Design practices and guidelines for mooring, anchoring system design

USTUTT, INNOSEA, DTU, RAMBOLL, UPC, FIHAC

March 2023

Disclaimer:

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No 815083.

Project details:

Duration:
1 Sep 2019 - 28 Feb 2023
Grant agreement:
No: 815083

Document information

Deliverable number	D2.4
Deliverable name	Design practices and guidelines for mooring, anchoring system design
Reviewed by	
Date	March 2023
Work Package and Task	WP2 - Design and optimization of station keeping systems Task 2.4 – Design practices and guidelines for mooring, anchoring system design
Lead Beneficiary for this Deliverable	FIHAC
Dissemination Level	Public

Authors

Name	Organisation	E-mail
Valentin Arramounet	INNOSEA	valentin.arramounet@innosea.fr
Maxime Chemineau	INNOSEA	maxime.chemineau@innosea.fr
Florian Castillo	INNOSEA	florian.castillo@innosea.fr
Lucas Mechinaud	INNOSEA	lucas.mechinaud@longitude-engineering.com
Mohammad Youssef Mahfouz	USTUTT	mahfouz@ifb.uni-stuttgart.de
Qi Pan	USTUTT	pan@ifb.uni-stuttgart.de
Leonard Willeke	USTUTT	willeke@ifb.uni-stuttgart.de
Henrik Bredmose	DTU	hbre@dtu.dk
Ozan Gözcü	DTU	ozgo@dtu.dk
Nicolò Pollini	DTU	nipol@dtu.dk
Friedemann Borisade	RAMBOLL	friedemann.borisade@ramboll.com
Pau Trubat Casal	UPC	pau.trubat.casal@upc.edu
Climent Molins Borrel	UPC	climent.molins@upc.edu
Raúl Guanche	FIHAC	guancher@unican.es
Miguel Somoano	FIHAC	somoanom@unican.es

Version control

Version	Date	Author	Description of Changes
00	[2023-02-01]	See above listing	Issued for Internal Review
[Draft V1.0]	[2023-02-15]	UL / DEWI-OCC	Revision
V2.0	[2023-04-24]	IHC	Revised according comments

Table of contents

1 ABBREVIATION LIST

Abbreviation	Description
ALS	Accidental Limit State
BEM	Blade Element Momentum
CAPEX	CAPital EXpenditure
DLC	Design Load Case
DNV	Det Norske Veritas
EOL	End Of Life
FEM	Finit Element Method
FLS	Fatigue Limit State
FOWT	Floating Offshore Wind Turbine
GC	Gran Canaria
LCOE	Levelized Cost of Energy
LL	Lifting Line
MB	Morro Bay
MBL	Minimum Breaking Load
NREL	National Renewable Energy Laboratory
O&G	Oil and Gas
PLR	Peak Loads Reduction
QSA	Quasi-static analysis
QTF	Quadratic Transfer Function
SLS	Service Limit State
SOL	Start Of Life
T&I	Transport and Installation
TDP	Touchdown Point
ULS	Ultimate Limit State
WoB	West of Barra
WP	Work package
wrt	With Respect To
WT	Wind turbine

2 EXECUTIVE SUMMARY

Corewind is a project funded by the Horizon 2020 research program, supported by the European Commission. The main objective of Corewind is to achieve 15% reduction of LCOE of floating offshore wind through research and optimization of station keeping systems, anchoring systems and dynamic cables, with a special focus on installation techniques and operation and maintenance activities. For the project, a semi-submersible and a spar buoy floating platform (respectively ActiveFloat and WindCrete) supporting 15MW large wind turbines have been developed. In the investigations, three different sites have been selected for the installations, at water depths of 100 m, 200 m and 870 m.

Work Package 2 of the Corewind project focused on design and optimization of both platform's mooring and anchoring systems. Four tasks have been defined to achieve the objectives of WP2. In the first task, a review of the state of the art of mooring and anchoring design has been conducted and summarized in deliverable D2.1. In the second task the ULS and FLS reliable designs and optimizations of the mooring and anchoring systems of the two floating platforms were developed. In the third task several innovations and breakthroughs of station keeping systems regarding LCOE reduction potential and feasibility were explored. Finally, the present report covers the last task, summarizing the design practices and guidelines for mooring and anchoring systems design.

The mooring design optimization tool developed has been used to design and optimize the mooring systems of both floating platforms at the three reference sites of the COREWIND project. Results are promising for designs driven by ULS. Coupled analyses have been performed and validated the ULS designs. However, the results also underline limitations in harsh environments and for FLS driven designs that were not validated through coupled fatigue analysis. To proceed, efforts regarding innovative platform connections have resulted in a stiff and reliable design, adapted to the optimized mooring systems and consequently cost effective.

A special focus has been dedicated to installation techniques, where methods from O&G and FOWT demonstrator project were analysed and compared. O&G installation processes are already well optimized in terms of cost and schedule, which can be used for FOWT installation with differences such as the anchor radius limitation due to the floating units spacing and the large number of turbines when compared to a single floater O&G project. In addition, floating wind farms are keen to hybrid mooring designs potentially combining clump weights, mooring buoys and possibly peak load reduction devices, which increases the failure modes and installation complexity, emphasized by the large number of floating units in a wind farm. Conclusions of the study point out the importance of streamlining the supply chain together with the installation process. Reducing the number of mooring lines can benefit to reduce the installation cost by reducing the number of anchors to be installed and lines to be hooked-up to the floating platforms, but on the other hand, heavier and bigger lines require larger and more expensive vessels.

Investigations regarding innovative solutions started with the use of peak loads reduction systems in the mooring lines, for the study of two different innovative technologies. Results are encouraging for catenary mooring where the use of both systems led to extreme load reductions of 50% and 25% for WindCrete and ActiveFloat respectively, and consequently led to important cost reductions of 37% and 18% respectively for WindCrete and ActiveFloat. Results are less promising for the semi-taut moorings studied, since almost no cost reduction has been demonstrated, probably due to the complexity of the mooring systems. In addition, the study underlines that the procurement costs of the devices determine the final cost of the mooring system in harsh environment. The investigations regarding innovative solutions have been completed with a study on solutions for mooring footprint reduction. The use of clump weights and the role of pretension have been investigated. Conclusions show that clump weights consist in a key element for cost reductions. In another study, the benefits of tuning the controller have been underlined in order to extend the lifetime of the mooring systems, through Ki and Kp tunning including nacelle fore-aft velocity. The investigations have been completed with a study for shared anchors and shared mooring lines at farm level. Results point out the suitability of surrogate models for shared mooring lines systems optimizations, as well as the positive impact of such farm design on the frequency modes of the system to potentially reduce the loads. To complete the study, mooring systems optimizations have been performed on multiple floating unit layouts anchored with mooring systems using shared anchors and shared mooring lines. The validation through time-domain simulations shows the suitability of such designs for ULS, and the cost optimization shows that sharing the anchors must be investigated in further studies to include installation costs and refine the spacing between floating units. On the other hand, the results of the study on shared mooring lines are promising, leading to 50% cost reduction mainly because of yaw stiffness increase.

Eventually, additional studies on modelling improvement have been conducted, proposing an accelerated method scales with O(n) cost compared to the O(n2) cost of the double sum method used to get second order wave loads, opening the door towards an improvement of floating offshore wind loads assessment. In another study the effect of second-order wave forcing on the low-frequency modes and response calculation of a wind farm using shared mooring lines were investigated. Results show that second order does not significantly affect mooring line tension, that the surge motion of the platform is increased in a shared configuration compared to a single FOWT and that second order provides larger offsets than first order ones, especially for surge. To complete the studies, an analysis has shown the applicability and benefices of vortex solvers for the loads and energy yield assessment.

Finally, mooring recommendations for floating wind turbines have been extracted from the tank testing results from experimental campaigns focusing on mooring and dynamic cables, conducted in the COCOTSU flume and in the CCOB basin facilities. The experimental testing campaign helped to understand and deepen the mooring dynamics, including line tensions. The mooring system of WindCrete was more strained than that of ActiveFloat, reaching in the main line 1 a maximum tension equal to 816 tonnes in this extreme wind-current-sea state. However, the limit of ActiveFloat was reached for maximum yaw with current, for mean excursion with regular wave with a height of 5.11 m and a period of 7.5 s, as well as for mean and maximum excursion with constant rated wind without or with regular wave and with operational conditions under turbulent rated wind. Eventually, the experiments on marine growth under real marine conditions in the MCTS El Bocal located in the coastal area of Cantabria (North of Spain) showed the efficiencies of different coating on marine growth.

3 INTRODUCTION

3.1 Introduction

Floating offshore wind is still a nascent technology and its LCOE is substantially higher than onshore and bottom-fixed offshore wind, and thus requires to be drastically reduced.

The COREWIND project aims to achieve significant cost reductions and enhance performance of floating wind technology through the research and optimization of mooring and anchoring systems and dynamic cables. These enhancements will be assessed and validated by means of simulations and experimental testing both in the wave basin tanks and the wind tunnel by taking as reference two concrete-based floater concepts (semi-submersible and spar) supporting large wind turbines (15 MW), installed at water depths greater than 100 m and 200 m for the semi-submersible and spar concept, respectively.

Within this project, Work Package 2 (WP2) main objective is to optimize mooring and anchoring systems from both costs and performances perspectives. To do so, several aspects of mooring systems designs have been investigated. A review of the state of the art of mooring and anchoring design was performed, providing up-to-date progress of the industry. This work is summarized in Deliverable D2.1. Following this task, ULS and FLS reliability were assessed for two platforms, WindCrete and ActiveFloat and three reference sites of the COREWIND project, with optimized mooring systems obtained using a new methodology developed as part of the project. In addition, fairlead connections have been designed for these optimized configurations and installation techniques investigations were assessed. The results of these work were addressed in Deliverable D2.2. Eventually, deliverable D2.3 focused on innovative solutions to help decreasing station keeping system costs while improving performances. The report covers peak loads reduction systems utilization, mooring footprint reduction, tunning of the controller to reduce fatigue, and innovative layout such as use of shared anchors and shared mooring lines configurations.

The current report proposes a summary of the work carried during WP2 and addressed in the different reports. In addition, it provides some guidelines and recommendations for further works, based on results obtained on the different topics mentioned earlier. Eventually, it is enhanced with additional topics, such as second order wave loads calculation and wake modelling or a summary of tank tests campaign performed during the project, as those aspects could allow a further costs reduction of mooring and anchoring systems.

Following this introduction, section 4 of this report introduces software solutions and tools used during the projects. It is followed by section 5 summarizing works dedicated to mooring system designs optimization and section 6 summarizes works performed on optimization of interface between moorings and structures. Section 7 offers a summary of improvement performed in system modelling while section 8 aggregates information about installation technique investigations. Eventually section 9 is dedicated to the tank tests campaign performed during the project.

3.2 Objective

The goal of the report is to satisfy task 2.4 as part of the WP2 of the COREWIND project. The objective of this task is diverse. Firstly, it aims at summarizing conclusions from different breakthroughs addressed in Task 2.3, with a focus on capitalizing the impact over ULS or FLS of the different innovations proposed. It also aims at defining design practices and guidelines regarding mooring and anchor design for 15MW turbines, based on works carried as part of WP2.

It is written as a summary of several deliverable, to allow readers to capture main conclusions of the works. Therefore, readers are encouraged to have a look at the other deliverables for more detailed results on the different sections.

4 FOWT MODELING TOOLS SPECIFICATION

The different sections of this report mentioned several software and tools used to design floating offshore wind systems. Hence, this section briefly introduces these tools to facilitate comprehension of other sections.

OrcaFlex

OrcaFlex is a commercial software developed by Orcina, that allows to perform dynamic analyses for offshore marine systems. It is widely used to model mooring systems of floating offshore wind turbines thanks to its versatility and different features. In the project, OrcaFlex 11.1 and 11.2 were used.

