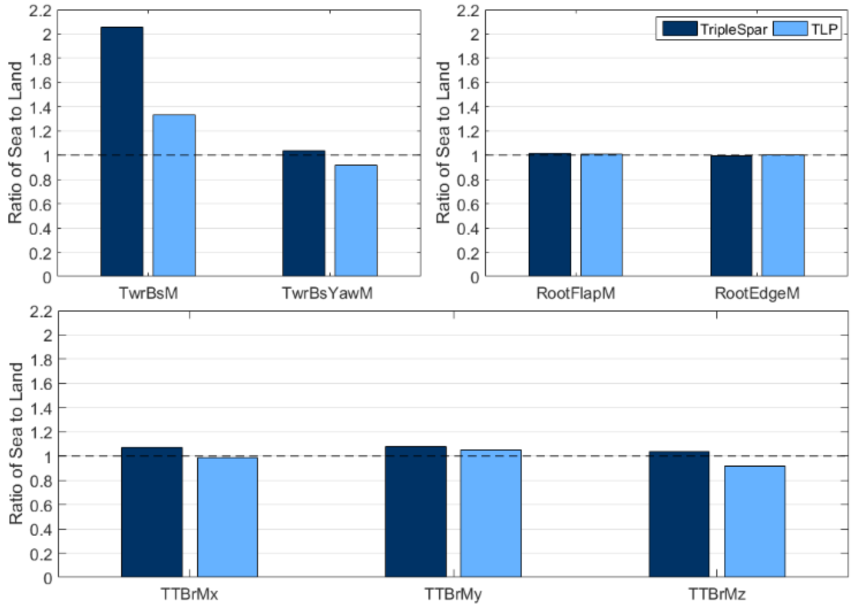

Figure 6: Sea-to-land DEL ratios from DLC 1.2

DLC 1.4: The extreme coherent gust with direction change during normal operation ($v_{hub} = v_{rated} \pm 2ms^{-1}$) was implemented taking into consideration the natural frequencies of the different substructures, as described in (Krieger, et al., 2015). The resulting maximum loads are summarized in Figure 7. The increased tower top loads with respect to the land based turbine are visible, but more relevant for the SWE TripleSpar. The tower base loads are increased up to53% of the onshore loading for the SWE TripleSpar. The blade root flapwise loads are just below a 15% load increase. The more flexible base for the floating wind turbines leads to a decrease in the yaw moments of the tower compared to the land based turbine (less than 90%).

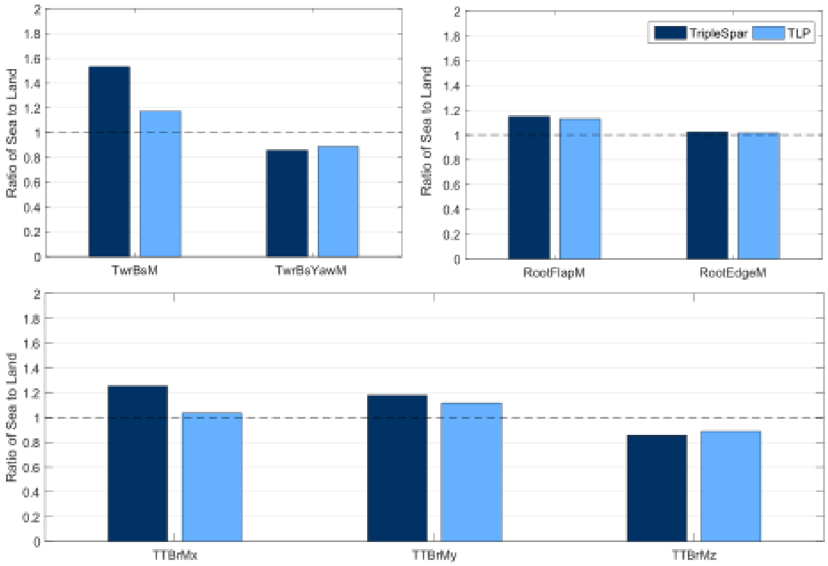

Figure 7: Maximum ratios of sea-to-land based turbine from DLC 1.4

DLC 1.6: This load case considers the severe sea state (in the LIFES50+ design basis: 1 year wave height below and at rated wind speed, 50 year wave height above rated wind speed, normal current, normal water level range) during normal operation and normal turbulence. Figure 8 shows the maximum ratios between sea and land based turbines. All positions show an increase in loading, in particular the tower base moments, where the load increase is over 6 times that of the onshore turbine. Note that the increase of the rotor loads (e.g. flapwise) is highest for wind speeds above the rated wind speed, whereas the absolute blade bending moment is lower than compared to the rated wind speed conditions (see Figure 9). Overall, the increase in loading is more related to the tower loads, as in previous findings.

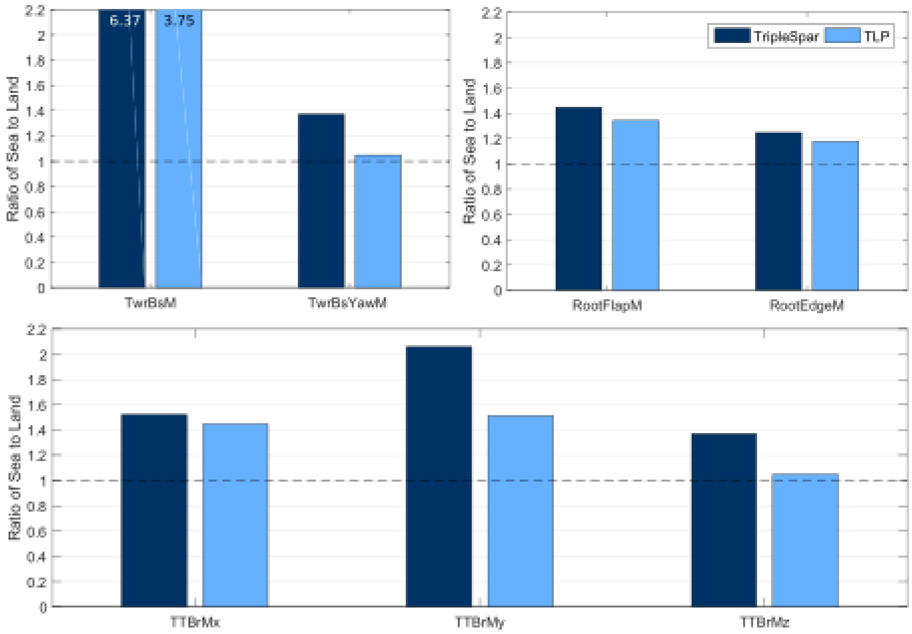

Figure 8: Maximum ratios of sea-to-land based turbine from DLC 1.6

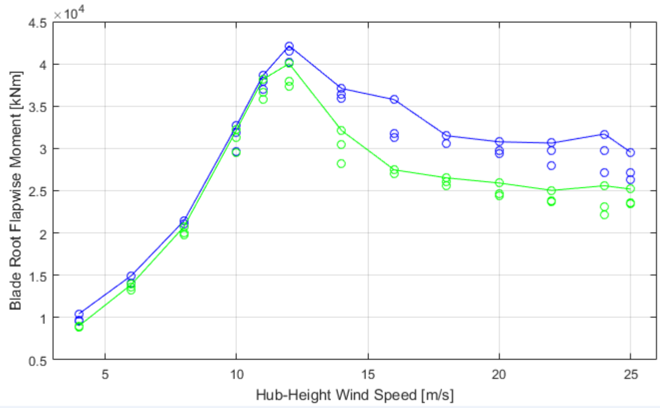

Figure 9: Maximum values of DTU TLP from DLC 1.6, comparing simulation results for onshore, (green circles) with offshore (blue circles). Points indicate max values for the considered wind speed.

DLC 6.1: In the final load case a parked turbine at 50 year wind speed in a severe sea state (here: 50 year wave height), extreme current speeds and extreme water level range (i.e. minimum and maximum values) were considered. It was found that the variation in the water level can lead to minor load increase for some positions. However, no consistent trend regarding the water depth for all positions could be established for either of the platforms (i.e. decreasing water depth may or may not lead to an increase in loading). Again, an increase in loading ratios for all evaluated positions could be observed, this time even larger when compared with the previous load cases. However, due to the lower absolute loads compared to DLC 1.6, for most positions, this load case did not mark the critical condition for either one of the platforms (see Table 6, Table 7). Figure 10shows the maximum sea-to-land ratios for DLC 6.1 as well as the maximum observed displacements in the 6 degrees of freedom. It can be seen that staying within displacement and SLS criteria is more likely to affect the SWE TripleSpar platform than the DTU TLP.

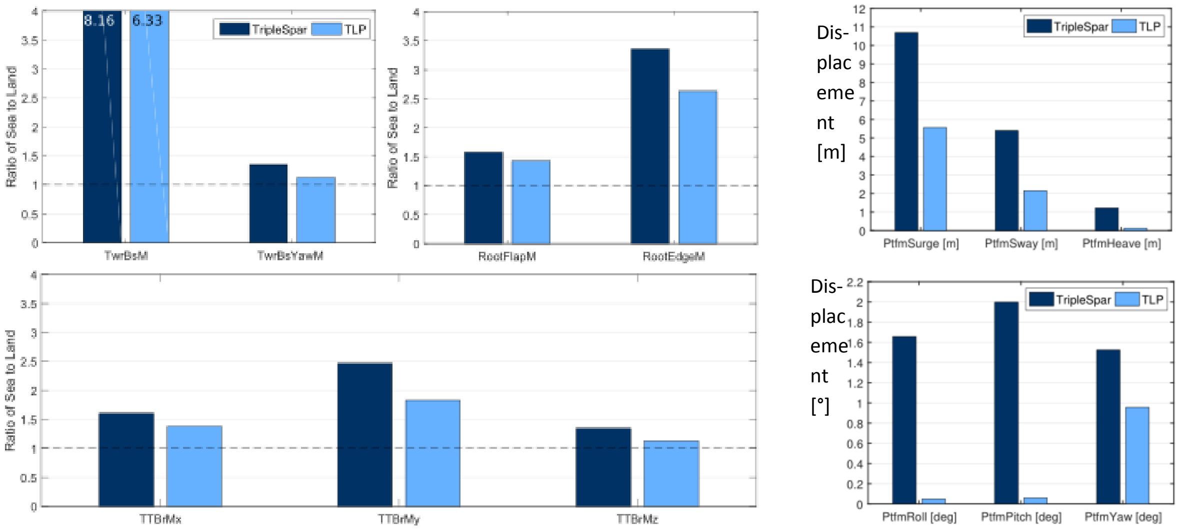

Figure 10: Left: Maximum ratios of sea to land based turbine from DLC 6.1; Right: Maximum values of platform motions from DLC 6.1

Table 6 and Table 7 show the maximum absolute ultimate loads for the different platforms and the different load cases. The load case for each position with the largest loads is marked in dark blue. If another load case generated close to the same loads (i.e. within 25%), it was marked in light blue. It can be observed that for the chosen site, platforms and evaluated load locations, there is no difference in the critical environmental conditions between the floating substructures analysed, apart from in-creased flap bending loads for the SWE TripleSpar in DLC 1.4.

Table 6: Maximum values of DTU TLP in ultimate load cases

	DLC 1.4	DLC 1.6	DLC 6.1
Tower base bending moment [kNm]	183 800	343 270	213 770
Tower base yaw moment [kNm]	24 680	17 720	3 670
Tower top bending moment [kNm]	18 971	25 760	23 730
Blade flapwise ben-ding moment [kNm]	37 530	42 140	25 780
Blade edgewise ben-ding moment [kNm]	13 520	16 120	6 810

Table 7: Maximum values of SWE TripleSpar in ultimate load cases

	DLC 1.4	DLC 1.6	DLC 6.1
Tower base bending moment [kNm]	302 520	412 550	269 350
Tower base yaw moment [kNm]	34 610	17 550	4 345
Tower top bending moment [kNm]	34 955	27 780	24 420
Blade flapwise ben-ding moment [kNm]	53 700	42 860	28 530
Blade edgewise ben-ding moment [kNm]	14 310	16 720	7 661

Overall, when using the same tower design, there are increased loads for the TripleSpar compared to the TLP. Also, the TripleSpar is more sensitive towards the Gust events as described in D1.4. DLC 1.6 does not seem to have a high importance for both substructures. For both platform types, the tower needs to be redesigned (larger tower weights are to be expected for semi-submersibles due to the increased tower loads. This goes in line with the fact that for the LIFES50+ public concepts from D4.2 (see (Wei, et al., 2017)), the tower weight of the semi-submersible platform is almost 3 times as high as the one for the TLP). Also, limitations on displacements are more likely to affect the design of semi-submersibles than the TLP. Rotor loads should be revaluated for both platform types even though they do not show a significant change in magnitude when comparing offshore with onshore loads (this is due to the relatively low influence of waves on the RNA loads).

3 Design of the station keeping system

3.1 Introduction

The aim of the mooring line system is (1) to keep the floating substructure within a specified limit from its reference position (i.e. control directional heading and limit maximum excursion defined by dynamic power cable or wind farm setup) and (2) to provide a certain portion of stability to the floating substructure. Assuming a substructure type (TLP, semi-sub, barge) is already selected, the remaining decisions to be made by the designer regarding the mooring line selection are summarized in this chapter. The chapter starts out with the design process, where a general description of the mooring line design process for spread and tension mooring lines is given in sections 3.3 and 3.4, respectively. Spread mooring systems are used as a baseline. Differences in the design approach for spread mooring systems are highlighted in section 3.4. Additionally, in the same way as for the platform concept selection an optimization problem is formulated for the mooring line selection in section 3.5, in order to provide information on the constraints, design parameters and performance indicators to be considered in the mooring line design process. Based on the experiences from the upscaling procedure performed in LIFES50+, the challenges expected from large wind turbines and upscaling procedures are summarized in section 3.6. Finally, an overview of the risk considerations in the design of station keeping system is given in section 3.7.

3.2 General Design Procedure

Typically catenary mooring systems are designed with the main target of being compliant with the motions of the floating substructure. The substructure motions in a given sea state are primarily dominated by motions around the wave frequency, with the motions increased for waves closer to the natural frequencies of the substructure. Most substructure types for FOWTs are designed to have natural periods out of the relevant range of wave frequencies (where most of the energy in the site wave spectrum is located), however for some types such as TLPs (at low wave periods / 3-5s) and barge-type floaters (around peak spectral wave periods / 8-12s), avoiding such coinciding of natural FOWT periods with wave periods of relevant energy content is not always possible. For such designs, however, typically either the damping is large enough in order to limit the increase in motion amplitudes in such resonance conditions, or the resulting ultimate and/or fatigue loads are not design critical.

Floating substructures are often exhibiting large displacement, for FOWTs primarily in surge direction. A viable mooring design should be performed in order to fulfil its main purpose of station keeping by being compliant and not forcefully restraining the translational motions of the floater. Mooring systems only restrain motions for TLP designs, and here mostly only in heave direction (allowing for inverted pendulum motions). However some TLP designs with cross-tendons (e.g. GICON's SOF TLP design) also restrain motions in pitch, roll and yaw to most extent

The actual design procedure utilized for FOWT mooring and TLP system designs cannot be generalized, with substructure designers following often individual approaches developed over time and experience in order to come up with an optimal design. On a high level however, most approaches share a common procedure, as e.g. outlined by Kim (Kim, et al., 2014) and shown in Figure 11 and described in Table 8. For TLP FOWTs, Bachynski (Bachynski, 2014) provides a good account of the particular design procedures applied for tendon systems. Other accounts for design methodologies for station keeping systems in floating wind are provided by Masciola in a book edited byCruz (Cruz, et al., 2016).