OpenFast

FAST code is an opensource code developed by the National Renewable Energy Laboratory (NREL) that allows to model land-based, bottom-fixed offshore and floating offshore wind turbines. FAST offers the possibility to perform a coupled analysis with aero-servo-hydro and elasto modules. Information can be found on NREL website and OpenFast Github [1], [2]. For the project, OpenFast v2.1 and v2.4 have been used.

HAWC2 – MIRAS

As part of the COREWIND project, DTU has investigated methods and designs for shared mooring/anchor designs, accelerated second order wave load calculations, floating wind turbine wakes and shared mooring line optimization. Investigations have been conducted by HAWC2 [3], MIRAS in-house DTU tools and surrogate model codes used in Python language. HAWC2 is an aero-servo-hydro-elastic wind turbine analysis tool and MIRAS is a vortex flow solver. Figure 4-1 shows the disciplines used in HAWC2 for response analysis of different turbine models. HAWC2 uses Blade Element Momentum theory [4] for aerodynamic load calculation. On the other hand it can use external aerodynamic solvers such as MIRAS and EllipSys when high fidelity flow solution is needed.

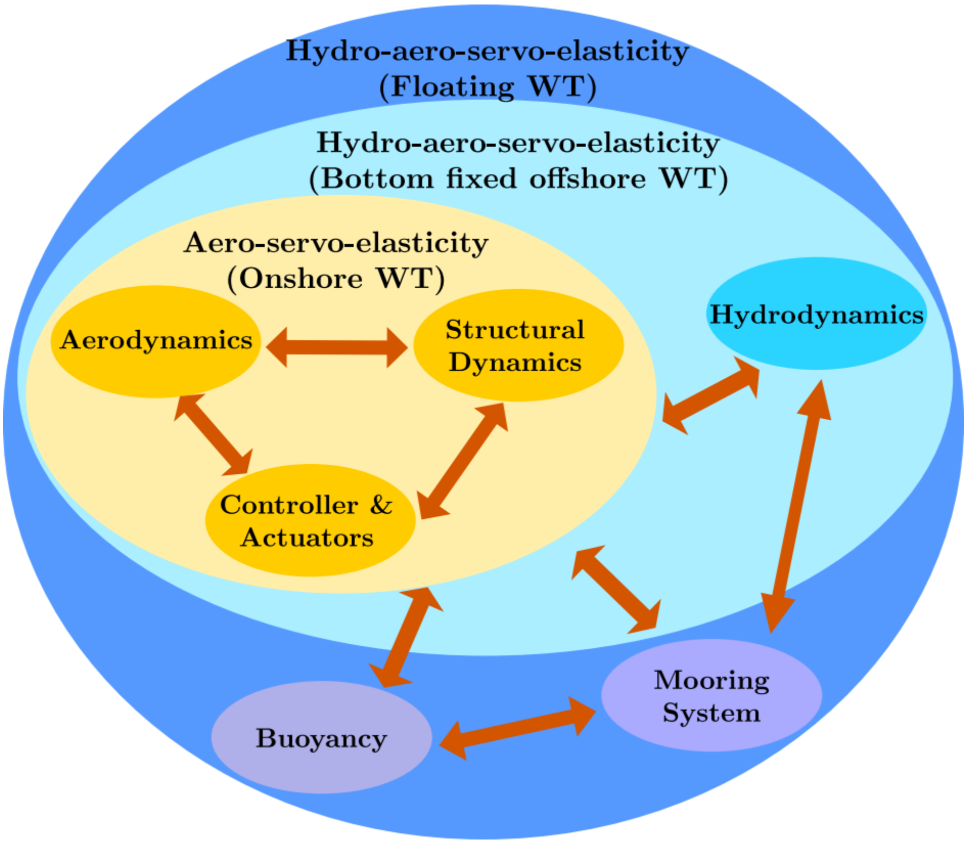


Figure 4-1 Wind turbine load computation sub-modules for different turbine configurations.

MIRAS is a multi-fidelity aerodynamic tool for wind turbine and wake analyses. In the herein presented research, the LL module is used as aerodynamic model, while the hybrid filament-particle-mesh method is used to model the flow. In the LL method, the rotor blades are modelled as discrete filaments, which account for the bound vortex strength and act by releasing vorticity into the flow. This vorticity can be subdivided into trailing vorticity, which is related to span-wise variations of the bound vorticity and shed vorticity, related to time variations of the bound vortex. Figure 4-2Figure 4-1shows flow solution of MIRAS [5].

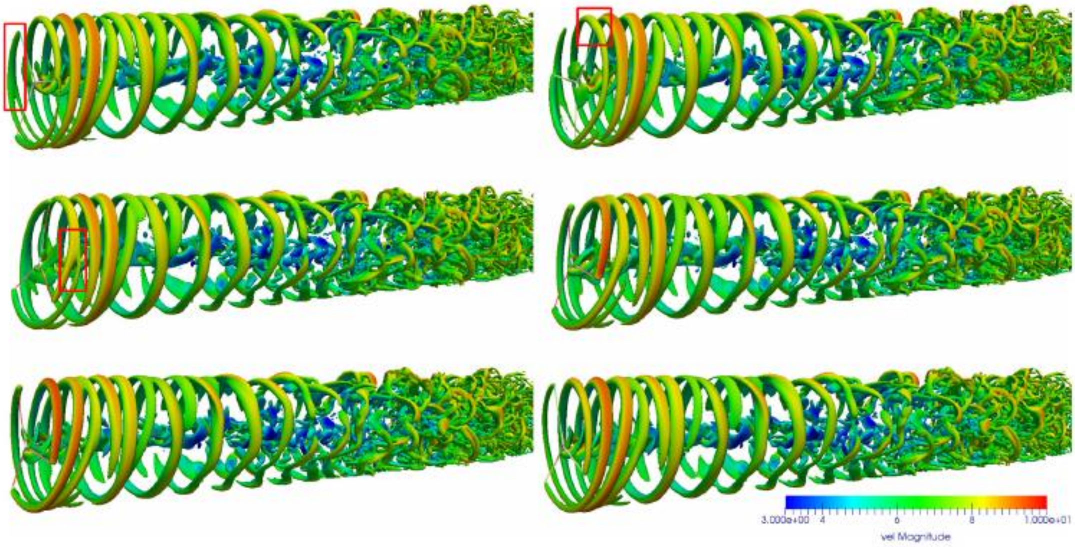


Figure 4-2 Three-dimensional vorticity contours at six selected times over the last cycle of a floater prescribed pitch motion with 6.38# amplitude and a frequency of 0.05676 Hz. From left to right and top to bottom, t1, t2, t3, t4, t5, and t6. Wind speed of 8 m/s [Colour figure can be viewed at wileyonlinelibrary.com]

Brief information about each task done by DTU about method and design investigations are listed in sections 5.6 and 7.

5 MOORING DESIGN

WP2 is dedicated to the optimization of mooring and anchoring systems. This optimization, from a cost and performances point of view, does refer to system optimization, with innovative layout (shared anchors and shared mooring lines) and footprint reduction, material selections or use of peak load reduction systems. It also refers to optimization of systems influencing mooring system behaviour, such as tuning of the turbine controller, or improving design strategy with optimization and autonomous tools development. This section aims at summarizing those works and offer some guidelines.

5.1 Mooring design optimization tool development and application

Mooring systems are key components of a floating offshore wind farm as they ensure maintaining floating offshore platforms within a targeted area. For Tension Leg Platforms (TLPs), the mooring system is even more important as stability relies on it. However, mooring systems design is a long iterative process and site and platform dependent. Designers must satisfy both standard requirements, such as sufficient ratio between design tension and materials minimum breaking loads, and design basis criteria, such as maximum platform motions. This process usually involves several engineers, developing a mooring system before assessing its reliability in both ULS and FLS conditions. Hence, loops are necessarily limited due to schedule and costs constraints. Consequently, costs and performances optimization are usually limited.

Developing automatization tools would therefore help mooring designers to save time and costs, while screening a large range of configurations, converging towards efficient and cheaper mooring systems. As part of the task 2.2 of WP2 of the COREWIND project, INNOSEA has developed such a tool. This section aims at presenting the main capabilities of this tool, hypothesis chosen, and main results obtained during its application as part of the COREWIND project. This work is a summary of detailed results presented in deliverable D2.2. This section also describes how this tool could be improved to help project developers and mooring designers.

Optimization process

Mooring systems are complex systems, composed of several materials (chain, synthetic, wires) and components (buoys, clump weights, etc.) with different properties and costs. Additionally, several layouts can be tested, driven by site conditions (water depth, soil type, environment). Testing all potential combinations is impossible, even for a screening tool, and choices should be made. Time domain analysis, usually required for floating offshore wind turbine design, combined with the number of design load cases to be analyzed, further reduce tested combinations. Hence, it is important to develop an optimization strategy to help the algorithm converging to a solution.

The mooring system design can be seen as a constraint optimization problem, where design parameters would be mooring system parameters, constraints would be the design criteria and cost function, the cost of the mooring system. Mooring system costs include different categories (engineering, procurement, installation, etc.), for which estimation can be complex. For the project, it was decided to focus on procurement costs derived from available data. These costs cover material costs (chain, nylon, polyester), anchors, clump weight and buoys costs. Other components (shackles, connections, fairleads, etc), were neglected at this stage. Installation costs were also neglected though important, because highly dependent on world region, site conditions, platform type, etc.

Regarding mooring parameters, several hypotheses were made, to simplify and accelerate optimization, based on previous experiences.

The mooring layout, which includes system type (either catenary, taut, semi-taut), the number of lines, the pattern and the type of materials is fixed and is not optimized directly by the tool. Impact of materials on system response is therefore analyzed by launching several optimizations.

In addition, the mooring system is split into several groups of lines, a group representing units which will be identical after optimization. This option was implemented to allow asymmetric optimization, when environmental conditions allow it, to reduce costs of less loaded lines.

Eventually for each group, several parameters can be optimized:

- Material's diameters
- Material's section length
- Number of clump weights or buoys if present
- Buoys and clump weights mass and volume if present
- Anchor radius
- Overall line length

At each iteration, several design criteria are also assessed to ensure mooring reliability:

- Platform motions (wrt design basis criteria as defined in [6])
- Turbine acceleration (wrt turbine manufacturer restrictions)
- No vertical loads at anchors (for catenary mooring system)
- Ratio design tension over MBL (standards such as DNV-ST-0119 [7])
- Pretension (if required)
- Minimum yaw stiffness (wrt floater foundation restrictions)

As explained previously, mooring system design requires running thousands of simulations for both ULS and FLS conditions. Additionally, time domain analysis is usually recommended to capture non-linear effects. To perform operational conditions, coupled analysis are required, adding complexity and time needed. However, those cases cannot be run for each configuration on typical analysis machines without increasing drastically computational time. Hence, a simplified approach was used in the project.

First, it was considered that ULS cases lead mooring system design. DLC 6.2 and 6.1 are considered as the most critical ones for mooring design. To perform the optimization, a first batch of simulations is run to identify the worst case among DLC 6.1 and 6.2. This analysis is done in two steps. First, simulations are performed with a fixed wind turbine in OpenFast to obtain aerodynamic loads. Then, these loads are applied as time series in OrcaFlex, to simplify modeling and accelerate time domain analysis. A comparison was carried out between a coupled model and this simplified approach to assess line tensions and floater dynamics, to ensure conservatism. Once selected, the optimization is done on the identified worst case. The analysis time is restricted to 1500sec. Seed and time origin is selected so that maximum wave height is included in the simulation. Both start of life conditions and end of life (including marine growth and corrosion effect) are considered. EOL conditions are usually driving utilization factor parameter and SOL conditions can drive maximum offsets. This trend is obtained because line submerged weight tends to be larger in EOL conditions due to the additional marine growth mass. Corrosion is not considered in the simulation (by reducing line mass) but by considering a minimum breaking load reduction. The full DLC list considered in this study is then run to verify that the case selected for the optimization is the governing one. If required, several loops are done until the correct selected case is used.

Results and discussion

The methodology presented above was used on the two platforms and for two reference sites of the COREWIND project for different classic mooring systems or moorings including peak load reduction systems. In this section, the focus is on classical mooring systems, while peak load reduction systems are detailed here after. For each mooring system obtained, costs were calculated and compared to the initial mooring system developed in the project. In addition, coupled analysis were run for DLC 6.2 and 6.1 to ensure that criteria are respected.

For the reference sites Morro Bay and Gran Canaria, the mooring system obtained was always cheaper than initial mooring system analyzed. For ActiveFloat at West of Barra, the comparison was not done as the initial mooring system did not pass design criteria and the optimization tool was not used. Indeed, West of Barra conditions are particularly harsh ($H_{s,50years} = 15.6, T_p = 16 - 18s, U_{wind,hub} = 50\ m.s^{-1}, U_{current,MSL} = 1.57m.s^{-1}$) and the tool did not find a working configuration. Design was done with a classical approach, and it ended up with 12 lines including nylon ropes.

From that perspective, the tool was efficient as it allows to optimize mooring systems for different type of sites, though it reaches some limits for particularly harsh conditions. The simplified approach used for the screening phase was satisfying, as design was validated later by a coupled analysis, reducing further time needed for the optimization.

Later in the project, fatigue cases were performed to evaluate optimized mooring system reliability over its lifetime. DLC 1.2 was simulated. It was found that for Morro Bay and Gran Canaria, optimized mooring systems did not pass the fatigue criterion. For West of Barra, ULS was driving the design, and FLS criteria were respected. At this stage, it is not possible to provide any guideline regarding case selection for optimization as design could be driven by either FLS or ULS. It seems that ULS will be driving for harsh environment. This topic could be included in a task in a future project, to predict if either ULS or FLS will be driving depending on environmental conditions. This could be done by analyzing energy content in a 50years return period spectrum and assessing both ULS and FLS for different sites.

Recommendations and guideline

Tools such as the one developed as part of the COREWIND project seem to have an important potential. They would allow to screen a large number of configurations, efficiently, allowing a cost reduction of the system and time savings during design phase. Several implementations and improvements could be performed to increase their efficiency. Python libraries offer features that could improve optimization, with different optimization algorithms or the help of artificial intelligence. These tools could potentially help to handle sites with harsh environmental conditions. In addition, the screening process could be improved to allow faster screening of the design space and avoid performing long time domain analysis for each configuration. It could be done in several steps:

- A quasi-static analysis (QSA) with mean wind loads, mean current and mean drift loads
- A dynamic mooring model analysis on the smaller design space obtained from QSA.

In the future, a frequency domain analysis could be added to further reduce design space analyzed in time domain, with tools such as RAFT developed by NREL. Machine learning could also be used to accelerate screening and optimization process with technics allowing tension prediction as investigated by Polytechnic university of Catalonia in [8].Eventually, this project emphasizes how complex and project dependent mooring design is. Depending on the platform type or environmental conditions, the mooring design process could be changed significantly. Hence, it is complicated to draw a generic conclusion or a guideline providing a process to design a mooring.

Further improvements could be achieved by the following mooring design optimization:

- Optimizing several critical DLC in parallel to avoid rerunning optimization several times

- Integration of fatigue DLC in the optimization tool using frequency domain analysis
- Integration of installation cost in the optimization. Tendencies should be available in the conclusions of the COREWIND project.

5.2 ULS and FLS reliability of optimized mooring designs

To verify the ability of the optimized mooring systems designs mentioned above, ULS and FLS checks were carried out for each of the three reference sites of the COREWIND project using the OpenFAST models. The ULS was checked using DLCs 6.1 and 6.2 making sure that at extreme load cases the mooring lines' ultimate loads are below their minimum breaking loads following the DNV-ST-0119 standard [9]. For the FLS check we used DLC 1.2 to check the fatigue loads on the mooring systems. The most probable wind and wave combinations for each wind speed during these simulations. The environmental conditions for these DLCs followed the environmental conditions of the sites as defined for the COREWIND project in Deliverable 1.2 [6]. The details of the ULS and FLS checks and the environmental conditions used were presented in details in deliverable 2.2. A summary of the ULS and FLS results is shown in the tables below.

Sites	Platforms‘ ULS results	
Site A (WoB)	ActiveFloat	
	Passed ULS	
Site B (GC)	ActiveFloat	Windcrete
	Passed ULS	Passed ULS
Site C (MB)	ActiveFloat	Windcrete
	Passed ULS	Passed ULS

Table 5-1 ULS design check DLCs 6.1 and 6.2.

Sites	Platforms‘ FLS results	
Site A (WoB)	ActiveFloat	
	Passed FLS	
Site B (GC)	ActiveFloat	Windcrete
	Didn't pass FLS	Didn't pass FLS
Site C (MB)	ActiveFloat	Windcrete
	Passed FLS	Passed FLS

Table 5-2 FLS design check DLCs 1.2.

The results show that all the optimized designs passed the ULS and FLS checks except for the designs at site B of Gran Canaria. The fatigue load on the Gran Canaria site is more due to the wind low frequency forces rather than the wave forces. Therefore, further wind turbine controller optimization can lead to decreasing the wind loads on the mooring system.

5.3 Peak loads reduction systems

In subtask 2.3.1, the implementation of Peak Loads Reduction systems (PLR systems) has been studied to investigate the potential improvement for the design of mooring systems and to optimize the cost of materials. For that, two PLR systems have been selected, named System 1 and System 2 below. They use different technologies but both act as shock absorbers and have a variable stiffness, having the effect to change the mooring system response and allowing to reduce the size of the mooring lines and anchors thanks to peak loads reduction. These systems have been implemented in the top sections of the mooring systems of WindCrete and ActiveFloat at the sites of West of Barra, Gran Canaria and Morro Bay.

The mooring costs have been calculated using cost functions of System 1 and System 2 shared by the developers of both technologies. Cost functions of the other materials are presented in deliverable D2.3. The total cost of a mooring system is a simple estimation used for comparisons.

The PLR systems have been modelled in OrcaFlex and implemented in the models of the previously optimized mooring systems. Then, developments of the mooring design optimization tool (presented in section 5.1 of this report) have been conducted in order to integrate System 1 and System 2 in the optimized variables of the moorings. Variables implemented were the number of units per mooring line and their physical properties (related to their size).

It has been interesting to look at the results per site location. Indeed, the results have shown a correlation between the benefits of the PLR systems in terms of cost and the site location. More detailed results are presented in deliverable D2.3.

Gran Canaria

At Gran Canaria, for both floaters, the implementations of PLR systems in the mooring helped reducing drastically the peak loads and consequently the cost of the mooring systems. System 1 and System 2 allowed to reduce the peak loads of almost 50% in the mooring of WindCrete, and 25% in the mooring of ActiveFloat. Consequently, the cost of the mooring system was reduced by 11% to 18% in the case of ActiveFloat, and by 27% to 37% in the case of WindCrete. Such cost reductions have been achieved by reducing the chain diameters and grades, as well as the anchor sizes.

Morro Bay

At Morro Bay, the results were not as much promising as for Gran Canaria. Indeed, the large water depth (870 meters) combined with more complex mooring systems, equipped with polyester sections and mooring buoys (to increase the yaw stiffness), has shown that both System 1 and System 2 were not able to reduce the costs of the mooring systems. When attached to the mooring of ActiveFloat on the top parts of the polyester sections, the peak loads were increasing by 11% to 21%. Therefore, no cost reduction was achieved on the mooring for this site and ActiveFloat platform. However, for WindCrete platform, the peak loads were reduced by 2% to 14%, and consequently the total cost of the mooring system was reduced by 6% to 8%.

The following figure is an illustration of the OrcaFlex model of ActiveFloat's mooring system . System 1 and System 2 have been implemented at the top of the polyester sections, just below the mooring buoys. It had the consequence to reduce their buoyancy, resulting in higher yaw angles of the platform. It might also be the cause of having higher peak loads. It could have been compensated by increasing the number or size of mooring buoys, but also increasing the costs. Finally, it can be noted that on this site the water depth is 870m, there is no current and the mooring is a semi-taut. The behaviour of the ActiveFloat platform is hardly exposed to peak loads under these conditions, therefore System 1 and System 2 do not seem to be suitable for ActiveFloat on this site.

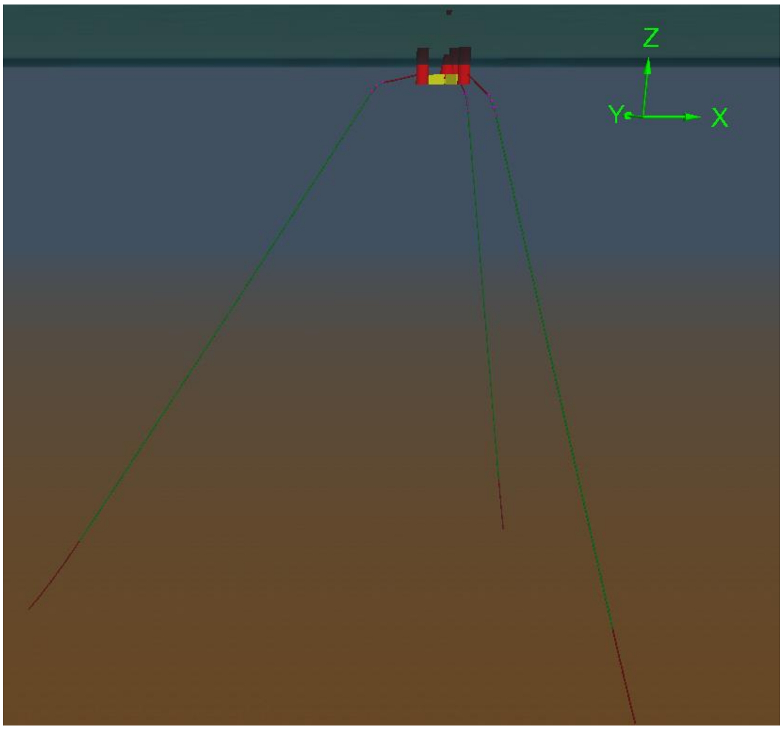


Figure 5-2 OrcaFlex illustration of the mooring system of ActiveFloat at Morro Bay

West of Barra

At West of Barra, the very harsh environment (low water depth of 100 meters combined with extreme weather) made the investigation more complicated. No solution for an adequate mooring system has been found with System 2, and the optimized mooring system equipped with System 1 was 20% more expensive than the initial optimized mooring system. The reason is that twelve mooring lines are needed at this site, so the number of System 1 units is very important, increasing drastically the total cost of the mooring system. The mooring system equipped with System 2 was not able to respect the maximum offset criteria. Indeed, attaching System 2 to the mooring lines had the effect to increase the surge motion of the platform. The following figure is an illustration of the top sections of the mooring lines equipped with PLR systems, in the OrcaFlex model.