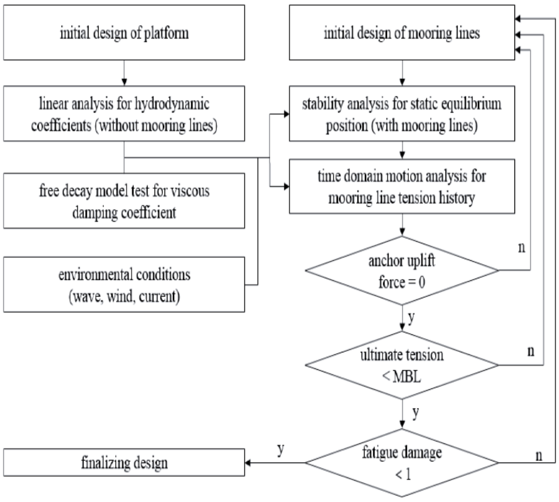

Figure 11: Catenary mooring design, (Kim, et al., 2014)

Step	Task
1.	Definition of floating substructure and design constraints and targets (e.g. metocean conditions, max. heel angle, etc.)
2.	Linear analysis of floater (RAOs)
3.	Initial/conceptual mooring design based on simplified (mostly quasi-static) approaches
4.	Floating stability check (static equilibrium)
5.	Design load determination by load case simulation in time domain (typically a combination of global fully coupled FOWT analyses and detailed de-coupled mooring analysis)
6.	Check of characteristic design tension against limit states (and slacking for TLPs)

Table 8 General mooring design steps

From related design works in LIFES50+, a two-step / decoupled design approach for mooring lines is recommended: (1) calculate movements and forces from coupled simulation and use these for (2) detailed mooring line design using higher-order hydrodynamics that cannot be considered in coupled simulation with feasible time.

3.3 Design methodology for a spread mooring system

3.3.1 Functional principle

3.3.1.1 Catenary mooring system

The upper end of the mooring chain is attached to the floater, the lower end is attached to an anchor. In the initial floater position a significant part of the mooring chain lies horizontally on the seabed. When the floater is moved in the horizontal direction due to static and dynamic environmental loads the shape of the mooring chain changes: the free hanging part (catenary) is tightened and raised, which results in an increased horizontal restoring force. Furthermore, the lower part of the chain is raised from the seabed, increasing the effective weight of the mooring line and, thus, the vertical reaction force on the floater.

As the lower end of the mooring chain lies on the seabed, it is possible to use drag anchors for catenary mooring systems.

3.3.1.2 Taut / semi-taut spread mooring systems

Taut and semi-taut mooring systems are often composed of synthetic fibre ropes, steel wire ropes or are hybrid solutions (e.g. synthetic fibre ropes + chains). The upper end of the mooring line is connected to the floater and the lower end to the anchor, the mooring line is taut between these two points. The shape of the mooring line does not change significantly with floater offset, hence, the restoring characteristic of these mooring systems strongly depends on line elasticity and general dimensions of the mooring system (line angles, line length, etc.).

In taut / semi-taut spread mooring systems the line uplift angle at the anchor point is > 0°, hence drag anchors are not suitable for this mooring type. Anchor piles are mainly used. However, in hybrid systems heavy chains may be used in the lower part of the line in order to reduce the uplift angle, so that drag anchors can be used.

3.3.2 Rules & standards

A number of classification societies have issued FOWT specific standards and guidelines, which cover – among other topics – the design of station keeping systems. In general, these documents adopt the requirements on the station keeping systems for oil and gas (O&G) floating structures defined in the respective standards (class rules, API, ISO) and combine them with wind turbine specific requirements (IEC 61400-3).

A selection of relevant rules and standards are provided below (this list does not claim to be comprehensive, other rules and standards for station keeping system design also exist):

- FOWT specific documents:
  - DNV-OS-J103, Design of Floating Wind Turbine Structures
  - BV-NI572, Classification and certification of floating offshore wind turbines
  - ABS Pub 195, Floating Offshore Wind Turbine Installations
  - ABS Pub 206, Global Performance Analysis for Floating Offshore Wind Turbine Installations
  - ClassNK, Guidelines for Offshore Floating Wind Turbine Structures

- General floating structures and station keeping systems (O&G):
  - API RP 2FPS, Recommended Practice for Planning, Designing, and Constructing Floating Production Systems
  - API RP 2SK, Design and Analysis of Station keeping Systems for Floating Structures
  - ISO 19904-1, Petroleum and natural gas industries - Floating offshore structures, Part 1: Monohulls, semi-submersibles and Spars
  - ISO 19901-7, Petroleum and natural gas industries - Specific requirements for offshore structures, Part 7: Station keeping systems for floating offshore structures and mobile offshore units
  - ABS Pub 82 (FPI Rules), Rules for building and classing floating production installations

- DNV GL-ST-0126, Design of wind turbine support structures
- DNVGL-OS-C103, Structural design of column stabilised units – LRFD method
- DNVGL-OS-C105, Structural design of TLPs – LRFD method
- DNVGL-OS-C106, Structural design of deep draught floating units – LRFD method
- DNVGL-OS-E301, Position mooring
- BV-NR571, Classification of column stabilized units
- BV-NR493, Classification of mooring systems for permanent offshore units
- Lloyds Register, Rules and Regulations for the Classification of Offshore Units

Furthermore, specific documents are available for the components of the mooring system (chains, steel wire ropes, synthetic fibre ropes, and anchors).

In Table 9 the major differences between O&G and FOWT requirements are addressed.

Table 9: Major differences between O&G and FOWT requirements

No	O&G	FOWT
1	ULS (survival) condition defined by environmental conditions with 100y return period.	ULS is defined as the combined load or combined load effect, whose return period is 50 years. Therefore 50y environmental conditions are used.
2	Number of relevant ULS conditions relatively small, mainly covering combinations of 100y environmental parameters (significant wave height, wave period, wind-speed, current).	Most severe loading condition is not necessarily the 50y storm condition with idling WTG. All relevant conditions (full spectrum of the design load cases DLCs adopted from IEC 61400-3) need to be investigated. This may lead to an extensive scope of load simulations necessary compared to O&G.
3	Different calculation methods for mooring lines are possible, from quasi-static to coupled dynamic analyses. The accuracy of the analysis method is accounted for in different safety factors to be applied.	Applicability of the quasi-static approach for FOWT is questioned, dynamic effects from the WTG are deemed to be important. Therefore, dynamic analysis methods shall be used for mooring design, unless it can be shown that dynamic effects are negligible
4	Generally in O&G redundant mooring systems are required.	Non-redundant systems are possible. Higher safety factors have to be then applied. E.g. 3-line spread mooring systems are possible.

The items 2 and 3 from Table 9 require a significant computational effort needed to design a mooring system for a FOWT. For practical application an agreement with the certification body will need to be found in this regard.

In the following, DNVGL rules will be taken as the basis for design of the station keeping system:

- DNV-OS-J103, Design of Floating Wind Turbine Structures
- DNVGL-OS-E301, Position mooring

3.3.3 Load cases and environmental conditions

The conditions to be investigated:

- ULS
- ALS
- FLS

In ULS the mooring lines are designed for 50-year value of the line tension, which is assumed to occur during a sea state along the 50-year environmental contour. This condition corresponds to the parked conditions DLC 6.x in IEC 61400-3. However, lower environmental loads may be more critical due to turbine thrust at rated wind speeds. This condition corresponds to the DLC 1.6 in IEC 61400-3.

Although the analysis for the mooring lines might be carried out separately, the DLC definition should be consistent with the other parts of the system, e.g. floater. The considerations in this sections are generally applicable also to the floater structure.

- From general design work in LIFES50+ it was mentioned, that for the design of mooring lines a particular focus was to be put on the LIFES50+ DLCs 6.1, 9.1 and 9.2, as well as the extreme states for wave and current conditions.

3.3.3.1 Design conditions

The design target for mooring systems is the reduction of the mooring system cost and at the same time ensuring compliance with the limiting technical design criteria:

1. Maximum tension in the mooring line: $T_d < S_c$
2. Uplift angle at the anchor (for drag anchors): $\alpha_{uplift} = 0°$
3. Maximum floater offset (dep. on dyn. cable): $\xi_{FOWT}(0+1+2) < 0{,}5 \cdot h$
4. No synthetic rope in contact with sea bed (hybrid system only)
5. No synthetic rope in water exchange area (hybrid system only)

In this chapter, the variables used are defined as follows:

- T_d Mooring line design tension
- S_c Characteristic strength of the mooring line segment
- α_{uplift} Uplift angle of the mooring line at the anchor position
- $\xi_{FOWT}(0+1+2)$ Floater excursion in surge, including static, first and second order loads
- h Water depth
- H_s Significant wave height
- T_p Peak spectral period
- v_C Current speed
- U_{hu} Hub height wind speed
- FE Finite element
- MBS Multibody system
- CFD Computational fluid dynamics

- FSI Fluid structure interaction
- RAO Response amplitude operator
- QTF Quadratic transfer function

The main design criterion is the design tension T_d in the mooring line.It is important to acknowledge and realize that the design loads are not only governed by the level of detail of the applied software, but are also highly influenced by the applied metocean conditions. Depending on the project, uncertainties in site conditions may have much greater impact on the design than e.g. the differences resulting from usage of quasi-static or dynamic models.

The first step for the determination of the characteristic 50-year sea state is to develop the 2D environmental contour ronmental contour with a 50-year return period, as presented in

Figure 12, and to select different sea states in terms of H_s and T_p. Therefore, the sea state corresponding to the extreme values of both H_s and T_p are selected. Additional sea states are selected uniformly in between. Sea states with wave periods close to the natural frequency of the floater, which might cause significant system response, should also be selected on the contour, if relevant.

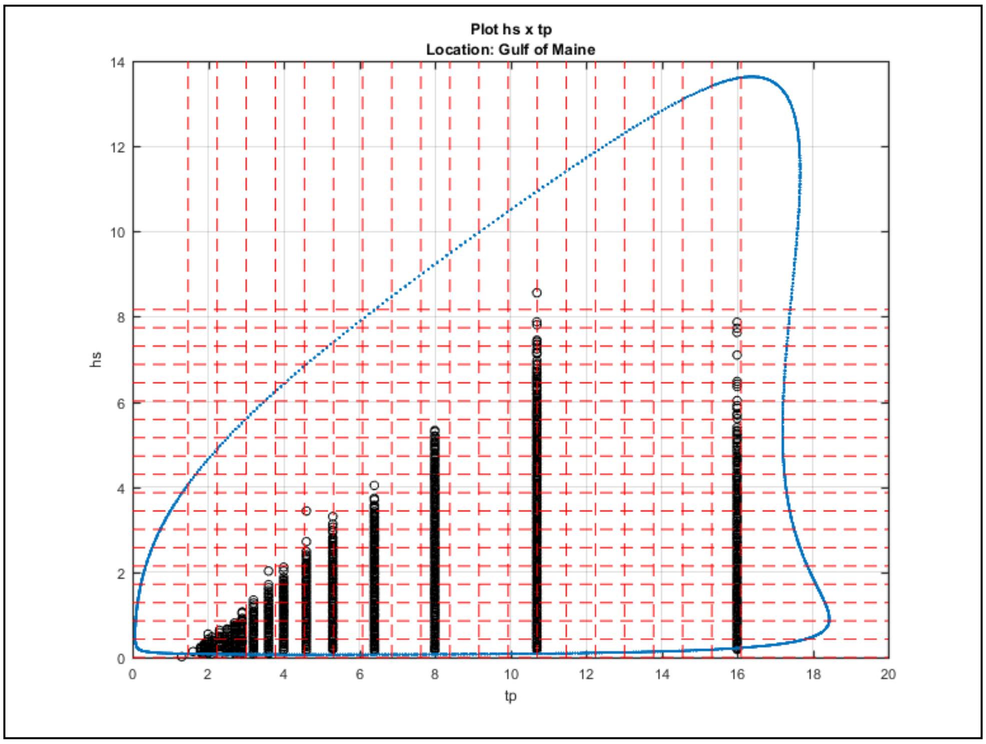

Figure 12: 2D-Contour of the 50-year environmental state (Gulf of Maine)

- Once the sea states are selected, a mooring system is designed to the highest load occurring in any condition along the contour.

- When using metocean data based on contours computed with the inverse first order reliability method (IFORM) caution is warranted in the selection of appropriate metocean conditions in order not to inadvertently lower and thus erode implicit safety levels. This can occur if e.g. 3D contours are used which are conditioned on the wind speed as its first, primary variable. This would result in rather benign H_s and T_p conditions. Thus, care must be taken when selecting the actual data on the contours, depending on considerations what the most relevant design driving parameters are. Typically, using 2D H_s, T_p contours are a good initial assumption to determine governing ULS conditions. The implications of the site conditions are aggravated by the highly nonlinear, progressively stiffening restoring behaviour of mooring lines, particularly steel chains. Thus, the system responds in the last part of the motion with an unproportionally higher tension and increases the effect on ULS loads from uncertainties in site conditions.

Another known challenge from mooring design is how to determine the characteristic design loads. Typically, following common recognized class societies (RCS) standards, a statistical database from established tension data is developed and design values are extrapolated based on probability distributions. DNVGL-OS-E301 in this respect provides detailed guidance on how this extrapolation should be performed.

3.3.3.2 ULS in parked conditions (DLC 6.x)

- On the 50-year environmental 2D contour (H_s, T_p) the following sea states are selected:
    1) maximum value of significant wave height H_s + corresponding wave peak period T_p
    2) wave periods T_p near the eigenfrequency of the floater + corresponding H_s values
    3) other points along the contour for sensitivity check
- For current speed v_C the 50y value is applied.
- For wind speed U_{hub} the 50y value is applied.

3.3.3.3 ULS in operation (DLC 1.6)

- 50-year sea states with corresponding operational wind speeds

To determine these conditions, below an exemplary method is presented (other methods also are applicable, see standards for details):

- The 50-year environmental 3D contour of (U_{10}, H_s, T_p) is determined and the 2D contour (H_s, T_p) corresponding to U_{hub} = WTG operational wind speeds (all relevant wind speeds, at least cut-out, rated, around rated).
- On the extracted 2D contour (H_s, T_p) the relevant sea states are selected as described above in Section 3.3.3.2.
- For current speed v_C, the 10y value is applied.
- For wind speed U_{hub}, the operational wind speeds for the DTU 10 MW wind turbine are applied.

3.3.3.4 ALS (Damaged condition)

The ALS analysis is carried out with the same environmental loads as for the ULS analysis. In the ALS analysis one line of the mooring system is assumed to be damaged (i.e. missing). Furthermore, in the ALS condition lower load factors are applied compared to ULS.

3.3.3.5 FLS

Fatigue assessment is required for the design of the mooring system. The long term environment should be represented by a number of discrete conditions. Each condition consists of a reference direction and a reference sea state characterised by a significant wave height, peak period, current velocity and wind velocity. Based on sensitivity analyses and/or other considerations, the reference directions for wind and wave and its combinations should provide a good representation of the directional distribution of a long-term environment (in the studies within this project, 8-12 combinations of directions were acceptable). The required number of reference sea states should be determined based on sensitivity studies and/or other considerations. Fatigue damage prediction may be sensitive to the number of sea states, and sensitivity studies may be necessary.

If a fatigue analysis based on time domain calculations and rainflow counting is not applied for FLS analysis due to the often time-consuming calculations, DNVGL-OS-E301 proposes alternative methods such as the "combined spectrum approach", which considers both wave-frequency and low-frequency components to compute the characteristic damage. For the calculation of the line tensions components due to wave-frequency motions, time domain analyses taking into account mooring line dynamics are required. Low-frequency components of the line tensions can be derived from the quasi-static analysis. However the applicability of this approach for a specific floating wind turbine and site must be demonstrated by comparisons to rainflow counting methods.

3.3.4 Calculation methods

3.3.4.1 Design Tools

Mooring system models combine structural mechanics for the representation of the line itself with hydrodynamics for computation of the external fluid forces and contact mechanics for the forces on the line from line-seabed interaction. In general, the marine environment continually disturbs each part of the mooring line by perturbation from surface waves, surface and subsurface currents, subsurface turbulence, and internal waves. The line responds to these disturbances with drift motions and translational and rotational oscillations along with structural deformations. In addition gravitational forces from the weight of the line in water are constantly forcing the line to assume a catenary shape. For lines with parts resting on the seabed, the line-seabed interaction in terms of friction forces on the line and damping must be considered as well, a problem where a wide variety of models exist (Inoue, et al., 1994; Ong, et al., 2003). The resulting motion of the line in turn gives rise to motion of the platform, i.e. both systems are in general coupled except for special built-in fairlead design features aiming to decouple the systems. Numerical mooring system models can generally be divided into two main categories: quasi-static and dynamic modelling approaches. Table 10 presents the two categories and the different methods within these categories together with their typical implementation in integrated aero-servo-hydro-elastic models.