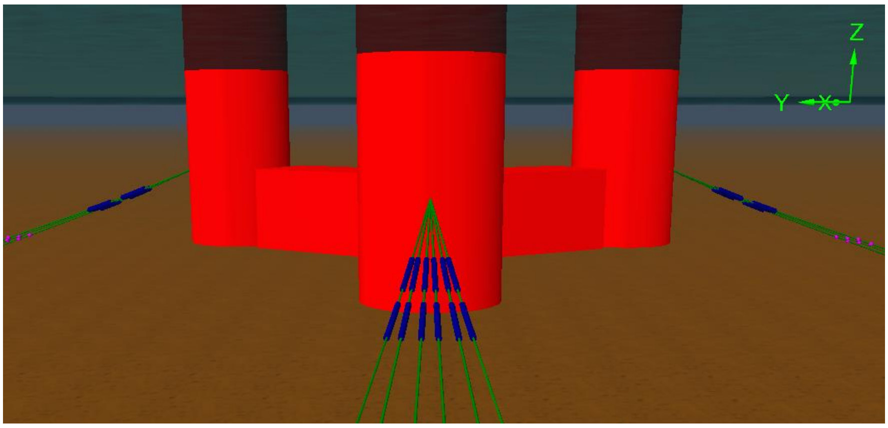


Figure 5-3 OrcaFlex illustration of the PLR systems attached to the mooring lines of ActiveFloat at WoB

Finally, a quick sensitivity analysis has been performed in order to investigate the potential benefits of the considered PLR systems on the lifetime of the mooring of ActiveFloat site B (Gran Canaria). Unfortunately, the results were not satisfying in terms of improvement. More details are given in the section 6.5 of deliverable D2.3.

5.4 Innovations on decreasing mooring footprint

To achieve cost-effective deployment of floating offshore wind farms, it is of economic and environmental importance to optimize the mooring systems of assembled Floating Offshore Wind Turbines (FOWTs). As mooring costs represent a significant part of the capital expenditures (CAPEX) of a floating wind farm, it is essential to reduce the mooring cost through optimization of mooring system design. Mooring footprint is a key indicator of a feasible mooring system design, as it determines the spatial interface among neighbouring FOWTs and has a considerable impact on CAPEX. Currently, the research of mooring system of a FOWT focuses on the analysis of mooring layout to maintain stability of the floater [[10][11][12]] and the investigation of mooring line property on motions of the floater [[13][14]], few studies cover a dynamic analysis of FOWTs to reduce mooring footprint.

The objective of this task is a first step to innovative mooring systems, namely an optimized application of the clump weights, as shown in **Figure 5-4**. It is intended to assess the feasibility of innovative mooring systems to reduce mooring footprint and mooring cost of a FOWT. These mentioned design elements are commonly utilized in offshore engineering and the existence of these elements can affect directly profiles and tension distributions of the mooring system. Hence, it is important to make use of these design elements derived from oil and gas industry and to adapt the applications for the dynamic characteristics of FOWTs.

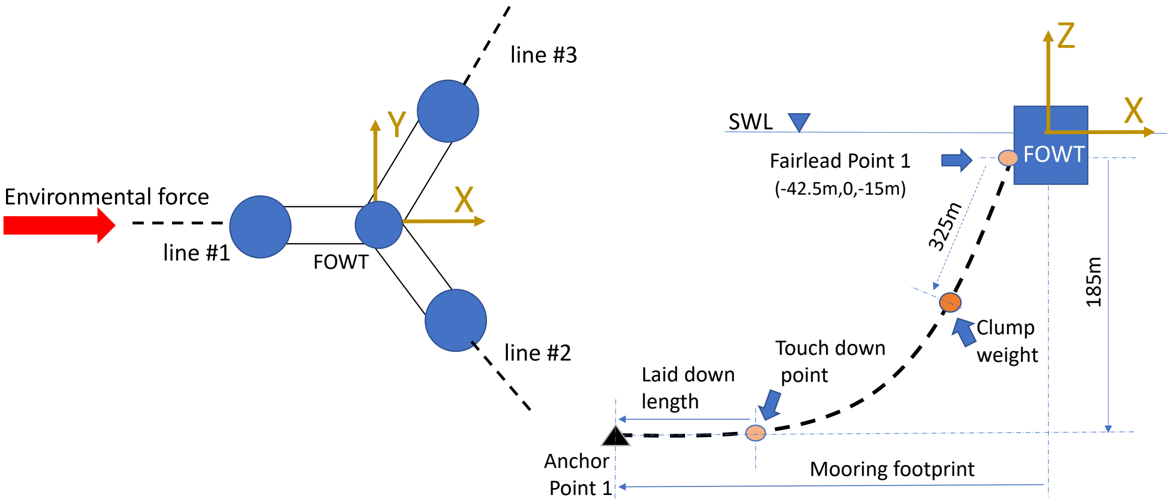
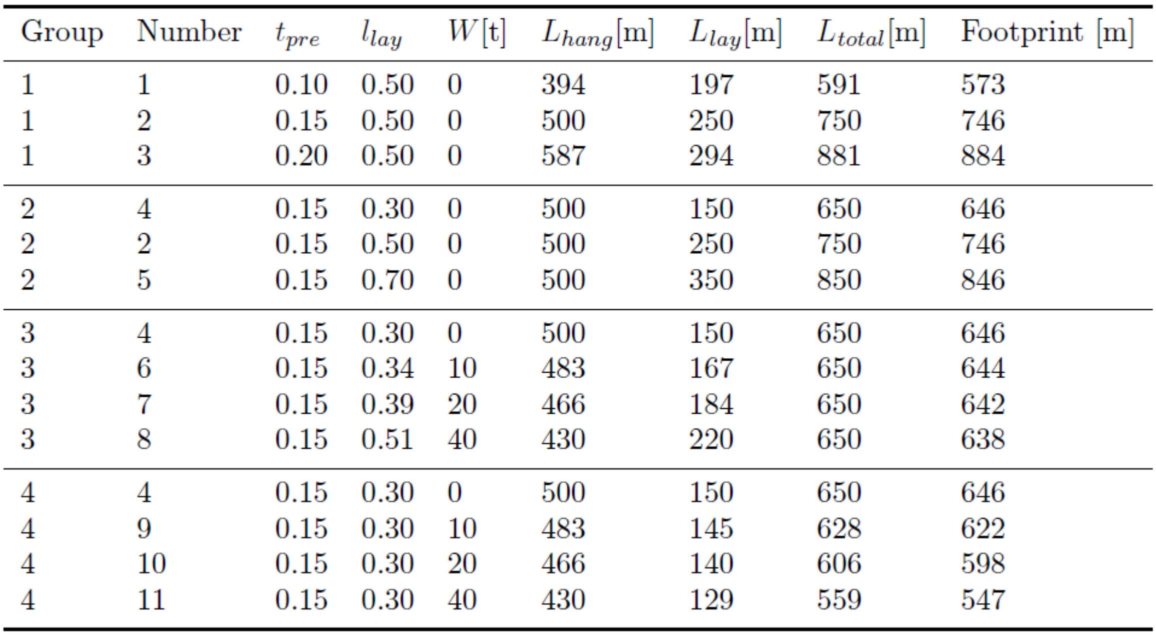


Figure 5-4 The layout of the mooring system for the floating offshore wind turbine with clamp weights

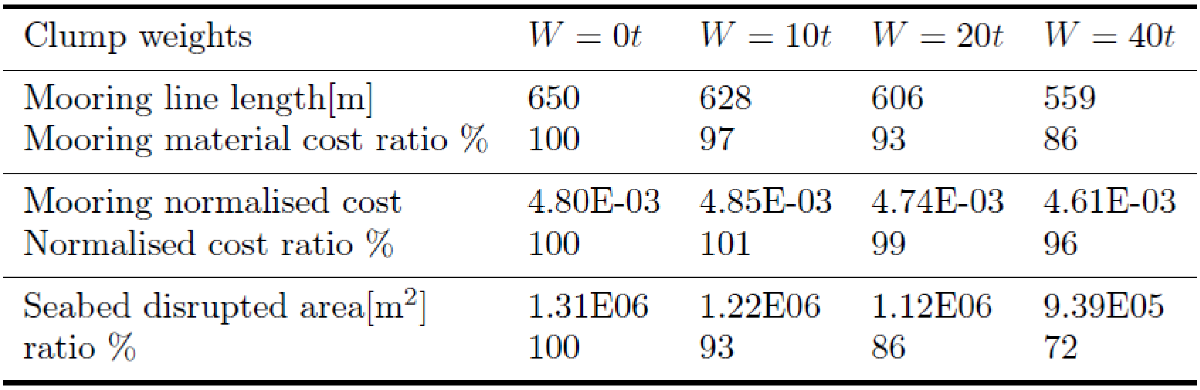
The methodology applied in this task includes dynamic analyses of FOWTs to investigate the effect of different mooring designs on mooring footprint and fatigue damage. First, a preliminary design of a 15 MW floating wind turbine from COREWIND is introduced for numerical simulations. The hydrodynamic properties of the floater are calculated in ANSYS. Second, integrated analyses are simulated in OpenFast to determine the dynamic responses of wind turbine, floater and mooring system. A design space of mooring system is explored to generate different mooring configurations, listed in Table 1. Parametric studies of three design elements (mooring pretension, laid-down length and clump weight) are carried out to investigate their impact on ultimate mooring loads and global performances of FOWT.



Group	Number	t_{pre}	l_{lay}	W[t]	L_{hang}[m]	L_{lay}[m]	L_{total}[m]	Footprint [m]
1	1	0.10	0.50	0	394	197	591	573
1	2	0.15	0.50	0	500	250	750	746
1	3	0.20	0.50	0	587	294	881	884
2	4	0.15	0.30	0	500	150	650	646
2	2	0.15	0.50	0	500	250	750	746
2	5	0.15	0.70	0	500	350	850	846
3	4	0.15	0.30	0	500	150	650	646
3	6	0.15	0.34	10	483	167	650	644
3	7	0.15	0.39	20	466	184	650	642
3	8	0.15	0.51	40	430	220	650	638
4	4	0.15	0.30	0	500	150	650	646
4	9	0.15	0.30	10	483	145	628	622
4	10	0.15	0.30	20	466	140	606	598
4	11	0.15	0.30	40	430	129	559	547

Table 5-1 Design space of mooring configuration

In addition, fatigue analysis of the mooring system is performed, the rainflow counting method is used and linear damage accumulation is considered for fatigue damage calculations. Variations of fatigue life reflect the trade-offs of various design parameters. For the mooring configuration with 40t of clump weights, the fatigue damage rises by 12% compared to the one without clump weights. Finally, a simplified cost function model is set up to evaluate the calculated mooring footprint and its impact on the CAPEX.



Clump weights	$W = 0t$	$W = 10t$	$W = 20t$	$W = 40t$
Mooring line length[m]	650	628	606	559
Mooring material cost ratio %	100	97	93	86
Mooring normalised cost	4.80E-03	4.85E-03	4.74E-03	4.61E-03
Normalised cost ratio %	100	101	99	96
Seabed disrupted area[m^2]	1.31E06	1.22E06	1.12E06	9.39E05
ratio %	100	93	86	72

Table 5-2 Cost comparisons of mooring configurations in Group 4

Quantitative evaluations of changes in mooring footprint and potential CAPEX are demonstrated in this task, and it is found that mooring pretension plays a dominate role in mooring footprint, and that adding clump weights is beneficial for the cost reduction. This task will serve as a basis for further work on mooring line innovations in the COREWIND project and provide an optimization method for the mooring system design for FOWTs.

5.5 Controller tunning

Within task 2.3, USTUTT analysed the effect of the FOWT turbine's controller on the mooring system fatigue loads. Blade pitch controller has been tuned in the above rated wind region, by changing the integral K_i and the proportional gains K_p. For this investigation the optimized mooring system for Gran Canaria site coupled to the Activefloat platform was used. The tuning was done by iterating over different combinations of controller gains values to decrease the fatigue loads on the mooring lines. The following figure shows the effect of tuning the controller gains on the mooring lines fatigue. As shown the tuning decreased the fatigue of the upwind line carrying most of the loads by up to 6%, while the two other lines have a small change in their fatigue loads.