Table 10: Categories of mooring modelling methodologies

Main Category	Sub-category	Common implementation
Quasi-static	Linearized representation of complete mooring system (valid only for small displacements) (Sandner, et al., 2012)	Linear stiffness matrix
	Nonlinear force-displacement relationship derived from either quasi-static or dynamic models (averaged) (Cordle, et al., 2011)	• 3D-lookup-table with interpolation for complete mooring system restoring force • 3D-lookup-table with interpolation for each individual mooring line restoring force
	Analytical solution of implicit nonlinear catenary equations (Jonkman, 2007)	Analytical subroutine
Dynamic	Discretized finite element or finite-difference approach with Morison or other potential flow hydrodynamic force (Armendariz, et al., 2011; Hall, 2013)	Various finite element formulations

Discretized multibody approach with Morison or other potential flow hydrodynamic force (Matha, et al., 2011)	Rigid or flexible connected multibody elements
Discretized FE/MBS with 3D CFD hydrodynamic force (Chakrabarti, 2008)	Full 3D FSI (FE-CFD) implementation (currently only applied for O&G structures)

In summary, except for quasi-static models, which do not represent the line structure itself, the structural mechanical representations used by dynamic models are lumped mass, rigid or flexible finite segment, assumed modes or FE approaches. In case of quasi-static methods only the hydrostatics loads acting on the mooring line are modelled, and in case of dynamic methods in addition the hydrodynamic forces from waves and currents and line motion are represented by potential flow or CFD based methods. Since a line is a slender cylindrical body, usage of Morison equation is suitable.

In O&G and floating wind industries, both quasi-static and dynamic models are used in the design. For conceptual analyses, the quasi-static models offer a good and robust tool to investigate important trade-offs and study a large variety of different systems. In the detailed design phase, ultimately dynamic mooring line models applied in time-domain simulations are primarily used. Here numerous commercial software packages exist which are capable of high fidelity modelling of the mooring systems, with some of commercial packages now also being able to model the wind turbine to a sufficient level of detail.

3.3.4.2 Quasi-static analysis

Tensions in the mooring lines at defined horizontal floater offset are calculated by static FE-analysis. The considered floater offset includes:

1) Static offset X_{mean} due to static environmental loads (steady wind, steady current, mean wave drift force) and steady turbine thrust if applicable.
2) Dynamic offset due to low-frequency motion (slowly varying oscillations) X_{LF}.
3) Dynamic offset due to wave-frequency motion X_{WF}.

The two dynamic offset components are referred to in DNVGL-OS-E301 (Ch. 2, Sc. 2.7.6) as the characteristic offset X_c, which is defined as the larger value of the following:

$$X_c = X_{mean} + X_{LF,max} + X_{WF,sig}$$

$$X_c = X_{mean} + X_{LF,sig} + X_{WF,max} \quad \textbf{(2)}$$

where either the maximum low-frequency offset is combined with the significant value of the wave-frequency offset, or, the significant value of the low-frequency offset is combined with the maximum wave-frequency offset.

The dynamic offset components are calculated using floater hydrodynamics (RAOs of motions, hydrodynamic added masses and damping coefficients, QTFs of wave drift forces) determined by means of a hydro-mechanic frequency domain analysis (e.g. with a radiation/diffraction panel method).

As the motion behaviour of the floater is dependent on the stiffness of the mooring system, the hydrodynamic analysis of the floater should take this into account.

The quasi-static analysis method can be employed very efficiently for a concept design of the mooring system. A large number of different mooring configurations can by analysed in a short time, which makes this analysis method suitable for parametric studies.

However, for the certification of a permanent mooring system for a FOWT the quasi-static method alone is not sufficient, as mooring line dynamics as well as the dynamic coupling between the mooring system, the floater and the wind turbine are considered to be relevant.

As the quasi-static analysis method contains a number of uncertainties and simplifications, suitable safety factors should be applied when using this method. Some of the documents listed in Section 3.3.2 provide safety factors, which account for the analysis method, however, the applicability of these values for FOWTs is not always clear and should be rather understood as a guiding value. The safety factor to be included in the quasi-static approach should be in the range of 1.7-2.0.

3.3.4.3 Dynamic analysis

For the detailed design of the mooring system for a FOWT a coupled dynamic analysis in the time-domain should be performed. The dynamic analysis takes into account the time varying effects due to mass, intertia, damping and fluid acceleration. Non-linear effects including line stretch (e.g. for synthetic line material), change in line geometry, hydrodynamic loads on the line (often computed with Morison equation, assuming the line is a slender cylindrical structure) and sea bottom effects can be modelled.

For FOWTs the dynamic loads from the wind turbine are deemed to be important. Hence, in the dynamic analysis a coupled model (coupling between mooring lines, floater and wind turbine) should be used. In each time step of the simulation the equation of motion including aero-dynamic loads on the wind turbine, hydrodynamic loads on the floater and the mooring lines, inertia forces and restoring forces of the mooring lines is solved.

For the time-domain analysis of mooring lines a number of commercial software packages, mainly from O&G, are available.

In order to perform a coupled dynamic analysis, it is a common practice to calculate the aerodynamic loads with a different software package (e.g. FAST) and to incorporate this loads into the finite element model of the floater and the mooring system in each time step of the dynamic simulation. Updated structural positions and wind loads are exchanged between the corresponding solvers until numerical convergence is reached.

Dynamic analysis enables an accurate calculation of the maximum line loads in the ULS and ALS conditions, extraction of the relevant cyclic load components for the FLS analysis as well as investigation of transient conditions (e.g. transition from the intact to the damaged condition, in which an “over-shooting” of the final equilibrium position in the damaged condition is investigated).

3.3.5 Safety factors

The safety factors or load factors to be applied in the mooring line design generally depends on:

- Type of installation, i.e. temporary or permanent (FOWT is considered to be a permanent installation)
- Type of analysis (ULS or ALS)
- Redundancy of the mooring system
- Analysis method, i.e. quasi-static or dynamic analysis (usually, in FOWT specific guidelines only factors for dynamic analysis are provided)

- Applied standard

In DNV-OS-J103 the design line tension is calculated from the mean and the dynamic component, on which different load factors are applied:

$$T_d = \gamma_{mean} \cdot T_{c,mean} + \gamma_{dyn} \cdot T_{c,dyn} \tag{3}$$

where $T_{c,mean}$ is the characteristic mean tension, $T_{c,dyn}$ is the characteristic dynamic tension and γ_{mean} and γ_{dyn} are the respective load factors. $T_{c,mean}$ is caused by possible pretension of the mooring system and the mean environmental loads: steady current, steady wind and mean wave drift forces. $T_{c,dyn}$ is caused by the low-frequency and the wave-frequency motions.

Redundancy of the mooring system is taken into account by definition of the safety class: redundant mooring systems for FOWTs can be considered as "normal" safety class, non-redundant systems correspond to "high" safety class.

In Table 11 and

Table 12 the load factors according to DNV-OS-J103 are compiled for the ULS and the ALS conditions, respectively.

Table 11: Load factors for ULS according to DNV-OS-J103

Load factor	Safety class	
	Normal	High
γ_{mean}	1.30	1.50
γ_{dyn}	1.75	2.20

Table 12: Load factors for ALS according to DNV-OS-J103

Load factor	Safety class	
	Normal	High
γ_{mean}	1.00	1.00
γ_{dyn}	1.10	1.25

In the fatigue analysis the calculated fatigue damage shall be increased by the design fatigue factor (DFF) as defined in Table 13. The design fatigue factors depend on the location of the structural detail and of the accessibility for inspection and repair. The design fatigue factors specified for structural details which are accessible for inspection are given with the prerequisite that inspections are carried out at intervals of four to five years. Typically mooring lines of a FOWT are considered as non-accessible elements. Note, that the given DFFs also may not be applicable for fibre ropes.

Table 13: Selected Design Fatigue Factors (DFF) for FLS analysis according to DNV-OS-J103 (ref. to DNV-OS-J103, Table 10 for full details)

Structural element	Safety class	
	Normal	High
External, not accessible for inspection and repair in dry and clean conditions	3.0	6.0
Non-accessible, not planned for inspection/repair	6.0	10.0

Note that according to DNVGL-OS-C105- "Structural design of TLPs - LRFD method" (Ch. 2, Sc. 6, 4.1.6), for TLPs other DFFs may need to be applied: "*Tendon and tendon components shall have a minimum design fatigue factor (DFF) of 10*".

3.4 Design methodology for a tension leg system

3.4.1 Functional principle

Although the first tension leg platforms (TLPs) in the O&G sector were very similar from a stability/seakeeping point of view to a classic semi-submersible platform and were self-stable in any operational condition, the latest and most optimized design TLPs (the so called "seastar") do not allow for this stability without any external means or its mooring system during the operational stage. In this sense, looking at the cost optimization at the floating offshore wind sector, most of the TLPs that are being currently developed are, in general, not self-stable and their buoyancy is larger than the weight at the still water draft. The bottom corners of the platform are connected with the seabed by means of vertical tension legs (arrays of tendons). The difference in the buoyancy and the weight (surplus buoyancy) is taken by the tension force in the tendons. The tension leg system (TLS) acts as station keeping system ensuring platform stability as well as restraining motion of the platform due to environmental loads to the specified design limits. The tendons are designed to be under a continuous tensile load that provides a horizontal restoring force when the platform is displaced laterally from its still water position. Positive tension should be achieved in all operational conditions. The mooring system is very stiff in the axial direction, thus heave, pitch, and roll response of the platform is very limited and stiff, i.e. with periods in the range of 1-5 seconds. In the transversal direction the mooring system is compliant and restrains surge, sway, and yaw response within operationally acceptable limits.

Currently there exist a number of designs of station keeping systems for FOWTs, which are similar to the O&G TLP tendon system concept. These systems utilize inclined "tendons" or a combination of vertical and diagonal "tendons", which are mostly composed of synthetic materials (for classical TLPs in the O&G sector steel pipes are normally used as tendons). These systems are in some cases used for relatively small water depths. Strictly speaking, these mooring systems are not tension leg systems, as they do not work according to a tension leg principle.

In this sense, although it is possible to perform the design of a TLP with a very simple approach for modelling the mooring system behaviour (e.g. mooring system stiffness) as it may be performed with the other FOWT typologies, the importance of the mooring system design for the behaviour of a TLP makes it more recommendable to perform a simultaneous basic design of the floating platform and the mooring system.

3.4.2 Considerations regarding platform design

The design of the platform (buoyant body) has a strong influence on the tendon design, e.g.:

- The platform should provide sufficient surplus buoyancy in order to achieve adequate initial tension in the tendons. Generally the initial tension should be as small as possible but provide positive tension (no compression) in all operational conditions.
- The hydrodynamic properties of the platform should be optimized with regard to limiting the vertical hydrodynamic forces in heave direction, i.e. advantage should be taken of wave cancellation effects in order to reduce heave motions and thus, the dynamic tension components in the tendons.
- While heave is the primary motion relevant for the tendon tensions, both extreme surge and pitch motions also may lead to peak loads or slack events and must be considered in the detailed design stage.
- The FOWT pitch natural frequencies are significantly influenced by the tendons and the tower flexibility. Particularly the tower must thus always be considered in the tendon design.
- Phases of transport and installation should be considered during platform design (e.g. sufficient floating stability for transport).
- Mooring system shall be designed to compensate the heeling effects produced by the wind turbine's thrust in operation.

3.4.3 Rules & Standards

In addition to the documents listed in Section 3.3.2 the following documents have particular focus on TLP design:

- API RP 2T, Recommended Practice for Planning, Designing and Constructing Tension Leg Platforms
- DNVGL-OS-C105, Structural design of TLPs - LRFD method
- DNVGL-OS-E303, Offshore fibre ropes
- DNVGL-OS-E304, Offshore mooring steel wire ropes
- BV-NR578, Rules for the classification of tension leg platforms

TLPs are designed according to general rules (O&G), as no specific requirements related to FOWTs are defined by classification societies. API RP 2T is referenced in the most other standards and provides relevant information on the TLP design.

3.4.4 Load cases and environmental conditions

API RP 2T defines a number of design loading conditions for TLP design related to different project phases (construction, load out, transportation, installation, in place) and system conditions (intact, damaged), see Table 14.

Table 14: Design cases for TLP according to API RP 2T

Design Case	Project Phase	System Condition	Environment
1	Construction	Various stages	n.a.
2	Loadout	Intact	Calm

3	Hull/deck mating	Intact	Mating
4	Tow/transport	Intact / Damaged	Route
5	Installation	Intact	Installation
6	In place	Intact	Normal
7	In place	Intact	Extreme
8	In place	Damaged	Reduced extreme
9	In place	Tendon removed	Normal
10	In place	Tendon removed	Reduced extreme
11	In place	Intact	Seismic (only if applicable)
12	In place	Intact	Fatigue

For FOWT additional design load cases related to the wind turbine operation could be relevant (see DLCs according to IEC 61400-3). For example, DLCs considering the transport of the platform to the harbour due to major repairs and/or decommissioning activity must be accounted if relevant.

As already mentioned in Section 3.3.2 significant computational effort is needed to design a TLS for FOWT in view of the very large number of DLCs. For practical application an agreement with the classification societies will need to be found in this regard.

3.4.5 Calculation methods

Dynamic effects are extremely important for a tension leg system. Therefore, fully coupled dynamic analyses as described in Section 3.3.4.3 should be used for the TLP design.

For the concept design stage it may be sufficient to make a rough estimate of the tendon tensions using a simplified approach based on experience with other TLPs. An example for the design process is out-lined in (Chakrabarti, 2005).

3.4.6 Safety factors

In general, the same considerations regarding safety class, redundancy, type of analysis (ULS, ALS) as mentioned for spread mooring systems in Section 3.3.5 are also valid for TLS design with respect to the applicable safety factors.

3.5 Optimization of station keeping system

As was done for the concept selection in chapter 2.4, an optimization problem is used to describe the selection procedure of mooring lines, considering that the mooring system is already selected (i.e. spread, taut, tension leg). This way, a systematic view is established on the decision making by pre-senting the constraints, the design variables and the performance indicators that need to be considered when optimizing a mooring system. The items presented here are based on available publications and on evaluation of the before mentioned questionnaire filled out by LIFES50+ participants. Note that all items provided here are resulting from the authors' evaluation of different sources of input and thus may not represent the opinion of all LIFES50+ partners to the last detail. Also, the provided lists may not be complete and could be subject to change in the future.

3.5.1 Constraints

In this section, relevant constraints in the selection of a mooring system are presented. They are classified according to different life cycle categories for better overview.

Table 15: Constraints in the selection of mooring lines

Life cycle category	Constraint
D	Numerical / design effort
D	Site conditions
D	Footprint
D	VIV constraints
D	Slackline events (more relevant for taut mooring lines)
D	Connection limitations
D	Corrosion allowance
D	Anchor constraints
D	Redundancy constraints
ML	Logistical constraints
OM	Required tension / system response
OM	Excursion / displacements / offset limits
OM	Load constraints / breaking strength (ULS, FLS, ALS)
DC	Decommissioning constraints

D – Design
ML – Manufacturing & Logistics
IA – Installation & Assembly
OM – Operation & Maintenance
DC– Decommissioning

Numerical / design effort: The numerical / design effort required to design a mooring system within guideline requirements might be excessively large, if the structure is too complex or too little information exists on the behavior of the structure.

Site conditions: Site conditions may prohibit the use of certain mooring systems (e.g. due to soil conditions, ice, wildlife, marine growth, seismic events, etc.).
In particular, the water depth may disqualify a certain mooring configuration altogether due to constraints from available installation procedures (e.g. excessive water depth). In addition, design conditions may affect design compatibility for both moorings and structure (e.g. shallow waters; dynamic cable demands that platform maximum drift allowed is 10-20% of water depth and this could lead to unrealistic stiffness demands for too shallow waters. Also, water depth limits the maximum tension producible by catenary mooring lines). Finally, the overall performance and FLS/ULS capacity of the mooring system may be dependent on the water depth.

Footprint: The station keeping system needs to stay within the maximum footprint per installed unit.

VIV constraints: In case of high currents, vortex induced vibrations (VIV) require consideration as they may pose constraints to the mooring line geometry.

Slackline events: The critical event of a taut mooring line being slack is to be avoided for all taut mooring systems. Tension is recommended to always be positive (no slack tendons), even though standards may allow exceptions. If designed for slack/snap phenomena, additional conservative load amplification factors shall be included.

Anchor constraints: E.g. maximum uplift angle, allowance regarding load direction.

Redundancy constraints: Redundancy constraints may be part of the considered design. If not, redundancy may be regarded as a design parameter (see below).

Logistical constraints: Logistical constraints may be present and limit the range of available systems (e.g. supply chain limitations; only stud chains available).

Required tension / system response: If the platform type and the stability provided by the mooring system is defined, a given tension is required from the mooring system for station keeping (e.g. substructure was designed to be very soft, hence the mooring might require being stiff).

Excursion / displacements limits: The structural properties of the used dynamic cable or the allowable distance to other wind turbines may define limiting criteria for maximal displacements of the system, which will be a restriction for the station keeping system. Also, the mooring connections may have limitations with respect to maximum angles at the fairleads, which need to be considered.

Load constraints / breaking strength (ULS, FLS, ALS): Site-specific load conditions need to be endured by the system. The applied guidelines can be used for definition of the relevant load cases.

Decommissioning constraints: Decommissioning requirements provided by local government must be met (i.e. allowance for leaving behind anchors or mooring lines, using certain materials, etc.).

3.5.2 Design parameters

Each design parameter can be the base for a new optimization problem.

Table 16: Design parameters in the selection of mooring lines

Design parameters
Mooring concept
Anchors / Foundation
Material
Analysis method
Mooring configuration
Mooring line orientation
Redundancy
Sharing of mooring lines and anchors
Breaking load

Mooring concept: In principle, three different mooring concepts can be considered of relevance: tension leg (vertical mooring lines), taut (taut mooring lines at an angle), and catenary (slack mooring lines). Hybrid forms are also possible and have been used in the past. Each concept has different advantages and constraints, which need to be accounted for in the decision. Catenary mooring systems are more reasonable with chains or studless chain due to lower bending loads compared to wires. It should be highlighted that the basic mooring concept is typically part of the platform definition and thus is likely to be selected designer-specific prior to the site-specific optimization of a substructure.

Anchors / Foundation: Different anchor types may be selected for spread and taut mooring lines. For both platforms, the use of suction and pile anchors is possible. For spread mooring lines, or drag anchors may also be used, while for taut mooring lines drilled/grouted piles or gravity anchors can be an option.
The foundation type for TLPs is selected under consideration of soil conditions, water depth, costs, installation effort, etc.
For spread mooring lines, constraints towards the mooring line may be introduced regarding the allowance of the uplift angle and the variation of load direction. Also for spread mooring lines, the anchor type may influence the redundancy of the mooring system (e.g. after line breakage in a 3-line catenary mooring system with drag anchors the load direction on the remaining 2 anchors will significantly change, probably causing failure of these anchors).
For TLP systems, a foundation may also be defined. Here, available options are:

- Foundation template (see, e.g. Gicon concept) anchored to the sea bed by piles. The tendons are attached to the template or directly to the pipes.
- Non-piled gravity foundations to which the tendons are attached.
- Pile foundations (suction, driven or drilled) foundations to which the tendons are attached.
- Combination of the above types.

Material: The material selection depends on the specific conditions of the site, the technology used and the available supply chain. It influences the breaking loads and the required load cases to be performed for structural integrity checks. The optimization problem for choosing a material focusses on the following options and related advantages:

- Steel
  - Advantages: conventional design procedure, no need for tensioning during lifetime
  - Options: wire, chain, pipes
    - Steel wire
      - Advantages: high fatigue reliability, light weight, compact
      - Options: spiral, multistrand
        - Steel wire spiral advantages: high breaking strength, stiffness
    - Steel chain
      - Options: studded, studless
      - Advantages: low cost, only local bending effects
- Synthetic fibers (see also e.g. (Weller, et al., 2015), (Ridge, et al., 2010))
  - Advantages: low cost, lightweight, compliant, reduced mooring footprint, good fatigue performance, not susceptible to corrosion, lower installation tension
  - Options: nylon, polyester

For a visual comparison of the different options available for steel-based mooring lines, Figure 13 shows the design S-N curves for different options.

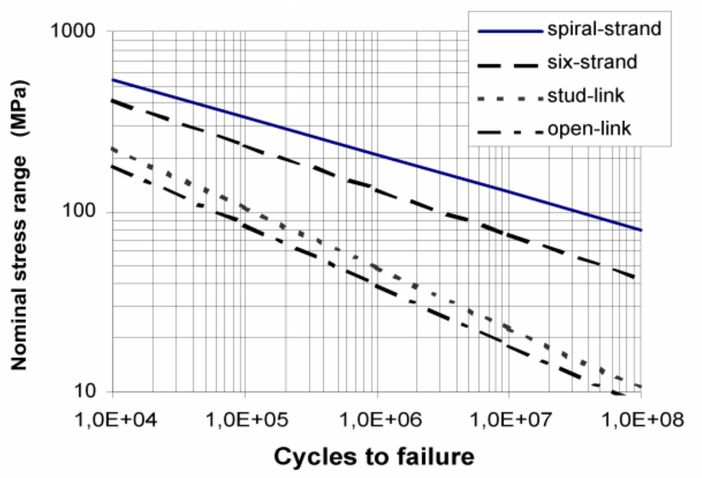

Figure 13: Design S-N curves for different steel-based mooring lines (Veritas, 2015)

Analysis method: Different analysis methods are possible for the design of the station keeping system. The general options are to perform the analysis coupled, uncoupled or semi-coupled and also considering a dynamic or quasi-static representation of the mooring line forces. Deciding for one model fidelity or another generally is a decision between effort and accuracy. Because the selection of the analysis method will have an effect on the accuracy, different safety factors may need to be applied, see Table 17.

Table 17: Partial safety factors for ULS (Veritas, 2015)

Consequence Class	*Type of analysis of wave frequency tension*	*Partial Safety factor on mean tension* γ_{mean}	*Partial Safety factor on dynamic tension* γ_{dyn}
1	Dynamic	1.10	1.50
2	Dynamic	1.40	2.10
1	Quasi-static	1.70	
2	Quasi-static	2.50	

Mooring configuration: The designer may chose a hybrid mooring concept and/or different materials to accomplish the mooring concept, in order to establish a certain restoring behavior. The configuration of the mooring system then needs to be established. This is a separate design process in itself, including decisions on segmentation, application and positions of clump weights and/or buoyancy elements, swivel types, etc. See (Giron, et al., 2014) for additional information.

Mooring line orientation: The mooring line orientation with respect to wave direction can be adjusted so that high stability is ensured for the most likely situations. Ideally, the mooring line orientation should be set such that the main wind inflow direction will cause the lowest loading on the structure. For load calculation, other incoming directions of wind and waves as well as misalignments need to be considered. This can be done taking the occurrence probability of different scenarios (e.g. wind and wave roses) into account.

Redundancy: Additionally to being a constraint, the decision whether the mooring system should be redundant or not can be seen as a trade-off with the increased safety factor, which is necessary for non-redundant mooring systems. Redundancy allows for lower safety class of single mooring lines (ALS cases for redundancy checks consider failure of a single mooring line, see (Krieger, et al., 2015) section 8.5.1. Analysis is for initial transient event and extreme condition of a failed line). It could be of benefit to increase the number of lines in order to limit single line dimensions for larger wind turbines.

Sharing of mooring lines and anchors: While this becomes of increased importance only when focusing on wind farm design, the sharing of mooring lines and anchors from different platforms is a design possibility that can be considered. Because anchors may scale better than mooring lines, for larger units it may be of benefit to increase the number of lines and share anchors rather than increase line dimensions.

Breaking load: The mooring lines may be designed for a specific breaking load and weak points may be defined so load peaks do not damage the substructure.

3.5.3 Performance indicators

The indicators evaluating the performance of the mooring system originate from different stages of the system lifetime and are listed categorized in Table 18 and described below.

Table 18: Performance indicators in the selection of mooring lines

Life cycle category	Performance indicator
D	Cost of components
ML	Manufacturing and logistics efforts
IA	Installation and assembly efforts
OM	Restoring characteristic
OM	O&M performance
DC	Ease of decommissioning

D – Design
ML – Manufacturing & Logistics
IA – Installation & Assembly
OM – Operation & Maintenance
DC – Decommissioning

Cost of components: The cost of the components such as mooring lines, connectors and anchoring system influences the overall cost of the mooring system. Catenary based mooring system concepts (spar, barge, semi-submersible) tend to require less expensive anchoring systems than TLPs.. Other auxiliary components may also have considerable costs.

Manufacturing and logistics efforts: As for the platform, a small effort in the manufacturing of the mooring system is expected from modular components, flexibility with respect to the manufacturing sites and a focus on simple and proven tools and methods. Manufacturing time may also be of importance (e.g. production of chain vs. synthetic robes).

Installation and assembly efforts: When the mooring system is installed (i.e. anchor installation, hook up, etc.), it must be tensioned to design pre-tension. If this can be done simple and fast with small overall effort and with needing as little extra equipment on the FOWT (e.g. chain stoppers, winches, etc.) as possible, it will be advantageous. Low masses and small dimensions of the mooring lines and anchors will only support this. In addition, the number and variety of components should be kept to a minimum to minimize assembly efforts.

Restoring characteristic: The restoring characteristic describes the mooring line behavior during dynamic movements of the platform (see

Figure 4). A linear behavior around the equilibrium position ensures lower load uncertainty.

O&M performance: The O&M performance describes the overall effort of performing operation and maintenance on the mooring system and the platform, and should be kept as low as possible (e.g. temporal disconnection of mooring lines from platform, duration of inspections, etc.). As mentioned, fibre ropes are likely to require tensioning during the lifetime, simple solutions to allow this are considered of benefit.

Ease of decommissioning: Requirements with respect to vessels, winches, decoupling systems, etc. will determine the cost of the decommissioning of the mooring lines.

3.6 Upscaling considerations and challenges for large wind turbines

From LIFES50+ design experience, no particular effect of larger WTG on the mooring line design was found. The same procedures and materials as were used for smaller WTGs could also be used for the up-scaled systems. Some general concerns related to upscaling the mooring systems were collected as part of the above mentioned questionnaire and are summarized next.

Although from a design perspective there is no general concrete limitation when increasing the size of the mooring lines, there are some constraints in the overall system evaluation which will pose new constraints which may limit the size of a turbine. For example, as the dynamic cable demands that platform maximum drift allowed is 10-20% of water depth, the up-scaled platforms with higher loads may require excessively stiff mooring systems for a given water depth. Additionally, with respect to the allowed footprint, the up-scaled wind farm may require too much additional footprint in order to mitigate overlap of the mooring system of different units. This could be avoided by increasing the number of mooring lines. Then, the total seabed contact area increases rather than the mooring radius.

Also, it is to be expected that at some point increasing the mooring line size will be less beneficial than increasing the number of mooring lines. For example, the transport of up-scaled chains/anchors may require larger vessels that are much more expensive. Other items driving the increase of mooring line number rather than size are installation methods, component availability and reliability. With respect to the modelling, increasingly large elements in the mooring line will limit the use of simplified mooring line models (hydro- and structural dynamics). As anchors may have better scalability than mooring lines, different configurations (e.g. share of anchors) may become cost efficient solutions. An alternative to increasing the size of mooring lines and hence reaching the required mooring line stiffness is the implementation of additional elements (e.g. clumps).

For an up-scaled anchoring system, the soil conditions could become inappropriate e.g. standard commercial anchors could not be suitable when certain soil conditions are present. In such case, a redesign of the anchors may be necessary.

3.7 Risk consideration in design of station keeping system

The risk-based design approach has long been used in the aviation, and the nuclear industries, where materialisation of a hazard can potentially lead to devastating consequences. However, more recently the risk-based design approach has been also applied to other industries (e.g. ship design).

As given by (Papanikolaou, et al., 2009), there are two main reasons that make the risk-based design approach attractive to ship design, but also to other industries. These are:

1. It allows novel designs to be realised that can be considered safe (i.e. considering safety as a paramount design constraint from early design stages).

2. It allows existing designs to be optimised with respect to safety without compromising on performance (i.e. considering safety as one of the constraints when optimising the initial designs, which could have been designed without significant or any consideration of safety in the first place).

It should be noted that the risk-based approach does not necessarily need to consider only safety. It can be equally applied to other risk areas (e.g. environment, reputational damage, cost).

The risk-based design approach is equally applicable and attractive to floating wind turbines and its elements (e.g. mooring lines) design, as all FOWTs can be seen as novel designs which have to maintain high performance, whilst not compromising on its other parameters or constraints (e.g. safety, environment, cost).

The risk-based design of the station keeping system for a FOWT can help with the following:

- To support a decision with regards to redundancy in the mooring system. This is particularly important to those designs that achieve stability by means of mooring, such as TLPs. However, this should not only be considered from the stability perspective, but also from a possible damage to other systems elements (e.g. dynamic cable, wind turbine).
- To compare different mooring designs/configurations (e.g. choice of material (steel versus synthetic), number of interfaces, use of auxiliary equipment (e.g. lump mass, buoyancy units), as well as choice of configuration (catenary versus semi-taut, versus taut).
- To act as a tool for de-risking a chosen design (i.e. to be used as a risk management tool that includes risk identification, risk analysis and evaluation, and risk mitigation).

Risk consideration with regards to the mooring lines should not only be associated with the technical parameters (e.g. material, configuration), but should also cover all life cycle phases (i.e. design, transport and installation, O&M, and decommissioning risks (e.g. wrongly approximated environmental loads, ease of inspection, marine growth).

Additionally, mooring system is just one part of the wider FOWT, hence it has to be considered not on its own, but within the FOWT environment (e.g. how mooring line layout could potentially complicate access for crew transfer vessels (CTVs), or how mooring lines could potentially damage dynamic cable) and within the wind farm environment (e.g. what are the other stakeholders that can be affected by or can affect FOWT depending on the choice of the mooring system used (e.g. fisherman, environmental consequence, MoD, air traffic). In other words, the consequence should not only be looked at from the technology and financial perspective, but should also include, amongst other, H&S, and environment.

3.8 LIFES50+ mooring design in WP5

In the Task 5.2 a conceptual mooring design for a 10MW semi-submersible FOWT (public LIFES50+ concrete semi-submersible as defined in D4.2) was performed. The conceptual design approach followed an advanced quasi-static design approach, focusing on ULS conditions. The quasi-static calculation was performed by computing the offsets of the floater from the static and dynamic environmental forces and analysing the resulting mooring line design tensions and restoring forces. The floater motion in the quasi-static computation was calculated with WAMIT, accounting for both 1st order hydrodynamic forces and 2nd order hydrodynamic drift forces and viscous drag forces from current. The mooring tensions were computed with a quasi-static catenary equation in-house software by Ramboll, which allows for multiple line materials and addition of clump weights and buoyancy elements along the line. As governing standards, aligned with the design basis D7.2, the DNV-OS-J103 and

DNVGL-OS-E301 standards were used. As environmental conditions, the Gulf of Maine site was selected as the average LIFES50+ site, and the ULS design conditions were selected along developed 50-year environmental contours by USTUTT. Since fatigue analysis usually requires rainflow counting of time series, FLS was not considered. While in a detailed design, fatigue analysis is required according to Offshore Standards, particularly DNVGL-OS-E301, fatigue analysis was neglected for the design work in D5.2. From experience, at least for steel chain mooring systems, this assumptions shall mostly hold true and lead to designs very close to the actual design when later considering FLS. The ALS case was not calculated separately either. This approach is not specifically covered in DNV-OS-J103, where only the approach for detailed mooring design is covered. Three different catenary designs were developed: a classic 3-line steel chain mooring system, a 3-line hybrid polyester rope catenary design with top and bottom steel chain, and a 6-line star-shaped configuration using steel chain. While no detailed cost analysis was performed within the scope of this task, from the results obtained the 6-line solution was considered as the most promising for further detailed design.