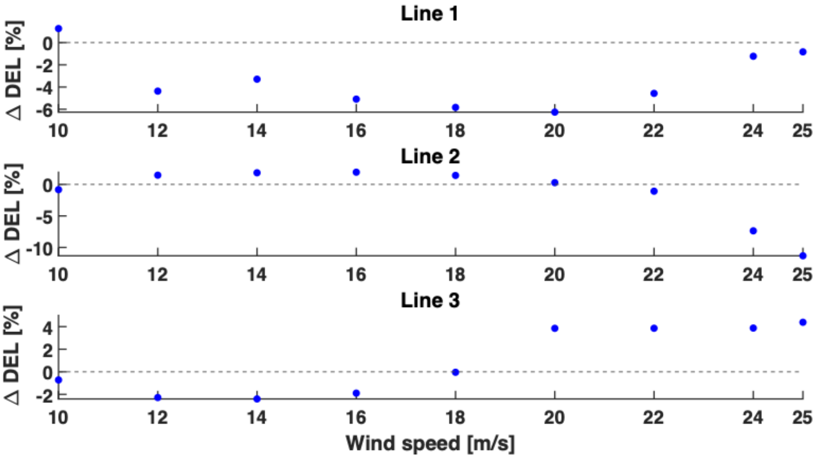


Figure 5-5 Percentage change in the mean mooring line DEL over different wind speeds for tuned $\mathbf{K_p}$ and $\mathbf{K_i}$ curves.

Another approach presented is not only based on the tuning of K_p and K_i but facilitates an additional function of the controller. The fore-aft velocity of the nacelle is measured, filtered, multiplied with a gain $K_{p,float}$ and then added on the output of the PI controller. The results can be shown in the figure below, and again we can see a decrease of the fatigue loads on the upwind line and almost no change on the two downwind mooring lines.

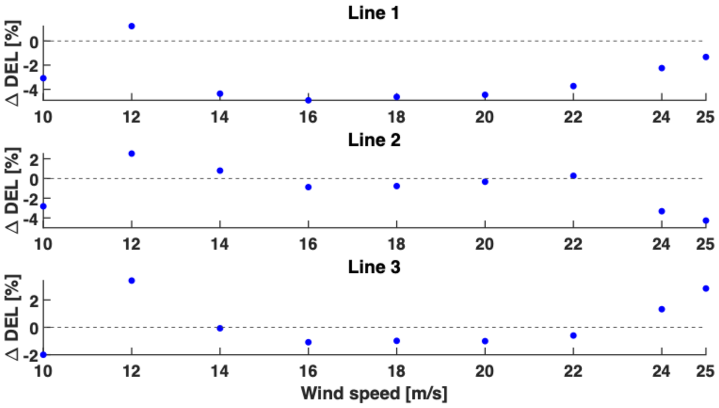


Figure 5-6 Percentage change in the mean mooring line DEL over different wind speeds for Floating Feedback control strategy.

The results show that there is a relationship between the mooring system and the controller tuning and open up the door for future work to be done carrying out a thorough investigation. The goal of the future work should be to include the mooring lines fatigue as part of the controller tuning process to decrease the fatigue loads on the mooring system.

5.6 Shared anchors and shared mooring lines

OrcaFlex investigations

In subtask 2.3.4, innovative mooring systems, such as shared anchor and shared mooring lines, were studied. A display of these configurations can be seen on Figure 5-7 and Figure 5-8. The study has been carried out on both a technical and economic point of view, for ActiveFloat platform only. The main objective of this analysis is to study the possibility of economic reductions induced by the decreasing number of anchors. ULS criteria have been investigated, but no FLS analysis has been conducted.

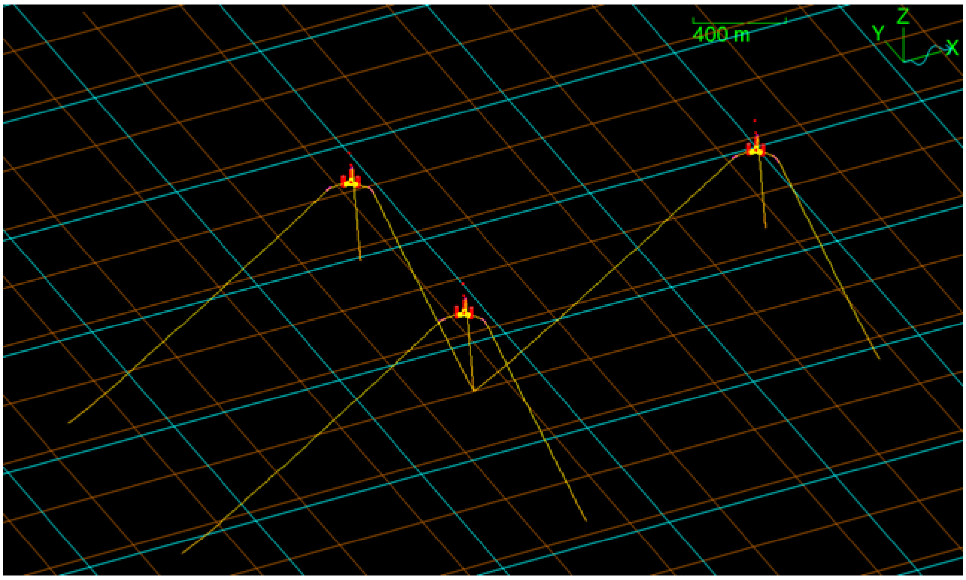


Figure 5-7 - Shared anchor configuration visualisation

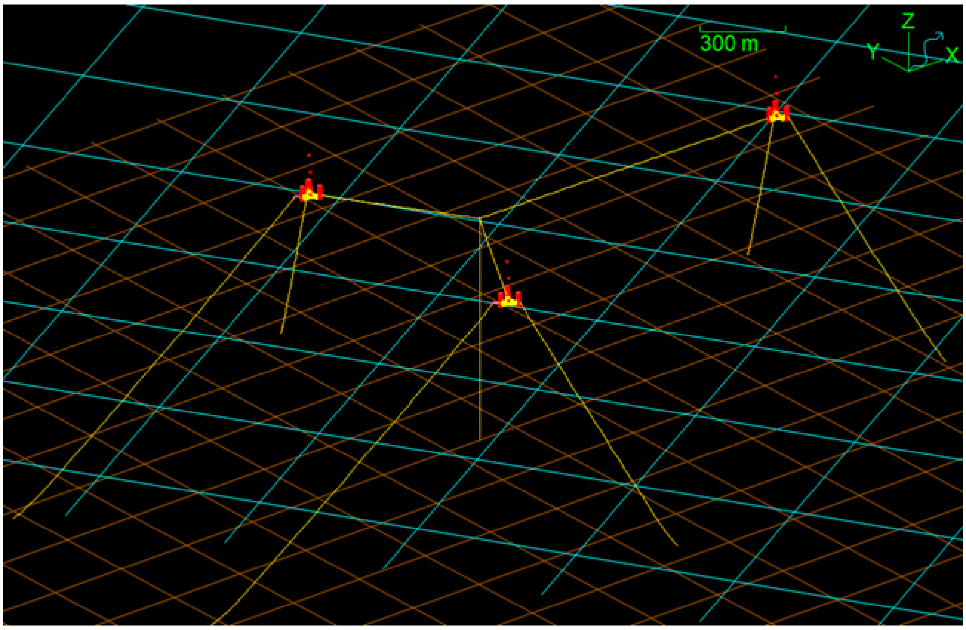


Figure 5-8 Shared mooring lines configuration visualisation

Shared Anchor

A shared anchor layout corresponds to a configuration where three wind turbines are linked to a common anchor. The mooring considered is either a catenary mooring (Gran Canaria) fully made of chain, or a semi taut mooring (Morro Bay), composed of both chain and polyester sections. Geometric constraints (spacing between the turbines) have been considered in order to reduce wake effect interaction between turbines, which reduces turbines efficiency. A techno-economical optimization has been carried out using the optimization tool presented in section 5.1. Shared anchor cost was estimated by taking into account the multidirectional loads applied on the anchor (Other procurement costs were estimated as per [15]).

Results showed that shared anchor layouts were technically feasible for both sites, but did not induce cost reductions relatively to the optimized layouts presented in [16]. Indeed, line lengths had to be increased in order to respect the geometric requirements, thereby counterbalancing the savings due to the decreasing number of anchors. Nevertheless, installation costs have not been taken into account, and are expected to decrease in shared anchor configurations. For more details, please see Section 9.1 of D2.3[16]. It could also be conceivable to choose a thinner chain for the section of the line that will always remain on the seabed, as its tension is inferior to the tension in the dynamic part of the line. Further studies could focus on the design of these laying sections in order to optimize even more the mooring system.

Shared Mooring Lines

A shared mooring line configuration corresponds to a configuration where the three turbines are linked to a common central buoy. This buoy is then anchored to the seabed via a vertical line. This layout have only been investigated on Morro Bay, with the same geometric constraints as described in the previous section. The optimization tool has not been used, because not suitable with shared mooring lines layout.

Results showed that such layouts were technically feasible. Moreover, it has been shown that it could reduce the cost of the optimized layouts by almost 50%. This is explained by the fact that the shared lines enable to reach important mooring yaw stiffness without using as much buoys as for the previous mooring. The reduced number of anchors added to the reduced number of buoys compensate the increasing line length needed to respect spacing criteria. Moreover, an ALS study showed that no domino effect was expected after a shared line failure. In other words, even if important yaw and surge motions were observed, tensions in the remaining lines were still respecting the criteria. Finally, a modal analysis indicated that the system formed by the three turbines could have mode frequencies in the waves frequencies range of the site, but not in the 1P region of the turbine. For more details, please see Section 9.2 of D2.3

Several aspects could be considered to decrease the costs further. As mentioned above, installation costs should be considered. More advanced studies on wake effect could lead to a decrease in the spacing required between the turbines, and consequently in line length. Nevertheless, fatigue should be taken into account as it has been proven to be a driving parameter for the design. Finally, practical aspects such as accessibility and maneuverability around the turbines shall be considered for shared mooring lines layouts, as the lines are relatively close to the sea surface.

It should also be kept in mind that those results are site/floater specific (50% of decrease in cost for shared mooring lines because the initial mooring used buoys), and generalities cannot be driven easily. Finally, it should be noted that the possibility of using such layouts with a spar platform (WindCrete) has not been studied.

HAWC2 investigations

DTU has also perform several investigations on shared mooring lines and anchors. The studies have been performed on HAWC2 software. The main conclusions of those studies are outlined below:

One shared mooring line connected directly between two floating turbines

A shared mooring line design with two turbines in Grand Canaria site and the effect of shared mooring line length were investigated. The models are generated in HAWC2 and natural frequencies and corresponding modeshapes of the designs with different length of shared mooring lines were computed and compared. The model has catenary type mooring lines for 200 meters water depth. For more details please see Section-4 in "D1.4 Methods for multiple floaters and dynamic cables at farm level". Figure 5-9 shows the investigated designs and Line-1 length as design parameter in the study [17]. Results showed that the mooring line forces become very large compared to the original single turbine design if similar natural frequencies are obtained with short shared mooring line.