The lines of the first mooring system were steel chains. Steel chains are a common solution for comparable cases: most current FOWT prototypes, as well as the world's first pre-commercial floating wind farm Hywind Scotland use steel catenary chain moorings. Also in research and development (R&D) this system is the most commonly analysed, as e.g. demonstrated by the theoretical mooring design approach in the South-Korean Jeju offshore area, developed by Kim, Choung and Jeon (Kim, et al., 2014). A steel chain mooring thus allows comparability, as the mooring system for the public LIFES50+ concrete semi-submersible from D4.2, developed by floater manufacturer Olav Olsen, also uses a steel chain catenary mooring system.

The second mooring design was a hybrid solution, utilising synthetic materials as the main component for the mooring lines. The catenary setup, however, does not allow a synthetic-only approach since friction on the seabed and the connection to the floater at the top in the splash/trash zone could damage synthetic mooring lines (Weller, et al., 2013), due to their higher sensitivity to wear and tear and abrasion. For such a solution a taut or semi-taut design would be required, which in O&G however is typically only applied at deep locations and thus has been disregarded for the current designs. Therefore the mooring line consisted of three parts. The bottom part, which connects the mooring line to the anchor, is a steel chain. A polyester line forms the main part of the mooring line. Polyester is chosen as synthetic material based on good O&G experiences with the material. As an example, Weller et al. state: "Nylon and polyester are the most commonly used rope materials for applications which require moderately high strength and ductility." (Weller, et al., 2013). Polyester is favoured by Weller et al. over nylon due to better performances in regard to abrasion, creep and strength. To prevent contact between the polyester line and the seabed, a buoyancy module can be utilised, and was considered as an option during the iterative concept development. The top part of the mooring lines is again steel chain, which prevents the synthetic part from being exposed in the splash zone. This hybrid design with top and bottom steel chain and a shackled in polyester rope is a typical mooring system design well known from O&G.

The third design was an innovative mooring system configuration, based on a proposal by Olav Olsen. The lines are also steel chains, comparable to those which are used in the first design. In contrast to the first design, however, the system contains six mooring lines. Both the number of the anchors and the number of the connection points at the floating structure remain three. To each of the anchors two lines are connected. These two lines are then linked to different connection points at the floater to form a "star configuration". Usage of this system promises the reduction of the loads on each single line allowing usage of smaller chain diameters than in a comparable 3-line configuration, and also potentially improves redundancy. The resulting total anchor load is not different between the 3 and 6-line configurations (essentially the maximum substructure excursion and resulting overall force in the worst direction remains the same and must be taken by the one anchor), except for the fact that one anchor needs to connect to two lines, making the anchor-line connection more complex.

The conceptual mooring design process and the numerical analysis require the use of different programs and pre-calculations. They were combined by a MATLAB tool, which used them as input parameters. The interactions between the programmes, which are described here, are summarised in the flow chart at the end of this chapter. The MATLAB tool, in which the actual quasi-static analysis was implemented, is a Ramboll in-house software tool, which was specifically developed to create preliminary mooring designs with various mooring setups. It was modified to some extent in LIFES50+ to be applicable particularly to more unconventional solutions such as the proposed 6-line system, where two lines connect to one anchor. In the tool, the initial mooring design and the mooring system parameters are read in. Depending on further inputs and the quasi-static calculation, the resulting tensions and overall system behaviour are computed. Based on these results, the initial mooring design is modified and reanalysed or set as final mooring design. This procedure is defined as *primary iteration cycle* in the flow chart.

The quasi-static calculation is performed by computing displacements for the floater and establishing a quasi-static equilibrium between tensions and restoring forces from the mooring system and static and dynamic environmental forces. The equilibrium floater displacements are the main results of each quasi-static simulation iteration. Once converged, the resulting tensions and system characteristics are output. As inherent in the quasi-static approach, the offset is static, and does not account for dynamic motions.

The programme differentiates between three different sources of environmental forces acting on the FOWT and establishing its displacement. The first contribution is the static offset, which represents the equilibrium position of the floater under steady environmental loads only. The linearized horizontal restoring stiffness of the mooring system is determined at this point and forms the basis for the calculation of the offsets due to first- and second-order hydrodynamic loads.

The second calculation is the determination of the system response at the largest offset due to first-order motions. Hereafter, the oscillations due to second-order drift forces are calculated. The largest offset and the corresponding system response are the characteristic results for the ULS case.

In summary, the considered environmental loads were:

- Steady wind and current loads (zero-order)
- Mean wave drift forces (second-order)
- Wave loads (first-order)
- Slowly-varying wave drift forces (second-order)

A missing analysis is the verification of the conceptual designs with dynamic simulations. For this purpose, SIMA simulations were setup and ran in this task, but due to time constraints related to the late publication of D4.2 and availability of substructure data, the calculations could not be included. In a planned update of D5.2, this verification study for at least one of the three conceptual designs is intended to be still included.

3.8.1 Key findings from LIFES50+ WP5 mooring design work

During the course of the conceptual designs in WP5, the following items were found which are of relevance when designing a FOWT mooring system:

- Design
  - Quasi-static design approaches offer robust and quick way to conceptually evaluate different mooring design options.
  - Dynamic time-domain mooring design, accounting for all DLCs in DNV-OS-J103, is necessary for the detailed design phase in order to verify initial conceptual designs.
- Standards
  - Redundancy of three line systems cannot be determined unless detailed analysis are performed.
  - Safety factors for quasi-static design are mentioned in DNVGL-OS-E301, but according to DNV-OS-J103 a final design must always be benchmarked against dynamic load simulations. Thus the safety factors for conceptual design with quasi-static tools from DNVGL-OS-E301 may be either overly or non-conservative, making the conceptual level design completely avoiding dynamic simulations rather challenging.
- Tools
  - Both with dynamic and quasi-static approaches, second-order wave loads and drift forces on the floater must be considered, as well as the current drag force.
  - The aerodynamic drag of the tower cannot be neglected.
- Steel chain moorings
  - Simplest with regard to simulation and analysis. However, in detailed design modelling challenges with respect to chain soil interaction, and chain link wear and tear may become relevant.
  - Mooring system behaviour is significantly affected by addition of clump weights. It increases the restoring capacities of the system due to its high weight and also minimises the uplift angle at the anchor point. Due to the impact of the clump weight the chain diameter can be reduced.
  - Dynamic response of clump weight was not validated.
  - Steel chain systems feature relatively high weight and associated higher line cost, when compared to fibre ropes, but also steel wires.
- Hybrid solutions with top and bottom chain and Polyester main line part
  - Low material costs and low weight.
  - Larger footprint.
  - Large floater offset.
  - Recycling of polyester undetermined.
  - Sensitivity to damages (abrasion, wear, tear) during installation and operation.
  - Periodical inspections might be required.
- Manufacturing
  - Quality controlled suitable mooring line manufacturers are available near all LIFES50+ site locations.
  - Current supply chain production capacities should be sufficient for mooring chain production required for LIFES50+ wind farms.
  - Synthetic ropes are generally less expensive in manufacturing and procurement.
- Installation
  - Pre-laying (of anchors and lines) is the less critical part of the mooring installation. However, vessel requirements may be a challenge.
  - Hook-up (of lines to floating substructure and final tensioning) requires special equipment such as winches, and also is on the critical project path – this makes this part of the installation most critical to delays and cost.
  - Synthetic lines are more challenging to handle during installation than chain.

- O&M
  - Proper structural integrity management is required for the lines and components, following DNVGL guidelines with regular inspections.
- Decommissioning
  - Generally better suited than fixed-bottom structures, with chain being more easily recyclable than fibre ropes.
- Environment
  - Nature reserves must be respected
  - The minimisation of the ecological impact must be ensured
  - The complete recovery of the offshore units including the mooring components is important.
- Shipping and Military
  - Shipping routes and military considerations are important to take into account for a site specific design.

4 Installation and marine operations

4.1 Introduction

In current offshore projects involving floating structures, marine operations in general and installation processes in particular constitute a large factor for cost reduction. Generally economies of scale result in the fact, that the larger the wind farm, the larger the possible cost reduction per unit. The same statement is likely true for usage of larger wind turbines reducing overall cost (however there may be a limitation for this trend if WT sizes grow beyond e.g. 15MW – but this is still very unclear). Marine operations of a floating wind project include:

- Seabed preparation (in case it is needed)
- Mooring system (pre-)installation / pre-lay
- Anchor installation
- Float out
- Assembly of the substructure with the rotor nacelle assembly (RNA) and tower (quayside or at the site)
- Towing or transportation of the platform
- Upending (relevant only for Spar buoys)
- Hook-up / connection of the mooring system to the hull, if relevant also including pre-stretching, proof loading, tensioning
- Application of the dynamic cable to the electric system of the wind turbine
- O&M operations
- Decommissioning of the platform.

Since the design of floating wind platforms is under larger economic pressure than those applied in offshore O&G, marine operations need to be optimized to make floating wind more feasible.

Marine operations are limited by the weather conditions including wave, current and wind. The assembly of the substructure with the tower and RNA is particularly affected by the present environmental conditions. A significant challenge is to find a suitable weather window for the installation of a floating offshore wind farm consisting of multiple units. There is also the possibility of connecting several floating wind turbines in a coupled mooring system.

Floating turbines have a significant advantage compared to conventional bottom-fixed offshore wind turbine that in case major corrective measures have been identified during O&M tasks, the floating platform can relatively easily detached from the dynamic cable and the mooring system, and towed back to a port for the repair.

The decommissioning of floating structures is less time-consuming as the platform only needs to be detached from the mooring system and dynamic cable and towed back to the port where it can be completely dismantled. In the case of Spars and TLPs, these may require tower and RNA removal before the towing back to the port, due to the water depth limitations and limited hydrostatic stability. Special attention needs to be placed on removing the tendons from a TLP.

4.2 Common installation procedures for floating structures

This chapter is meant to give an overview of existing installation procedures applied in the floating wind business and related industries. The installation procedures are split into those applied for catenary, semi-taut and taut mooring systems and those applied for tension leg systems.

The mooring system is usually pre-installed and the attachment of the lines to the substructure is done as soon as the platform has been towed to the site. The mooring line is usually pre-installed and the connection to the platform usually takes 9-12 hours (this is an indicative assumption and may vary significantly depending on the design). In the Fukushima FORWARD project, the installation of the mooring system for the electrical substation took about 4 months (Fukushima Offshore Wind Consortium).

The inter-array cable is usually also pre-installed. The longest part of the inter-array cables are typically buried, if soil conditions allow, as done for bottom-fixed offshore wind turbines. The cables are buried to reduce fatigue loads (limits motions), to reduce risk of damage from other subsea equipment (e.g. anchors dropped on the cable, fishing nets catching on the cable, electromagnetic radiation, sharks biting cables) and to reduce the risk to other subsea equipment or creatures living in the sea (entanglement of fish or equipment). The last part of the inter-array cables (the so called dynamic cable) close to the turbine is kept to most extent above the seabed by buoyancy modules to avoid scraping of the cable with the seabed. The buoyancy units are also used to introduce a slack in the system to account for FOWT motion. This means the dynamic cable is hanging loose to be able to adapt to large horizontal offsets of the platform under maximum thrust force or harsh environmental conditions or at the event of line failure. There is usually a touch down point anchor, as well as some protection, like stiffeners, at the transition from the static to dynamic part. Similar to bottom- fixed wind turbines, floating turbines are normally equipped with a J-tube which requires a cable pull-in procedure during the installation process although other alternatives are also feasible (e.g. a direct connection at the bottom section of the floating structure).

4.2.1 Installation of anchors

4.2.1.1 Drag Anchors

Drag anchors are usually applied as the anchoring point of catenary mooring systems as they do not allow a vertical lifting force. For the installation of drag anchors, in general, an Anchor Handling Vessel (AHV) is chartered. The anchors, and, depending on the mooring system design, the anchor chains and/or the (synthetic) ropes are lifted by an onshore crane onto the AHV deck area where it is fastened for the sea transport. At the site, the position of the vessel and the drag anchor needs to be tracked continuously. The anchor is connected to the anchor chain and the subsequent mooring line and lowered from the stern utilizing the winch mounted on the AHV deck. To ensure that the drag anchor will reach the seabed in the right orientation, a supporting second line may be used which is later disconnected from the anchor by an ROV. As soon as the anchor touches the seabed, the vessel moves forward. The vessel's thrust and the angle between the fluke and shank makes the anchor embed into the soil. If this angle is determined incorrectly, the anchor might lose its holding power. The tension in the line is monitored and the line is paid out completely. The upper end of the mooring line is connected to buoyancy modules to ensure easy pick-up for the platform installation and to avoid clashing of the line with the seabed.

4.2.1.2 Plate Anchors

In case a larger holding capacity than those provided by drag anchors is needed, plate anchors might be a solution. Larger holding capacity is required in case a taut or semi-taut mooring system is chosen. Plate anchors are pushed into the soil and rotated so that the plate is directed orthogonally towards the tension force direction. Plate anchors can be pushed into the soil by suction piles or drilled piles. The plate anchor is mounted to the lower end of the pile by a tension force. The plate is directed orthogonally to the seabed to reduce the friction force. When reaching the design penetration depth, the anchor is released from the pile. The pile is pulled upwards and stored on board the support vessel for the next anchor to be installed. The plate anchor is connected to transition lines made of steel which are kept above the seabed. Those transition lines are later connected to the mooring chain and mooring line utilizing an ROV. The upper end of the line is kept at sea level by a buoyancy module. When the mooring lines are connected to the platform, the lines are tautened. By applying the tension force, the plate anchor rotates into a position where the plate is directed orthogonally towards the mooring line and the tension force. The pressure of the soil wedge in load direction is keeping the plate anchor in place. Figure 14 visually illustrates the procedure.

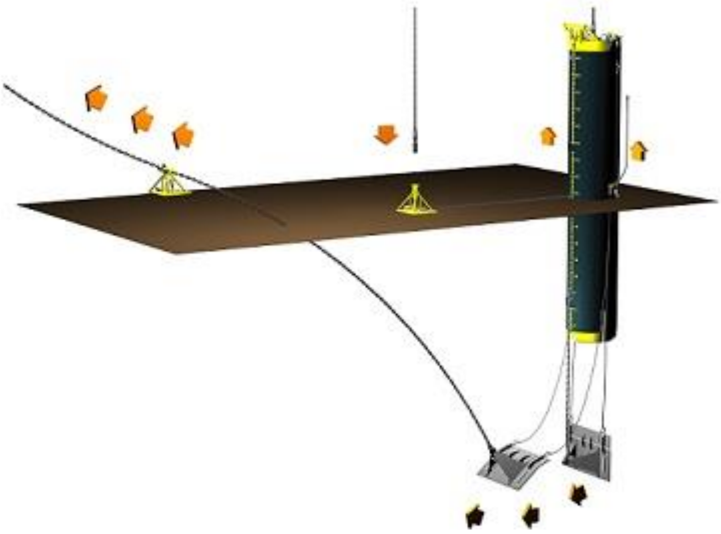

Figure 14: Plate anchor installation (www.intermoor.com)

4.2.1.3 Suction Anchors

Suction anchors are piles that are *pulled* into the soil by applying a negative pressure in the inside of the pile. The anchors are stored on the installation vessel which needs to be equipped with a high capacity crane and a (subsea or at the side of the vessel) pile guide (see Figure 15) or an A-frame crane at the stern of the vessel and a deck transporting system to move the piles on the deck. The suction anchors are lifted and lowered down to a pre-installed template which might be required under specific soil conditions to ensure the correct position of the anchor and their verticality. The suction anchor penetrates the upper soil level by its own weight. An underwater pump (typically pre-installed on the pile in dry condition) which is controlled by the operator on board the vessel is applying a negative pressure in the top part of the suction anchor. This task mostly involves an ROV operation. As soon as the design penetration depth is reached, the pump is released and stored on board. An ROV links the chain connector of the suction anchor with the anchor chain and the mooring line.

If a suction anchor is installed for a TLP, a receptacle for the bottom connector of the tendons needs to be installed on the upper end of the suction anchor. This will most likely be pre-installed and used to lower the suction anchor onto the seabed (e.g. steel rope already installed on the anchor before anchor installation and used to lower the anchor down).

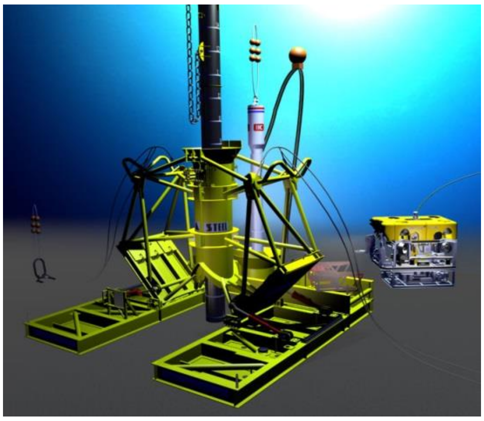

Figure 15: Pile guide (www.dredgingengineering.com)

Figure 16: A-Frame (www.macgregor.com)

4.2.1.4 Driven and Drilled Piles

The installation of driven or drilled piles is similar to the installation of suction anchors. The piles are stored on board the installation vessel. The piles are lowered onto the template (if needed). In case of the driven piles, an underwater hammer is driving the pile until the required penetration depth is reached. The hammer is controlled by the operator on board the vessel. In case of rocky seabed conditions which do not allow for dragging or driving an anchor. Gravity anchors (with the limitation regarding slopes) or drilled piles are the only solution currently available on the market. A vessel equipped with drilling equipment is driving the holes through a template. The piles are then lowered into the holes and the annulus is filled with grout material. The strength of the grout material may be the critical parameter in the anchor system as it needs to withstand the large vertical forces introduced by a taut mooring system or tendons. Similar to suction anchors, an ROV links the piles to the anchor chain and the mooring line.

4.2.1.5 Gravity Anchors

Gravity anchors are characterised by a large mass as they do not penetrate the seabed. Their holding power is completely generated by their large mass. Gravity anchors are usually stored on board of a heavy lift vessel. To guarantee an optimised holding power of a gravity anchor, seabed preparation is often required. The upper soil layer is treated to provide a seabed without slope and soil layers with a reduced supporting strength are removed. A crane lowers the gravity anchor on its supposed position. Gravity anchors are connected to the anchor chain and mooring line utilizing ROVs.

4.2.2 Installation of catenary mooring systems

In this chapter, a possible installation scheme for catenary mooring systems is presented. These procedures differ only slightly from those procedures applied for semi-taut and taut mooring systems. Note that the installation procedure described below is only one of many possible alternatives. The installation sequence applied for a specific project will be dependent on the companies involved, the environmental conditions at the site, the mooring line material, the water depth, the anchor types, the type of substructure and the soil conditions.

Assuming that the anchors and the mooring lines have been pre-installed which is common industry standard, the upper end of the mooring line is connected to a buoyancy module. This buoyancy element is marked in a bright colour to make it easier to find in case of bad visibility.

- A previously mentioned in chapter 4.1, the substructures are floated out, the assembly of the substructure with the rotor nacelle assembly (RNA) and tower (quayside or at the site) are performed and the assembled system is transported to the installation site.

In case a Spar platform is used, the upending process is initiated. The ballast water tanks are flooded with sea water and additional high density ballast material is filled into the lower ballast tanks if intended in the design.

Assuming a chain stopper is installed on each mooring line and that no mooring line section is pre-installed on the substructure, an AHV (typically already chartered for the platform installation and probably used as tugs for towing the platform to position),picks up the upper end of the mooring line. The upper end is connected to a chain stopper and the buoyancy modules are removed and stored on deck of the vessel. The AHV approaches the FOWT structure close to one fairlead. A messenger line which is connected to the platform chain is shot over from the FOWT and the platform chain stopper is activated. The messenger line is connected to the deck winch of the AHV and the platform chain stopper is deactivated. The AHV winch starts hauling in the messenger line and the platform chain. A specified length of the platform chain is stored on the AHV deck. The platform chain stopper is activated. The platform chain is released from the messenger line and connected to the (synthetic) mooring line. The platform chain stopper is deactivated and the platform winch starts hauling in the platform chain until a pre-defined line tension is reached. The chain stopper is once again activated. This process is repeated until all mooring lines are connected to the FOWT. The tensions of all mooring lines are monitored and the position of platform is checked and corrected if necessary. In case the winching equipment is temporary, the winching equipment and power supply is dismantled and installed on the next platform. In case no chain stoppers are used, a modified procedure is applied, e.g. using a winch to generate the required pre-tension in the line, then using a shackle to connect the line and disconnecting the excess part of the chain.

After installing the mooring system, the dynamic inter-array cable needs to be handed over to the floater. A crane vessel picks up the pre-laid cable and hands it over to the platform where a messenger line is guided through the J-tube and connected to the cable end. The messenger line can also be pre-installed. The cable is pulled through the J-tube and connected to the electrical system of the turbine. If the commissioning has not been done at the quay, it needs to be done at this point.

During the installation process, a careful monitoring of the line tensions is required by offshore standards. There are different ways to determine the line tension. One method is to install load cells at the winches or chain jacks on the platform. Another method is to monitor the departure angle of the mooring lines. The latter is recommended by (Bhattacharjee, 2017) for shallower water depths. When monitoring and assessing the line tensions during installation, the tidal variations need to be taken into account.

In case a taut or semi-taut mooring system is used, the installation sequence is similar to the one applied for catenary mooring systems. The anchor and mooring lines are pre-installed and the upper ends of the synthetic lines are kept afloat by buoyancy modules. After the pick-up of the line by an AHV and the taking over by the platform, the mooring lines are tautened and the plate anchor is rotated into its final position (only in case a plate anchor has been selected). As indicated above, the synthetic lines should have been pre-stretched by two AHVs pulling the line in opposite direction. An inelastic stretch called creep is applied to the lines. If creep is not applied in advance, it might occur under harsh environmental conditions during operation, changing the restoring stiffness (ABSG CONSULTING INC., 2015), hence reducing the safety and reliability of the floating wind platform.

4.2.3 Differences in installation processes for Spars, semi-submersibles and TLPs

There are some major differences in the installation processes of the common offshore floating platforms. Because the installation sequence of Tension Leg Platforms (TLPs) differs significantly, it is presented in a separate section. TLPs and semi-Submersibles are usually fabricated upright, flooded with ballast water, attached with buoyancy elements (if required for sufficient hydrostatic stability) and towed to site by tugs (wet tow). There is also the opportunity to transport the platforms with a semi-submersible vessel to the site (dry tow). Dry tow has the advantage that – depending on the size of the cargo ship – multiple substructures may be carried at once as well as better towing conditions reached (e.g. higher towing speeds, wider weather windows…). However for a specific design and site, only a cost-benefit analysis will show the most cost-effective means of transportation.

Spar platforms are characterised by a large draft. Hence, they cannot be fabricated and towed upright. During tow-out, buoyancy elements may also be attached to the hull to provide additional hydrostatic stability. At the site, the spar is upended by means of the ballast tanks being flooded. In some cases, the ballast tanks at the lower end of the spar will be ballasted with additional high density material to lower the overall centre of mass and improve stability. Once the spar platform is upended and is ballasted, it is hydrostatically stable, even without the mooring system. Spars require the installation of the wind turbine and the tower at the site or in an alternative site with sufficient water depth (as done with a deep near shore area for the Hywind Scotland project). For this process, crane vessels are needed.

In general, semi-submersible FOWTs will have large overall dimensions, which means that fabrication is only possible at limited number of shipyards. Spars in comparison are much longer structures, however much more slender, which may be an advantage for common shipyards, mainly designed for shipbuilding (ships are also rather slender, long structures). Before assembly and tow-out, the semi-submersible is ballasted and achieves a hydrostatic stable position. The assembly of the substructure with the tower and wind turbine can be done utilizing the onshore cranes. Semi-submersibles have a larger draft than TLPs or barges and thus they require a larger harbour water depth. Semi-submersibles can be towed by tugs to the site where they are connected to the mooring system and the dynamic cable.

In general, an optimised manufacturing process requires the adaption of the yard layout towards a line production with time and cost efficient structure handling processes.

4.2.4 Installation of Tension Leg Platforms (TLPs)

Tension leg mooring systems are installed in a different manner as described in the section above. TLPs usually have a significantly lower steel and total weight and have smaller dimensions than the other platform types. The fabrication of TLPs will be possible at many shipyards. TLPs are typically not hydrostatically stable without the tendon system installed/attached. Hence, they need to be connected to buoyancy elements that provide sufficient stability. Dry towing of the structure is also a feasible option due to the dimensional optimization and light platform weight. Another approach has been introduced by Glosten. For the TLP design named Pelastar, a U-type barge has been designed for installation. The TLP is ‘clamped’ under its arms and towed to the site, see Figure 17. In this case, the turbine and tower can be attached to the substructure by onshore cranes.

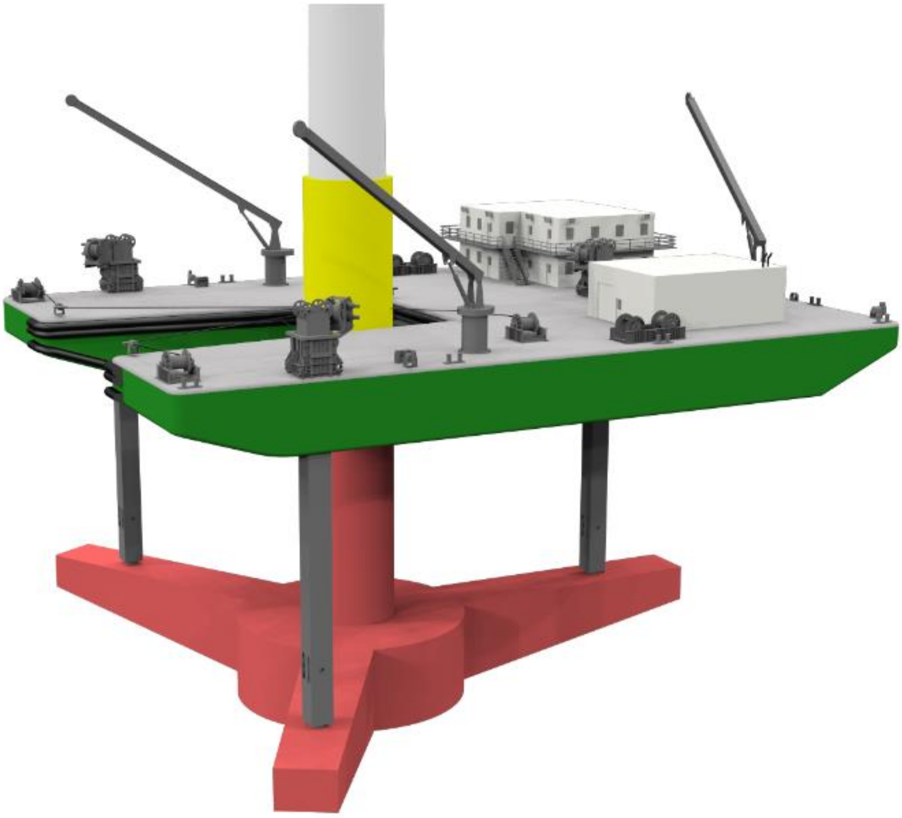

Figure 17: Installation barge for the Pelastar Tension leg Platform (Pelastar)

A similar approach using a U-shaped semi-submersible barge has been introduced by Iberdrola for its TLPWIND® concept, see Figure 18. The combined system of TLP and semi-submersible barge is hydrostatically stable at any stage/draught of the transport and installation operation.

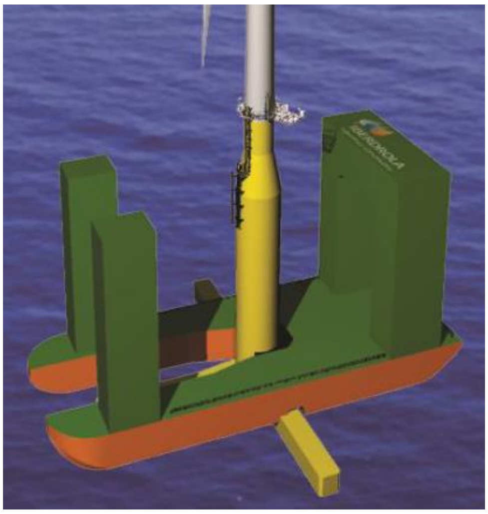

Figure 18: Semi-submersible barge TLP transport concept (figure by Iberdrola)

The GICON SOF TLP will be manufactured in a dry-dock and the wind turbine will be installed at the quay. The structure will be towed to the site by four tugs. During the towing, the structure will be in a hydrostatically stable position as a heavy gravity anchor will be attached to the bottom of the substructure and the four lateral columns will contribute sufficient flotation inertia. At the site, the anchor will be lowered to the seabed utilizing the synthetic tendons already attached to the anchor and the hull. Ballast tanks in the TLP columns will be filled to provide hydrostatic stability during the installation process. As soon as the anchor will be placed on the seabed, the ballast tanks will be emptied and the tendons will become tensioned (GICON-SOF).

In offshore O&G, there are two main principles of tendon installation sequence – vertical and lateral installation (see the next sections). The floating wind installation sequence varies significantly from these, as has been indicated by the two examples of FOWT TLPs shown above.

4.2.4.1 Vertical installation in O&G

To reduce the installation time with the platform being at site, the anchors can be pre-installed. To ensure verticality of the tendons, a seabed template might be necessary for their installation. The TLP is towed to its final site. Since floating TLPs usually have a reduced hydrostatic stability, they are ballasted and kept stable by tugs or being transported on top of a barge/vessel. The tendons are stored, lifted and lowered from an installation vessel through the porches at the TLP hull. Depending on the water depth at the site, a connection process of the tendon parts might be required. This is because the available individual lengths of tubular steel tendon sections is limited and multiple tendon sections may need to be used to achieve the required overall tendon length. The lower end with the bottom connector is placed into the receptacle of the suction anchor and the top connector is above the porch at the TLP hull. As soon as all tendons are installed, the TLP de-ballasts and applies tension force to the tendons and hence reaches a stable floating position.

In a second installation sequence of the vertical installation, the tendons are completely pre-installed from the installation vessel. In O&G industry, the tendons are made of steel pipes which require an offshore welding process at the installation vessel, since steel pipes cannot be spooled. The lower end of the tendons is equipped with the bottom connector and the upper tendon part is equipped with the top connector. The tendons are brought under tension by temporary tendon buoyancy modules (TBMs). Distance holding wires are installed in some cases which protect the tendons from clashing against each other. The TLP is towed to its final position and positioned above the tendons. A guide element for the top connector is lowered by a platform winch though a porch at the hull and connected to the top connector at the tendon upper end. As soon as all tendons are connected, the TLP is ballasts further until the tendon top connectors are above the porches. The final top connectors are installed and a fixed vertical connection is applied. The TLP de-ballasts to apply a tension force to the tendons and hence reaches a stable floating position. Finally, the TBMs are removed.

4.2.4.2 Lateral installation

Another possible TLP installation approach is a lateral installation. The anchors and tendons are pre-installed from an installation vessel as described for the second vertical installation sequence. The TLP arrives to site by dry or wet tow and is kept stable by tugs. The TLP is ballasted and the tendons are inserted into the porches on the hull laterally. As soon as all top connectors have been inserted into the porches, the TLP starts to de-ballast and apply the tension force in the tendons required for a stable floating position. Finally, the TBMs are removed from the tendons.

The main difference between offshore O&G and floating wind TLP concepts is that the type of tendons use is completely different. Whereas in O&G the tendons are made of steel pipes, for floating wind TLPs synthetic lines or steel ropes are usually used. In floating wind industry, there are several concepts based on the TLP principle, some of which use inclined tendons.