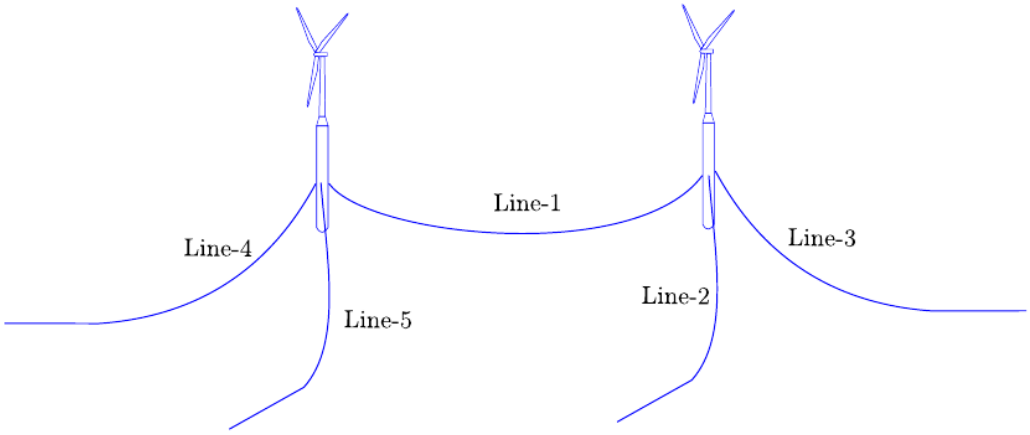


Figure 5-9 Shared mooring line design for Grand Canaria site

One shared anchor with a vertical mooring line which is next connected to two floating turbines

Designs with a shared anchor with vertical mooring lines and buoyancy elements were investigated. Designs have taut mooring lines in Morro Bay site which has deep water with 870 m. Additional to the HAWC2 calculated natural frequencies, a simple method was developed to estimate the frequencies of designs with taut mooring lines as an independent check. Its results are very accurate when compared to HAWC2 results for single turbine design. Designs with 2 turbines have $\sqrt{2}$ times lower first frequency than the single turbine design when the intersection point moves with the turbines in symmetric surge motion. This frequency can be increased by adjusting the mooring line lengths and buoyancy forces. On the other hand, these changes introduce coupling between surge and sway motion. Figure 5-10 shows shared anchor design for Morro Bay [17]. For more details please see Section-5 in “D1.4 Methods for multiple floaters and dynamic cables at farm level”

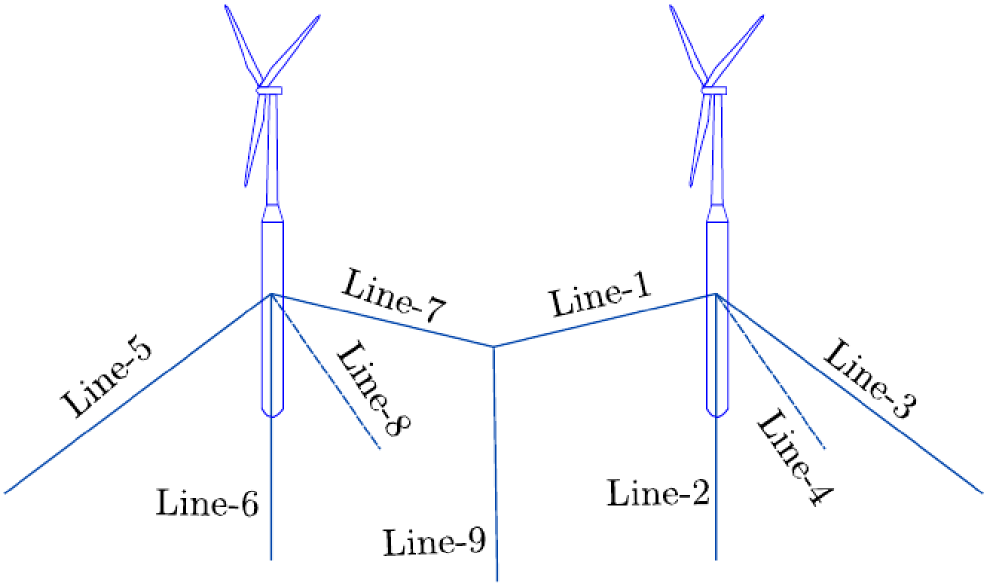


Figure 5-10 Two turbines with shared anchor point in Morro Bay

A four-turbine farm, where the turbines pair-wise share an anchor between them

Four turbine design with shared anchor points was also investigated by computing the equilibrium point and natural frequencies. The design was done for Morro Bay with taut mooring lines. Figure 5-11 shows the design which includes 20 lines. Results show that there are many symmetric and unsymmetric mode shapes for this system and the complexity of the system increases exponentially with the number of turbines. For more details please see Section-6 in “D1.4 Methods for multiple floaters and dynamic cables at farm level”.

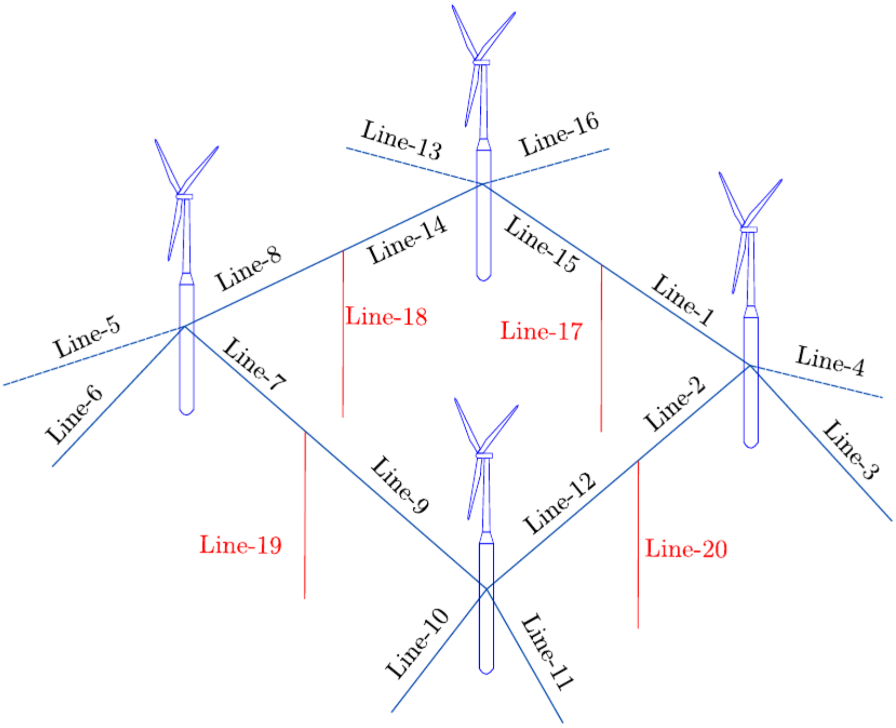


Figure 5-11 Four turbines with shared anchor point in Morro Bay

The shared mooring line design optimization by means of a surrogate model in Morro Bay site

The shared mooring line design optimization by means of a surrogate model in Morro Bay site was studied. Optimization of shared mooring line was carried out with one design parameter. The surrogate model was generated using HAWC2 simulation results where equilibrium points and response analyses were performed for Morro Bay shared anchor design with 2 turbines. Results show that surrogate model is very accurate and suitable for optimization. Figure 5-12 shows the mooring line tension forces at equilibrium for Morro Bay design (see Figure 5-10). The optimization results in the optimum design with 11.08 meters shorter shared mooring line length than the original design. The study showed that the surrogate model approach is suitable for optimization of shared mooring lines, therefore it can also be used with multiple design parameters in the future for optimization of shared mooring lines.

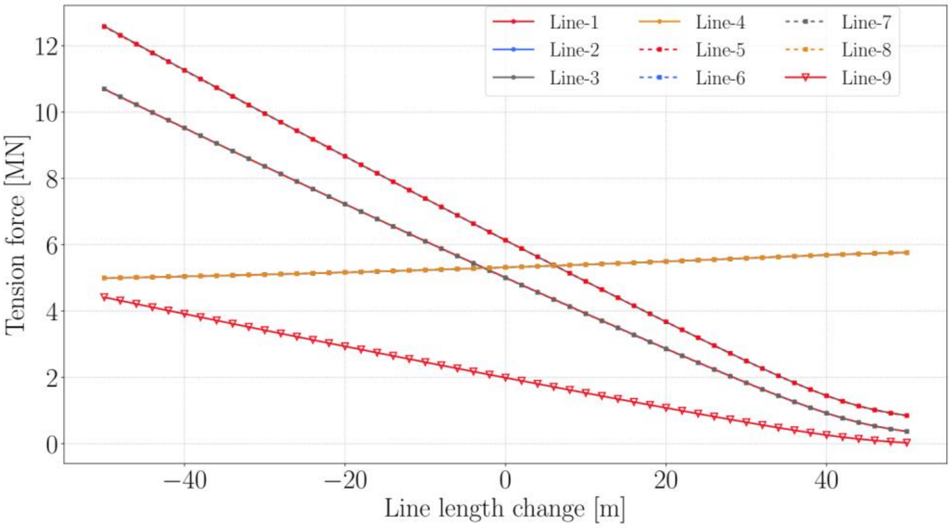


Figure 5-12 Mooring line tension forces for different lengths of shared mooring lines

6 INTERFACE MOORING AND STRUCTURE

Mooring connections to concrete structures were studied and designed in task 2.2.4 for the WindCrete and ActiveFloat designs. These connections are designed to ensure a significant contribution to the de-risking of this particular weak points. Connections are always a very sensitive aspect of any new design. These new designs are stiff, and make compatible the concrete floater with the moorings, assuring a good performance of both.

Detailed analyses using FEM and strut and tie models were applied to assess ultimate, serviceability and fatigue limit states (ULS, SLS and FLS). Moreover, a detailed structural analysis was performed to ensure the correct transmission of mooring loads to the concrete structure and the design of the local strengthening which is required. We further found that the SLS in DLC16 is the driving case for designing the local strengthening in the concrete wall in order to ensure the minimum compression for the water-tightness requirement of the wall. On the other hand, the number and location of the post-tensioning bars required are governed by ULS design against shear and traction mooring loads.

The connection element consists of a steel anchor plate connected to the concrete wall by means of post-tensioning bars. The fairlead is welded to the anchor plate through the two vertical and the two horizontal padeyes. The padeyes are used to place the horizontal and vertical shafts that allows the alignment of the anchor point with the mooring line loads by the rotation in horizontal and vertical direction. Moreover, the padeyes act as plate stiffeners reducing the deformations due to external loads. Figure 6-1 shows a typical fairlead that allows vertical and horizontal rotations, and the base plate.

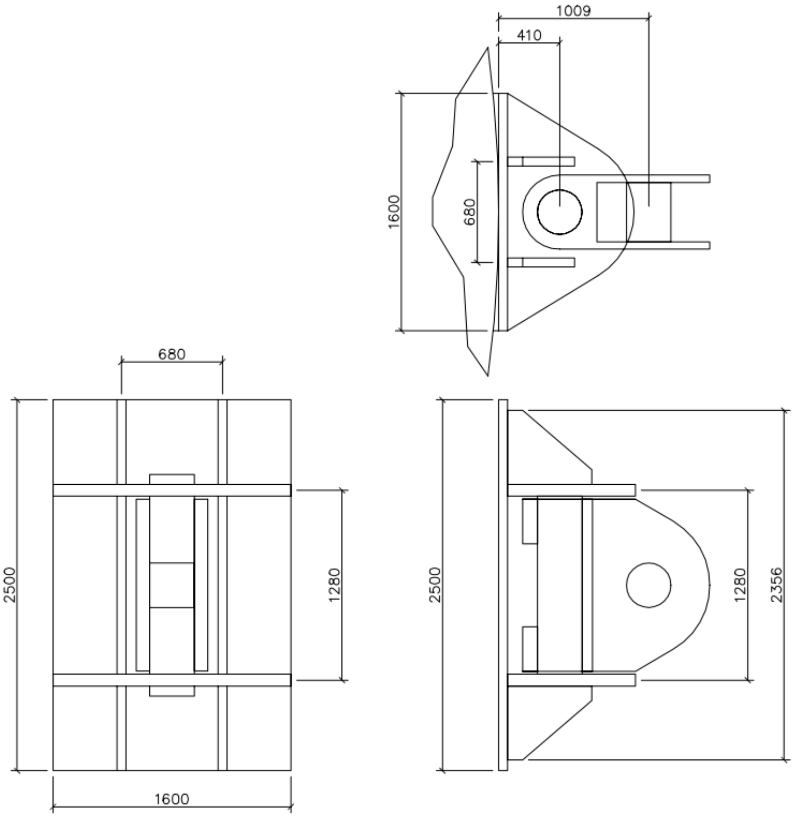


Figure 6-1 – Fairlead proposed for Activefloat. General arrangement

Codes, Standards and Reference documents

The standards used for these designs are in the following list.

- General leading codes:
    - DNV-ST-0119: Floating wind turbine structures
    - DNV-ST-0126: Support structures for wind turbines
    - DNV-ST-0437: Loads and site conditions for wind turbines
    - IEC TS 61400-3-2 Wind energy generation systems - Part 3-2: Design requirements for floating offshore wind turbines
- Structural Design:
    - DNV-ST-C502: Offshore concrete structures
    - EN 1992: Eurocode 2: Design of concrete structures
    - EN 1993: Eurocode 3: Design of steel structures
    - Model Code 2010
- Mooring Design
    - DNV-OS-E301: Position Mooring
    - DNV-RP-C103: Column-stabilised units

Design Basis

Design load cases

DNV requirements are employed for the design loads and load directions of support structures for mooring equipment. Two main design load conditions are specified (1 and 2). However, last update of DNV-ST-0119 on June 2022, presents some new considerations regarding design load cases for connection points.

1. The support structure influenced by mooring forces shall withstand forces equivalent to 1.25 times the breaking strength of any individual mooring line, considering the most unfavourable operational direction of the anchor line. The following equation presents the calculation of the design load $F_{d,w1}$ resulting from this requirement.

   $$F_{d,w1} = F_B \gamma_f$$

   where F_B is the characteristic breaking strength of one mooring line and $\gamma_f = 1.25$ is the load factor. In this case, the material factor for design of all affected structural components is considered as $\gamma_M = 1$.

2. The design of all structural elements influenced by mooring forces shall consider relevant loads resulting from mooring analysis.

   The relevant load combinations for this design condition were selected in accordance with DNV-ST-0437 section 4.8.2 **Source spécifiée non valide.**, which specifies the minimum design load cases (DLC) to be considered for an extreme load analysis as DLC 1.1, DLC 1.3, DLC 6.1 and DLC 6.2. However, CoreWind D1.2 [6] identified DLC 1.6 to represent a more demanding design event than DLC 1.1 and DLC 1.3 and therefore, it was considered for the design in detriment of the two latter combinations. The DLCs analyzed in the design process are described below.

   DLC 1.6: Considers a severe sea state (SSS) for a turbine in operation and connected to the electrical grid, with an active control system. A normal turbulence model (NTM) is specified for wind and a normal current model (NCM) for current loads. Wind and wave loads are assumed to be co-directional.

DLC 6.1: Parked turbine with rotor in idling conditions. Considers an extreme turbulence model (ETM) in the case of offshore turbines, in combination with a stochastic wave model with a wind-wave misalignment of ± 30 deg. Involves an average oblique inflow of ± 8 deg.

DLC 6.2: Similar to the DLC 6.1, models a parked turbine with rotor in idling conditions and considers an extreme turbulence model (ETM) in the case of offshore turbines. The difference between these two cases is that DLC 6.2 accounts for the possibility of a grid failure in an early stage of the storm with the extreme wind situation, specifying a yaw error of up to ± 180° if no independent power supply is available.

3. DNV-ST-0119 (June 2022) [7.1.9.1] states that designing these elements to resist a force close to the minimum breaking load of the connected lines might be excessively conservative in the case of offshore platforms because its design may be governed by the fatigue assessment and corrosion allowance of the mooring itself. Therefore, the alternative is to design the connection based on the design tension of mooring lines (Td). Nevertheless, notice that DNV-ST-0119 requires some additional DLCs for floating wind turbines, in particular special attention to the DLC 6.6 for ALS robustness check should be paid (500 yr of RP for wind or wave loads).

Load factors

DNV-ST-0119 **Source spécifiée non valide.** table 5.1 specifies the following load factors for ULS combinations.

Table 6-1: General load factors

Limit state	G	Q	E	D	P
ULS a	1.25	1.25	0.7	1.0	0.9/1.1
ULS b	1.0	1.0	1.35/1.55	1.0	0.9/1.1

where *G* stands for permanent loads (mass of structure, mass of permanent ballast, hydrostatic pressure), *Q* represents variable functional loads (actuation loads, loads on access platforms, boat impacts from service vessels due to normal operation, crane loads), *E* represents environmental loads (wind loads, hydrodynamic loads, earthquake loads, tidal effects, snow and ice loads), *D* are deformation loads and *P* corresponds to prestress loads.

Design Requirements

The design requirements applied for the design of the anchor point are summarized and described following:

- **Water-tightness**

DNV-ST-0119 section 7.5.3 establishes that elements whose water-tightness is key to ensure floatability of the structure shall be designed with a minimum compressive stress of 0.5 MPa over the entire cross section for SLS combinations.

- **Stress limitation**

DNV-ST-0126 section 5.8.4 defines the compressive stress limit for prestressed concrete structures under characteristic extreme load combinations (SLS) to $0.6\ f_{ck}$ for design according to EN-1992-1-1, and $0.45\ f_{ck}$ under permanent loads. Additionally, the strain in the reinforcement under characteristic extreme loads is restricted to that corresponding to a stress equal to $0.9\ f_{yk}$.

- **Non-decompression in the contact between concrete and the Plate**

Stress concentration at tendons may occur if contact decompressions appear between the plate and the concrete wall. This stress concentration will increase significantly the stress amplitude in the posttensioned bars across the decompressed zone, hugely reducing its fatigue capacity. Then, contact decompressions in SLS must be avoided to ensure adequate posttensioned bars fatigue resistance.

- **Contact decompressions**

Isolated contact decompressions between the plate and the concrete wall will increase the traction on the posttensioned bars. Decompressions are allowed only in ULS. However, non-Linear analysis must be applied in order to check the traction increase on the bars, as well as, the reduction of the friction force against the shear forces, as any sliding has to be prevented.

- **Shear forces**

Friction between the plate and the concrete wall is the responsible of the shear force capacity of the connection. The friction force must be large enough to hold the plate under the shear forces in ULS accounting both factored forces coming from the mooring: tension, perpendicular to the wall, and shear, tangent to the wall.

Design characteristics

A key factor on the design of the mooring connections is the distance of the hinges to the base plate, which will define the eccentricities of the mooring forces and, therefore, the moments that influence the design as shown in Figure 6-2.

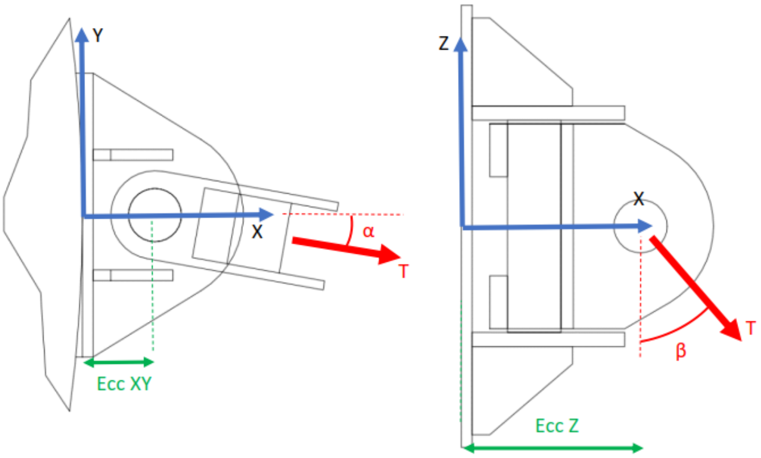


Figure 6-2 – Free rotations and eccentricities of the fairlead proposed for Activefloat.

It is worth noting that the need of clearance space between the vertical shaft and the plate, with the minimum eccentricity of the fairlead, makes that any post-tensioning bar cannot be installed within the padeyes stiffeners, as shown in Figure 6-3.

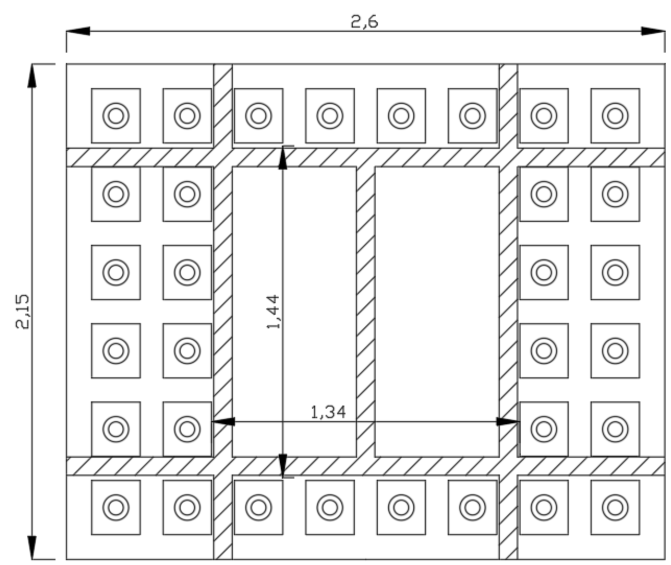


Figure 6-3: WindCrete fairlead anchor plate basic scheme with 32 posttensioned bars

7 SECOND ORDER WAVE LOADS AND WAKE INVESTIGATION

Mooring systems optimization goes with improving comprehension of phenomenon driving and influencing the design, and by improving their modeling either by a better estimation or a better computational efficiency. This section summarizes work by DTU on second order wave loads and wake effect.

An accelerated method for evaluation of second-order wave loads from Quadratic Transfer Function (QTF)

An accelerated method for inviscid second order wave loads is presented based on QTFs determined by a potential flow panel code. The accuracy and efficiency of the method is tested by simulating the loads of mild and severe sea states on the WindCrete spar-buoy floater. The method is implemented in FORTRAN as part of the HAWC2 software and in Matlab, to be included in Matlab based optimizers. The accelerated method scales with O(n) cost compared to the O(n2) cost of the double sum method. When using 8 modes the error of the accelerated method is below 5% in the translational degrees of freedom and around 18% for roll and pitch. When 30 modes are used the error drops below 1% for all degrees of freedom. The method is suitable for use as part of software that uses simplified models for the response calculation, e.g. optimization tools. It then provides good accuracy with a decreased cost. For more details please see Section-2 in "D1.5 Methods for nonlinear wave forcing and wakes".

The effect of second-order wave forcing on the low-frequency modes and response calculation for a farm with shared mooring line in HAWC2

The capabilities of HAWC2 in simulating floating wind turbine farms with shared mooring, under turbulent wind and irregular waves including second order wave loads, are presented using a two turbine design with a shared anchor in Morro Bay. The DLC61 is selected as case study to investigate the effect of second order waves on the response of the farm. We also compared the response of the individually moored turbine to the response of the two turbine design. For more details please see Section-3 in "D1.5 Methods for nonlinear wave forcing and wakes". Important conclusions from the investigation has shown that:

- The second order wave loads do not have a significant effect on the mooring line loads both for the single and the two turbine design. This could be attributed to the taut mooring line design that is less sensitive to wave drift loads.
- The surge motion of the shared mooring design is significantly larger compared to the individually moored turbine. As a result, the maximum mooring line force is increased by 21%.
- The second order hydrodynamic model gives larger surge motions than the first order hydrodynamic model for both designs. However, second order wave load effects are not as large as in the surge direction for the floater motions in other directions. See Table 7-1 for maximum and minimum values for floater motions with first order and second order wave loads.