4.2.5 Logistical constraints

There exist some logistical constraints for FOWT installation that need to be considered. These are listed below:

- The size of the fabrication dry dock or construction area must provide enough space to accommodate the selected platform (or several platforms if a line production of multiple substructures is selected) OR the platform needs to be designed according to the dimensions of the chosen yard. Only a few dry docks worldwide would be able to accommodate the large dimensions of substructures for 10 MW wind turbines.
- The transport routes towards the fabrication yard should not limit the supplied part masses and dimensions significantly.
- The storage and construction area needs to have a sufficient bearing capacity.
- The harbour water depth needs to be sufficient if the substructure is designed to be towed out on a large draft taking into account the tidal variations. Otherwise, cost intensive transport alternatives (semi-submersible barges or towing on a reduced draft with additional stabilization pontoons) need to be evaluated.
- The canal width needs to be significantly larger than the substructure dimensions.
- If the turbine and tower are designed to be attached to the substructure using the onshore cranes, the overall height must be lower than the lower bound of any bridge between yard and installation site.
- The onshore (gantry) cranes should have sufficient height and capacity to lift the tower and RNA onto the substructure. The requirements for the cranes increase with larger turbine ratings as the RNA height and total masses increase. Currently onshore gantry cranes do not have the capacities required for the reference LIFES50+ 10MW WT, thus large and expensive mobile cranes (temporarily constructed and operated at the installation port) must be used currently.
- The yard should provide enough (sheltered) storage space for the turbine towers, blades and nacelles as well as for the mooring system components.
- The quay should provide enough space for multiple substructures if a line fabrication is selected.

- Depending on the main floater material (steel or concrete), appropriate yard infrastructure needs to be available.
- Concrete floaters are restricted regarding the environmental conditions during fabrication. Here particularly moisture (rain, snow) and temperature (mainly cold) could affect the pouring and curing process.
- If a line production is selected, sufficient means of transporting components within the port need to be available.
- The distance between the port and the wind farm has a direct impact on the length of the weather window for platform installation. Weather is often not predictable for the complete time of transport.

It is likely that the facilities and the infrastructure of the fabrication port will require modification for a specific floating wind project. It needs to be analysed whether the infrastructure of the installation port would be able to accommodate a floater in case of repair.

4.3 Equipment

4.3.1 Vessels

Marine operations in floating wind industry require use of different types of supporting vessels. This includes, among others, vessels for towing, lifting (and upending), anchor and mooring handling, positioning of the platform, cable laying and for crew transfer in the operation phase. As indicated above, unique vessels, such as the transport barge for the Pelastar TLP concept, may be designed to guarantee an optimal solution for the special requirements of floating offshore wind.

In general, sea going tugs are utilized for the harbour and sea towing, as described by the FLOATGEN partners for its benchmark FOWT (FLOATGEN) and by Mitsubishi Heavy Industries for the Fukushima Shimpuu (Komatsu, et al., 2016). These tugs should have a dynamic positioning (DP) system to position the floater exactly. For the attachment of the mooring lines to the floater, one or more AHVs are generally needed, since common tugs are not able to execute this type of work.

The sea towing is in general limited by the sea states present on the route. The maximum significant wave height that can be survived by the towed structure is dependent on the type of substructure, its dimensions, the angle of attack of the sea state and the type of tugs used. Since AHVs, which are larger than sea tugs, can operate under harsh environmental conditions, it might be preferable, for some locations, to charter the more expensive but more reliable AHVs instead of sea going tugs.

It might also be necessary to utilize multi-purpose support vessels or platform supply vessels taking advantage of their additional deck space and crane capacities.

For O&M processes and minor repairs, the structure can be accessed by common CTVs since the substructures are equipped with a boat landing structure.

The vessels required for FOWT installation constitute a large proportion of the overall project cost. Prices and availabilities vary strongly depending on season, geographical location and market situation. The vessels needed for installation of one or multiple FOWTs should be determined carefully for an economically optimised installation process. The larger the distance between the installation base and the site, the more tugs or AHVs are needed to avoid a delay of a multiple turbine project.

It can be concluded that marine operations for floating structures require less sophisticated and less expensive offshore vessels than marine operations for bottom-fixed offshore wind turbines, if the assembly of wind turbine and substructure has been carried out at the quay.

4.3.2 ROV, AUV

For the installation of the anchors and for inspection purposes during the operation lifetime, the use of ROVs or autonomous underwater vehicles (AUVs) or divers (not recommended) is required. The ROVs can monitor the position and orientation of drag anchors, connect the bottom connector with the suction anchor of the tension leg system and connect a mooring chain to a suction anchor or pile. ROVs are also used to inspect the condition of the mooring lines in defined periodic intervals. ROVs can also follow subsea equipment down to the seabed as it is lowered from the installation vessel. This significantly reduces the reaction time of the operator in case a process was not executed as designed.

4.3.3 Mooring equipment

The mooring equipment may provide a large contribution towards the total mass of the FOWT depending on the specific mooring and platform typologies... It consists of various elements of different sizes. It is likely that those elements are manufactured by several suppliers at different locations. The mooring elements are transported to the storage area at the installation port either on road or on a river/the sea. The port which serves as base for installation does not necessarily need to be the port of fabrication of the substructure. The mooring line which is most likely to be made of a synthetic material is typically transported and stored on reels. Synthetic lines can be stored in reels with a smaller diameter than steel wire lines (Chakrabarti, 2005). Other mooring elements that are provided by suppliers may be one or more of the following: clump weights, anchor chain weights, buoyancy elements, shackles or other chain connectors, rope socket, top, intermediate and bottom connectors for tendon systems and monitoring devices. The reel diameter needs to be chosen with respect to transportation limitations and a suitable bending radius. There should be heavy lift systems available at the port. If the mooring equipment is transported by a heavy lift vessel, the vessel cranes may be used for offloading. Nevertheless, for a loading on deck of the multi service vessel (MSV), onshore crane capacities are needed. Fastening equipment for the sea transport should be provided by the suppliers. The mooring system is dependent on the turbine rating and on the installation site (water depth, soil conditions, metocean conditions, etc.). Larger turbine thrust will increase the loads in the mooring system, but the environmental conditions are relatively of a higher impact (at least when considering moderate differences in WT ratings, e.g. 8-10MW range). Smaller turbines in a harsh environment likely require stronger mooring elements than a large turbine at a calm location.

4.3.4 Tower and wind turbine

Assuming 10MW+ ratings, the tower and RNA are usually transported by the respective manufacturer on a river or by the sea. Since the blades and the tower are large elements, the wind turbine requires large storage areas at the yard. The storage area required will increase for turbines with a larger power rating, for a wind farm with multiple turbines and if the storage time from supply to system assembly is increased. The tower and RNA will either be installed at the quay utilizing large capacity onshore cranes or be transferred to a barge for a later assembly offshore. If a fabrication yard of the substructure and an installation port which are not the same, the assembly of substructure and wind turbine can be done at either of the ports assuming that there is sufficient crane capacity at both ports.

4.4 Assembly

4.4.1 On site

It is common practise to pre-install the anchors and mooring lines of catenary mooring systems. Tendon systems may also be pre-installed. When arriving at the site, the floating wind turbine can be directly attached to the mooring lines or tendons. Another method is to execute the mooring system installation at the site as soon as the platform arrives. The first procedure has large advantages regarding the weather window required for platform installation.

An offshore assembly of the wind turbine and the platform is for some types of substructures not required and it is in general not favoured by designers and operators. Bottom-fixed structures are assembled at the site using jack-up vessels. It is rather unlikely that towers and RNAs of floating offshore wind turbines will be installed at site using jack-up vessels due to large water depths and larger tower and RNA sizes. Hence, for the assembly at site crane vessels would be required. Those vessels are characterised by large rental costs and a very restricted availability on the market.

Thus, an assembly at site would in general increase installation costs (larger and/or more installation vessels required) and increase the offshore installation time frame.

4.5 At port

A full assembly at the port is technically not possible, since the mooring system and the electrical cables will be attached to the platform at site. Nevertheless, designers, operators and manufacturers strive to assemble as many FOWT elements as possible at the port and in sheltered areas (Spar). If the port conditions (e.g. size of the production facility, crane capacities, harbour water depth, bridge heights) allow for an almost complete assembly of the platform and the wind turbine, this is done. The substructure of the 7MW V-shaped semi-submersible Shimpuu in the Fukushima FORWARD project has been manufactured in Nagasaki, but the assembly of the platform with the wind turbine has been performed at the port of Onahama close to the installation site (Komatsu, et al., 2016). It is likely that due to economic reasons and hydrostatic stability, the port of production of the substructure and the port of assembly are not the same.

A big advantage of the full assembly at port is that the commissioning of the wind turbines can take place in protected areas. The duration of this process could exceed several days under offshore conditions.

For the assembly of the substructure with the tower and RNA, relatively cost and time efficient onshore harbour (gantry) cranes of the yards may be utilized, if the size of the WT and tower allows. As commented earlier, for the LIFES50+ considered 10MW class, currently no suitable gantry cranes are available at ports and yards and special, mobile cranes or heavy lift vessels are required.

4.6 Risk consideration for installation and marine operations

As explained in Section 3.7, risk should not only be considered for the design phase of a FOWT, but should also be considered for all other lifecycle phases.

This section considers risk during installation and marine operations of FOWTs. Several risks manifest during the installation and marine operation of FOWTs. Some of these risks are industry agnostic such as the generic risks of working with electrical and mechanical equipment, manual lifting, etc., whilst some are similar to risks inherent in other offshore industries such as oil and gas and bottom-fixed offshore wind. Examples are:

- Health and safety risks to offshore personnel resulting from events such as diving operations, vessel capsize, collapse of structure, etc.
- Health and safety and environmental risks resulting from steel corrosion leading to compromised structural integrity.
- Weather risks linked to metocean conditions leading to health and safety risks to personnel, vessels and the environment.
- Navigation and aviation risks leading to health and safety risks to personnel, vessels, and the environment.
- Environmental risks resulting from the pollution of the environment from multiple sources such as vessels, working materials like paint, etc.

Yet apart from the industry agnostic risks and risks transferred from bottom-fixed offshore wind, there are specific risks inherent to installation and marine operation of FOWTs. Examples of these risks are:

- Health and safety risks arising from loss of mooring line during installation leading to instability of the structure or even collapse of the structure.
- Health and safety risks arising from incorrect ballasting of the substructure leading to instability of the structure or even collapse of the structure.
- Health and safety risks arising from relative motion between turbine and vessel during crew transfer.
- Increased weather window risks due to relatively low towing speeds for FOWTs.
- Health and safety risks due to higher need for divers during installation operations.
- Health and safety risks resulting from damage to dynamic cables during marine operations.

Also, apart from the health and safety risks to personnel mentioned above, there are also other risks associated with FOWTs during installation and marine operation such as project cost increases, environmental pollution, reputational damage to the industry and companies, etc.

Due to the nature of FOWTs (multiple processes are repeated in different lifecycle phases), various hazards are applicable (but at varying probabilities and consequences) to both installation and marine operations. To name a few, these include weather delays; damage to equipment coating which can lead to accelerated corrosion; damage to cables when installing or connecting the mooring system; mooring line or anchor failure due to excessive pulling loads applied.

Some of the risks during installation and marine operations can be a direct result of insufficient consideration of the implications of various actions and events or ineffective communication between different parties involved in all life cycle phases during the design phase, as shown in Figure 19.

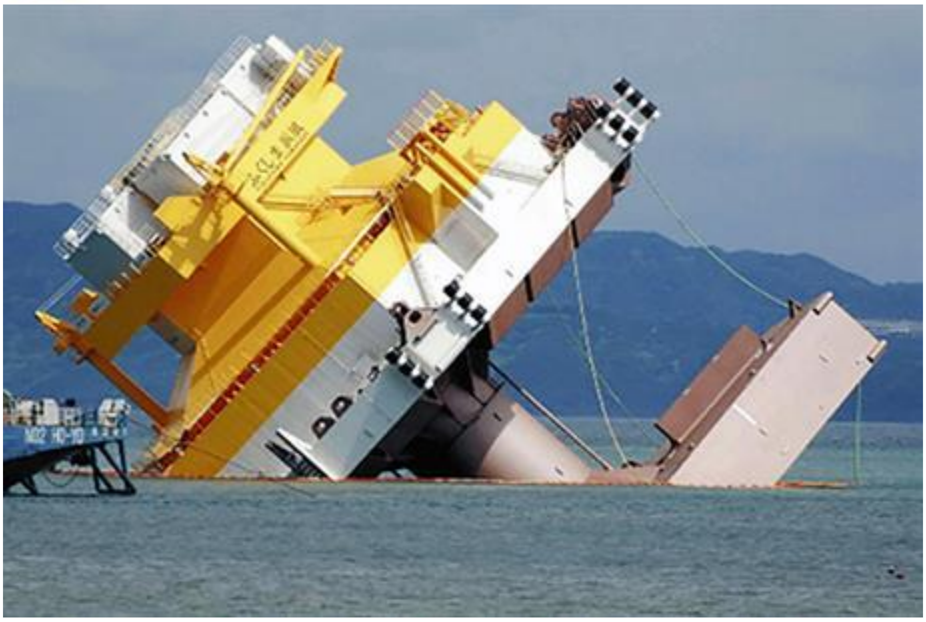

Figure 19: Uncontrolled heeling of an advanced Spar substructure

In the bottom-fixed offshore wind industry, subsea cabling failures are the main cause of financial losses in the industry. The same report goes on to say that “two-thirds of cable faults recorded by GCube are down to contractor error during the installation”. Floating wind subsea cabling is even more complex compared to the bottom-fixed offshore wind industry, which can potentially lead to additional cable failures in floating wind, if the lessons learned in other industries are not transferred across. One possible solution could be to perform a detailed risk assessment of the subsea cable across its all lifecycle phase (as oppose to concentrating on mechanical and electrical properties) and implement risk mitigation where appropriate.

5 Bibliography

ABSG CONSULTING INC. 2015. *Study on Mooring System Integrity Management for Floating Structures.* Arlington : s.n., 2015.

Adam, F, et al. 2015. *Comparison of Three Different TLPs for Wind Turbines by Tank Tests and Calculated Results.* s.l. : American Society of Mechanical Engineers, 2015.

Amate, J., et al. 2015. Iberdrola Ingenería y Cnstrucción. How to install a TLP Substructure for offshore wind? TLPWIND Case Study. *EWEA Offshore.* 2015.

Andrawus, Jesse A., et al. 2006. *WIND ENGINEERING VOLUME 30, NO. 6,PP 471–486, "The Selection of a Suitable Maintenance Strategy for Wind Turbines".* 2006.

Arabian-Hoseynabadi, H, Oraee, H und Tavner, P.J. 2010. *Failure Modes and Effects Analysis (FMEA) for wind turbines.* 2010.

Armendariz, J. Azcona, et al. 2011. *Development of OPASS Code for Dynamic Simulation of Mooring Lines in Contact with Seabed.* National Renewable Energy Centre, CENER. EWEA OFFSHORE 2011, 29 November – 1 December 2011, Amsterdam, The Netherlands : s.n., 2011.

Bachynski, Erin E und Moan, Torgeir. 2012. Design considerations for tension leg platform wind turbines. *Marine Structures.* 2012, Bd. 29, 1.

Bachynski, Erin Elizabeth. 2014. *Design and Dynamic Analysis of Tension Leg Platform Wind Turbines.* ISSN 1503-8181 : NTNU Doctoral thesis, 2014.

Bai, Yong und Bai, Qiang. 2005. *Subsea Pipelines and Risers.* s.l. : Elsevier, 2005.

Bak, Christian, et al. 2013. *Description of the DTU 10 MW Reference Wind Turbine.* s.l. : DTU Wind Energy, 2013.

Benveniste, Gabriela, et al. 2016. D2.3 LCOE cost tool description and D2.4 Technical and environmental impact evaluation toolLCOE cost tool description and D2.4 Technical and environmental impact evaluation tool. *LIFES50+ deliverables 2.3 and 2.4.* 2016.

Bhattacharjee, S. Design and Installation Challenges for Deepwater Mooring Systems. [Online] ExxonMobil Development Company. [Zitat vom: 07. 06 2017.] www.vryhof.com/pdf/Exxonmobil.pdf.

Bjerkseter, Catho und Ågotnes, Anders. 2013. *Levelized Costs of Energy for Offshore Floating Wind Turbine Concepts.* 2013.

Borg, Michael, Mirzaei, Mahmood und Bredmose, Henrik. 2015. LIFES50+ D1.2: Wind turbine models for the design. 2015.

Bredmose, Henrik, et al. 2015. Experimental study of the DTU 10 MW wind turbine on a TLP floater in waves and wind. *EWEA Offshore 2015 Conference, Copenhagen.* 2015.

Burton, Tony, et al. 2011. *Wind Energy Handbook.* [ed.] Tony Burton. 2nd. Oxford : Wiley, 2011. pp. XXXVII, 742. ISBN: 978-0-470-69975-1.

Butterfield, S., Musial, W. und Jonkman, J. 2005. Engineering Challenges for Floating Offshore Wind Turbines. *Copenhagen Offshore Wind Conference.* 2005.

Castro-Santos, Laura und Diaz-Casas, Vicente. 2013. *Life-cycle cost analysis of floating offshore wind farms.* 2013.

Chakrabarti, S.K. 2005. *Handbook of Offshore Engineering.* Oxford : Elsevier, 2005.

Chakrabarti, Subrata. 2008. Challenges for a Total System Analysis on Deepwater Floating Systems. *The Open Mechanics Journal.* 2 2008, S. 28-46.

Christiansen, Soren. 2013. *Model – Based Control of a Ballast – Stabilized Floating Wind Turbine Exposed to Wind and Waves.* Aalborg University. 2013. Ph.D. dissertation.

Cordle, Andrew und Jonkman, Jason. 2011. *State-of-the-art in Floating Wind Turbine Design Tools.* GL Garrad Hassan. ISOPE : s.n., 2011.

Cruz, Joao und Atcheson, Mairead. 2016. *Floating Offshore Wind Energy - The next generation of wind energy.* Lisbon : Springer, 2016.

de Boom, Wim. 2011. Floating Support for Offshore Wind: Small Structures - Big Challenges. *Proceedings of the 30th International Conference on Offshore Mechanics and Arctic Engineering.* 2011.

DNV-GL. 2015. *DNV-GL.* [Online] 12 2015. https://www.dnvgl.com/Images/2020-2030-1200x800_tcm8-13540.jpg.

—. 2011. *DNV-OS-J101: Design of Offshore Wind Turbine Structures.* 2011.

—. 2001. *DNV-RP-A203: Qualification Procedures for New Technology.* 2001.

Ebenhoch, Raphael. 2014. Comparative levelized cost of energy analysis for a floating offshore wind turbine concept. July 2014.

Fingersh, L., Hand, M. und Laxson, A. *Wind Turbine Design Cost and Scaling Model.*

Fischer, Boris. 2012. *Reducing rotor speed variations of floating wind turbines by compensation of non-minimum phase zeros.* 2012. pp. 144-147.

Fischer, Tim. 2012. *Mitigation of Aerodynamic and Hydrodynamic Induced Loads of Offshore Wind Turbines.* University of Stuttgart. 2012. Ph.D. dissertation.

Fleming, Paul, et al. 2014. *Evaluating Methods For Control Of An Offshore Floating Turbine.* 2014.

FLOATGEN. *Demonstration and benchmarking of a floating wind turbine system for power generation in Atlantic deep waters. Floating Structure and wind turbine transportation procedure. Deliverable no. 5.1, EC-GA no. 295977.*

Fujii, Shigeru, et al. 2013. The Development if the Power Transmission System for Fukushima FORWARD Project. *Furukawa Review.* No. 43, 2013.

Fukushima Offshore Wind Consortium. *Fukushima Floating Offshore Wind Farm Demonstration Project (Fukushima FOR-WARD) – Construction of Phase 1.*

Fylling, Ivar und Berthelsen, Petter Andreas. 2011. WINDOPT - an optimization tool for floating support structures for deep water wind turbines. 2011.

GICON-SOF. Impressions from development and fabrication. [Online] [Zitat vom: 29. 05 2017.] http://www.gicon sof.de/en/impressions.html.

Giron, Aldo Roberto Cruces, et al. 2014. An integrated methodology for the design of mooring systems and risers. *Marine Structures.* 2014.

Hall, Matthew. 2013. *Mooring Line Modelling and Design Optimization of Floating Offshore Wind Turbines.* 2013.

—. 2013. *Mooring Line Modelling and Design Optimization of Floating Offshore Wind Turbines.* University of Victoria. 2013. Ph.D. Dissertation.

Hall, Matthew, Buckham, Brad und Crawford, Curran. 2013. Evolving offshore wind: A genetic algorithm-based support structure optimization framework for floating wind turbines. *OCEANS'13 MTS/IEEE.* 2013.

—. 2014. Hydrodynamics-based floating wind turbine support platform optimization: A basis function approach. *Renewable Energy.* 2014.

Hansen, A. M., et al. 2014. Small scale experimental study of the dynamic response of a tension leg platform wind turbine. *Submitted for journal publication.* 2014.

Härer, Arne. 2013. *Optimierung von Windenergieanlagen-Komponenten in Mehrk• orpersimulationen zur Kosten- und Lastreduktion.* Stuttgart : s.n., 2013.

Heilskov, Nicolai F., et al. 2016. Results of codes validation with wave tank tests. *INNWIND.EU report, Deliverable 4.25.* 2016.

Henderson, Andrew R und Witcher, David. 2010. Floating offshore wind energy—a review of the current status and an assessment of the prospects. *Wind Engineering.* 2010.

Hobohm, Jens, et al. 2013. *Cost Reduction Potentials of Offshore Wind Power in Germany.* Berlin : s.n., 2013.

Hutton, Gail, et al. 2015. *Lifes50+ Deliverable - Risk Management for Deep Water Substructures.* 2015.

Inoue, Y. und S., Surendran. 1994. *Dynamics of the interaction of mooring line with the seabed.* Osaka, Japan : s.n., 1994. S. 317-23.

—. 1994. *Dynamics of the interaction of mooring line with the seabed.* Osaka, Japan : s.n., 1994. S. 317-23.

Interational Renewable Energy Agency. 2012. *Renewable Energy Technologies: Cost Analysis Series-Wind Power.* 2012.

IRENA. 2015. *RENEWABLE POWER GENERATION COSTS IN 2014.* 2015.

ISO. 2009. *IEC 31010 — Risk Management: Risk Assessment Techniques.* 2009.

—. 2009. *ISO Guide 73: 2009 Risk Management - Vocabulary.* 2009.

—. 2010. *Safety of machinery - General principles for design - Risk assessment and risk reduction (ISO 12100:2010).* 2010.

James, Rhodri. 2015. *Floating Offshore Wind: Market and Technology Review.* 2015.

Jonkman, J. 2007. *Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine.* NREL/TP-500-41958. Golden, US-CO : National Renewable Energy Laboratory, 2007.

Jonkman, Jason and Buhl, Marshall. 2005. *Fast User's Guide.* 2005.

Jonkman, Jason. 2008. *Influence of Control on the Pitch Damping of a Floating Wind Turbine.* Reno : s.n., 2008.

Jonkman, JM und Matha, Denis. 2011. Dynamics of offshore floating wind turbines—analysis of three concepts. *Wind Energy.* 4, 2011, Bd. 14.

Kacprzak, Przemyslaw. *Possibilities of Utilization the Risk – Based Techniques in the Field of Offshore Wind Power Plants.*

Karlynn Cory, Paul Schwabe. 2009. *Wind Levelized Cost of Energy: A Comparison of Technical and Financing Input Variables.* 2009.

Kim, H., Choung, J. und Jeon, G. 2014. *Design of Mooring Lines of Floating Offshore Wind Turbine in Jeju Offshore Area.* San Francisco : s.n., 2014.

—. 2014. *Design of Mooring Lines of Floating Offshore Wind Turbine in Jeju Offshore Area.* San Francisco : s.n., 2014.

Kim, Hyungjun, Choung, Joonmo und Jeon, Gi-Young. 2014. *Design of mooring lines of floating offshore wind turbine in jeju offshore area.* OMAE2014-23772 : s.n., 2014.

—. 2014. *Design of mooring lines of floating offshore wind turbine in jeju offshore area.* OMAE2014-23772 : s.n., 2014.

Komatsu, M., et al. 2016. Development of Offshore Wind Turbine Floater that Blends into Japanese Waters – Evaluation of the Validity for Design and Applied Methods for V-shaped Semi-submersible Floating structure. *Mitsubishi Heavy Industries Technical Review.* 2016, Bd. 53, 2.

Krieger, Antonia, et al. 2015. *LIFES50+ D7.2 Design Basis.* 2015.

Lackner, Matthew and Rotea, Mario. 2011. *Structural control of floating wind turbines.* s.l. : Elsevier Ltd, 2011. pp. 704-719. ISSN: 09574158 DOI: 10.1016/j.mechatronics.2010.11.007.

Larsen, T J and Hanson, T D. 2007. A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine. *Journal of Physics.* 2007, Vol. 75.

Laura, Castro-Santos und Vicente, Diaz-Casas. 2014. Life-cycle cost analysis of floating offshore wind farms. *Renewable Energy.* 2014.

Lemmer, Frank, Amann, Florian und Raach, Steffen, Schlipf, David. 2016. Definition of the SWE-TripleSpar Floating Platform for the DTU 10MW Reference Wind Turbine. *online: http://www.ifb.uni-stuttgart.de/windenergie.* 2016.

Lemmer, Frank, et al. 2016. Optimization framework and methodology for optimized floater design. *LIFES50+ Deliverable 4.3.* 2016.

Lemmer, Frank, et al. 2015. *Prospects of Linear Model Predictive Control on a 10MW Floating Wind Turbine.* St. John's/Canada : s.n., 2015.

Lindeberg, Eivind. 2009. *Optimal Control of Floating Offshore Wind Turbines.* Norwegian University of Science and Technology. 2009. Master Thesis.

Luengo, Maria Martinez und Kolios, Athanasios . 2015. *Failure Mode Identification and End of Life Scenarios of Offshore Wind Turbines: A Review.* 2015.

Luo, N, et al. 2011. *Semiactive Control for Floating Offshore Wind Turbines Subject to Aero-hydro Dynamic Loads.* Las Palmas, Gran Canaria/Spain : s.n., 2011.

Mankins, John C. 2009. *Technology readiness assessments: A retrospective.* 2009.

Matha, Denis. 2010. *Model Development and Loads Analysis of an Offshore Wind.* 2010.

Matha, Denis und Scheffler, Ron. 2017. Specification for industrialization. *LIFES50+ Deliverable 5.2.* 2017.

Matha, Denis, et al. 2016. Design Brief. *LIFES50+ Deliverable 5.1.* 2016.

Matha, Denis, et al. 2014. *Efficient preliminary floating offshore wind turbine design and testing methodologies and application to a concrete spar design.* 2014.

Matha, Denis, et al. 2011. *Non-linear Multi-Body Mooring System Model for Floating Offshore Wind Turbines.* University Stuttgart. OFFSHORE 2011, Amsterdam, Netherlands : s.n., 2011.

Moné, C., et al. 2015. *2013 Cost of Wind Energy Review.* 2015.

Müller, Kolja, et al. 2014. *Improved Tank Test Procedures For Scaled Floating Offshore Wind Turbines.* Hannover : s.n., 2014.

Müller, Kolja, et al. 2016. State-of-the-Art FOWT Design Practice and Guidelines. *LIFES50+ Deliverable 7.4.* 03 2016.

Myhr, Anders, et al. 2013. *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective.* 2013.

—. 2014. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy.* 2014.

Namik, Hazim. 2012. *Individual Blade Pitch and Disturbance Accommodating Control of Floating Offshore Wind Turbines.* University of Auckland. 2012. Ph.D. dissertation.

Neto, Alfredo Gay, Martins, Clovis A. und Pimenta, Paulo M. 2014. Static analysis of offshore risers with a geometrically-exact 3D beam model subjected to unilateral contact. *Computational Mechanics.* January 2014.

NREL. 2015. http://www.nrel.gov/analysis/tech_lcoe.html. *Levelized Cost of Energy Calculator.* [Online] 2015. [Zitat vom: 23. January 2016.] http://www.nrel.gov/analysis/tech_lcoe.html.

Ong, PA und Pellegrino, S. 2003. *Modelling of seabed interaction in frequency domain analysis of mooring cables.* 2003. OMAE2003-37465.

—. 2003. *Modelling of seabed interaction in frequency domain analysis of mooring cables.* 2003. OMAE2003-37465.

Papanikolaou, A. und Soares, C. G. 2009. *Risk-based ship design: methods, tools and applications.* Berlin : Springer, 2009.

Papanikolaou, Apostolos D. 2011. Holistic ship design optimization: merchant and naval ships. *Ship Science & Technology.* 2011.

Pegalajar Jurado, Antonio Manuel, et al. 2016. Experimental and numerical study of a 10MW TLP wind turbine in waves and wind. *Journal of Physics: Conference Series.* 2016.

Pelastar. Installation. [Online] [Zitat vom: 29. 05 2017.] http://pelastar.com/?page_id=55.

Pérez, Germán und Mendikoa, Iñigo. 2017. Upscaling procedures. *LIFES50+ Deliverable 1.6.* 2017.

Raach, Steffen, et al. 2014. *Nonlinear Model Predictive Control of Floating Wind Turbines with Individual Pitch Control.* Portland, Oregon, USA : s.n., 2014.

Ramboll. 2015. *Design Brief - Design Risk Assessment.* 2015.

Ridge, I.M.L., Banfield, S.J. und Mackay, J. 2010. Nylon Fibre Rope Moorings for Wave Energy Converters. *OCEANS 2010.* 2010.

Robertson, Amy N und Jonkman, Jason M. 2011. Loads analysis of several offshore floating wind turbine concepts. *The Twenty-first International Offshore and Polar Engineering Conference.* 2011.

Robertson, Amy, Jonkman, Jason and Musial, Walter. 2013. *Offshore Code Comparison Collaboration , Continuation : Phase II Results of a Floating Semisubmersible Wind System.* Frankfurt : s.n., 2013.

Sanchez, Miren J. und et al. 2017. Concepts design. *LIFES50+ Deliverable 1.3.* 2017.

Sandner, Frank, et al. 2014. *Integrated Optimization Of Floating Wind Turbine Systems.* San Francisco : s.n., 2014. ISBN: 978-0-7918-4554-7 DOI: 10.1115/OMAE2014-24244.

Sandner, Frank, et al. 2012. *Reduced Nonlinear Model of Spar-Mounted Floating Wind Turbine.* DEWEK 2012, Bremen : s.n., 2012. S. accepted for oral presentation.

Savenije, Feike and Peeringa, Johan. 2014. *Control development for floating wind.* 2014. p. 012090. ISSN: 1742-6596 DOI: 10.1088/1742-6596/524/1/012090.

Schlipf, David, et al. 2013. *Nonlinear Model Predictive Control of Floating Wind Turbines.* 2013.

SI OCEAN. 2013. *Ocean Energy: Cost of Energy and Cost Reduction Opportunities.* 2013.

Strach-Sonsalla, Mareike, Muskulus, Michael und al., et. 2016. Dynamics and Design of FloatingWind Turbines. *The 26th International Ocean and Polar Engineering Conference.* 2016.

Tavner, Peter. *Offshore Wind Turbine Reliability.*

Tongdan Jin, Zhigang Tian, Miguel Huerta, Jett Piechota. 2012. *Coordinating Maintenance With Spares Logistics to Minimize Levelized Cost of Wind Energy*. 2012.

Tracy, Christopher . 2007. *Parametric design of floating wind turbines.* s.l. : Massachusetts Institute of Technology, 2007.

Valpy, Bruce und English, Philip. *Future renewable energy costs: offshore wind.*

Veen, Gijs Van Der, Couchman, Yan and Bowyer, Robert. 2012. *Control of floating wind turbines.* 2012. pp. 3148-3153.

Veritas, Det Norske. 2015. Offshore standard DNV-OS-E301: Position mooring. 2015.

Wei, Yu, et al. 2017. Public Definition of the Two LIFES50+ 10MW Floater Concepts. *LIFES50+ Deliverable 4.2.* 2017.

Weller, S., Johanning, L. und Davies, P. 2013. *Guidance on the use of synthetic fibre ropes for marine energy devices.* Channel : MERiFIC (Marine Energy in Far Peripheral and Island Communities), 2013.

Weller, SD, et al. 2015. Synthetic mooring ropes for marine renewable energy applications. *Renewable Energy.* 2015.

Wright, Christopher, Pakrashi, Vikram und Murphy, Jimmy. 2016. Dynamic Effects of Anchor Positional Tolerance on Tension Moored Floating Wind Turbine. *Journal of Physics: Conference Series.* 2016.