	Single-F		Single-S		Shared-F		Shared-S	
	max.	min.	max.	min.	max.	min.	max.	min.
Surge [m]	8.22	-5.32	8.51	-5.68	10.82	-4.03	11.41	-4.48
Sway [m]	9.19	-7.91	9.08	-7.77	8.09	-9.36	8.07	-9.39
Heave [m]	6.94	-4.64	7.14	-4.02	5.99	-4.98	6.66	-4.45
Pitch [deg.]	3.79	-2.58	4.34	-2.83	3.52	-2.38	3.89	-2.80
Roll [deg.]	5.07	-4.36	4.91	-4.42	4.11	-3.89	4.04	- 3.89
Yaw [deg.]	3.67	-3.79	3.54	-4.05	3.32	-3.17	3.42	-3.23

Table 7-1 Maximum and minimum floater motions for both designs with two different hydrodynamic models. The maximum and minimum values are selected among the all time series result

Response analysis of floating wind turbines with Miras – HAWC2 coupling

A detailed investigation of the floating IEA Wind 15 MW [18] reference wind turbine and its wake has been carried out under a large variety of conditions. The main numerical approach relied on the in- house multi-fidelity vortex solver MIRAS, equipped with a Lifting Line (LL)) aerodynamic model and coupled with the multi-body finite-element solver HAWC2. The turbine behaviour predicted by the MIRAS-HAWC2 coupling has been compared against the HAWC2-BEM lower fidelity method. Overall the study demonstrates the applicability of vortex solvers to supplement and detail the engineering calculations offered by BEM methods for the loads and energy yield of floating wind turbines. The generic nature of the study allows generalization to arbitrary floater designs, based on their natural frequencies in surge and pitch and the associated typical motion amplitudes.

A preliminary comparative study of MIRAS-HAWC2 farm and FAST.Farm using the floating IEA Wind 15 MW reference wind turbine is also carried out. Statistical differences in power and wake wind fields are investigated at two turbulence intensities, with and without floating effects for 8 m/s average inflow wind speed. Although it was a limited study which does not propose generalized differences between the two tools, it identifies several differences that can be analysed in a larger comparative study, where uncertainties related to medium fidelity floating wind farm simulations can be better determined. For more details please see Section-4 and Section-5 in “D1.5 Methods for nonlinear wave forcing and wakes”.

8 INSTALLATION TECHNIQUES INVESTIGATION

Study Overview

The investigation of installation technologies was carried out in Subtask 2.2.5 of WP2 by Ramboll. First, a review of technologies with track record in the Oil and Gas (O&G) and FOWT industry was conducted. Different anchors, mooring lines, and their installation methods as well as hook-up procedures were outlined. For the three most common anchor types – i.e. driven pile anchors, drag embedment anchors and suction pile anchors – required equipment and preferred installation techniques and strategies were described.

Mooring lines for floating foundations, such as spar and semisubmersible type, typically consist of either steel chains or a combination of steel chains and synthetic fibre ropes or wire. The choice of material and installation technique depends on boundary conditions like water depth, soil condition, anchor type and weather conditions but also developer preferences, supply chain and risk/cost considerations. This leads to a large variety of technical solutions, of which the most likely and common strategies from floating wind installations and O&G were discussed. This qualitative evaluation also considered requirements in terms of equipment, assets and suitable installation methodologies.

Hook-up strategies for floating foundations with towing, mooring line connection, ballasting and tensioning are mainly influenced from proven O&G procedures. Such approaches were shown with corresponding assets, procedural insights, and detailed equipment overview. Also new technologies like quick connectors were addressed, aiming to increase safety and reduce offshore installation duration and risks.

Installation strategies were developed for the COREWIND reference floating foundations and the reference site B at Gran Canaria. Four cases as a combination of mooring pattern and floating foundation were investigated as shown in the figures below. A semi-taut mooring system was chosen for the base case of the study with top- and bottom chain and a fibre rope mid-section connected to driven pile anchors as probable anchor solution for the given water depth and assumed soil conditions at site.

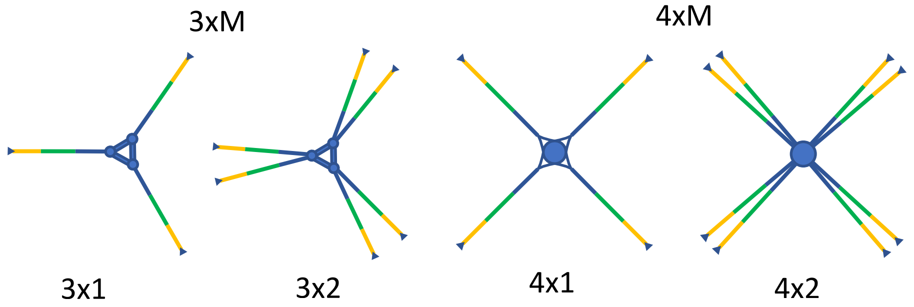


Figure 8-1: Exemplary mooring patterns [Source: Ramboll].

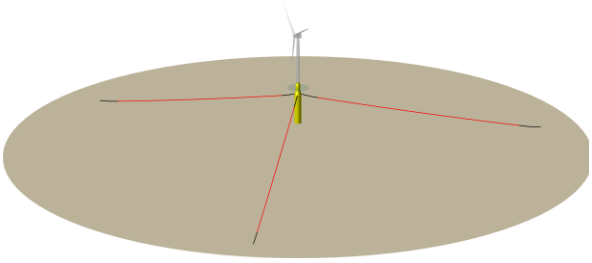


Figure 8-2: Generic spar buoy, 3x1 mooring pattern [Source: Ramboll].

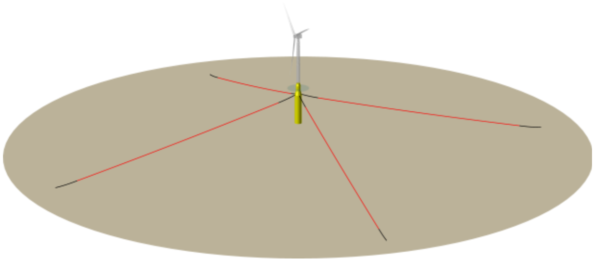


Figure 8-3: Generic spar buoy, 4x1 mooring pattern [Source: Ramboll].

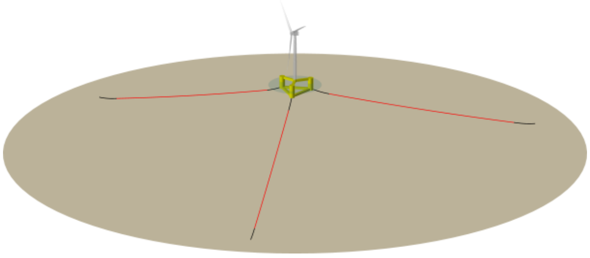


Figure 8-4: Generic semi-Submersible, 3x1 mooring pattern [Source: Ramboll].

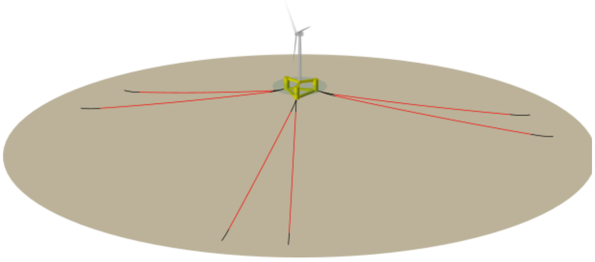


Figure 8-5: Generic semi-Submersible, 3x2 mooring pattern [Source: Ramboll].

The developed installation strategies were subdivided into different phases/ sub campaigns with different requirements regarding assets:

- Anchor and bottom chain installation,
- Fibre rope installation,
- Wet tow to site and floating foundation hook-up.

Deployment of a driven pile anchor for a semi taut mooring system requires the bottom chain to be installed together with the anchor pile because the ground chain shall be connected to the anchor pile padeye (see Figures below) leading to the inverse catenary.

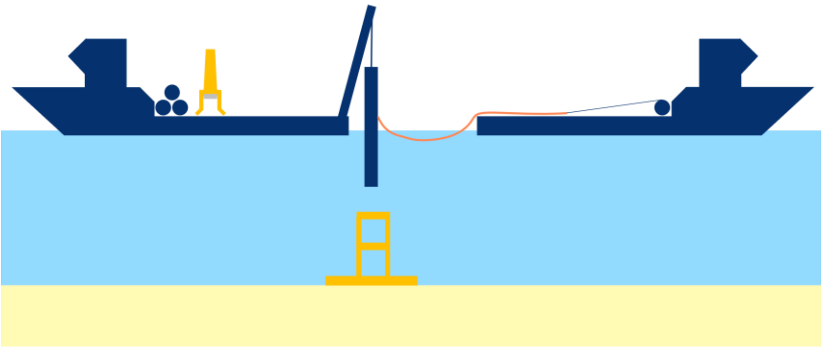


Figure 8-6: Connection of ground chain to pile [Source: Ramboll].

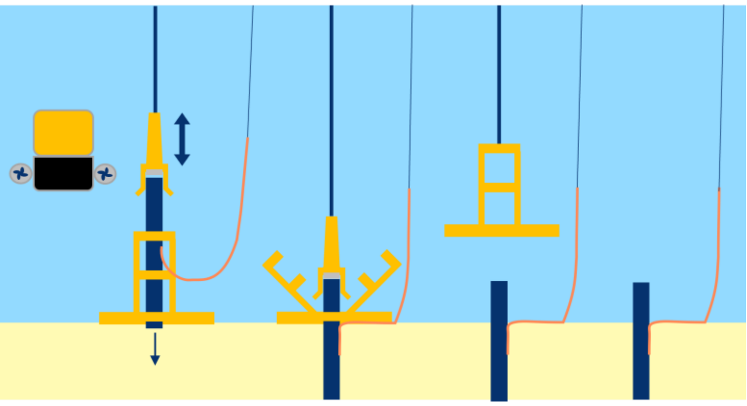


Figure 8-7: Pile driving [Source: Ramboll].

Technical constraints to fibre rope wet storage and, additionally, de-risking considerations resulted in a decoupling of the anchor and fibre rope installation. The latter is installed shortly before the foundation hook-up (see Figure below) to ensure a short wet-storage phase. The top chains were installed prior to the wet tow of the floating foundation, as it reduces offshore operations time and enables fast floater hook-up. For the hook-up procedure, a storm safe state with a minimum of three installed mooring lines was defined for all mooring patterns (semi: one per leg, spar: both cases 4x1 or 4x2) to allow reduced weather windows for the marine operations.

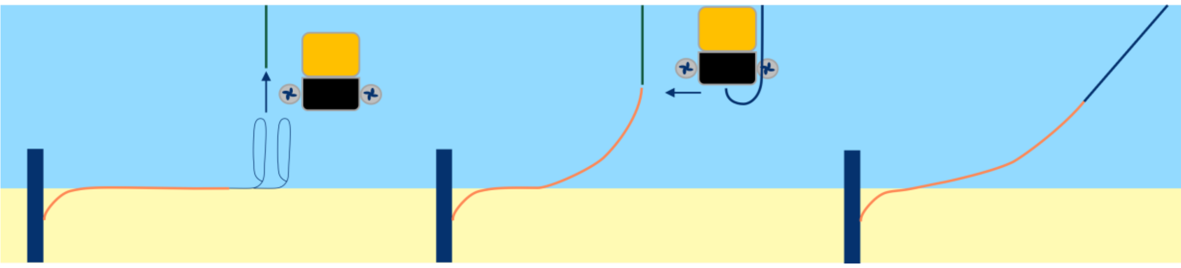


Figure 8-8: Ground chain pick-up and subsea connection to fibre rope thimble by ROV [Source: Ramboll].

For the base case, a state-of-the-art approach was developed focussing on minimum number of mobilised assets and reduced operational costs. Deviations to the process relying on innovative technologies were discussed. Up- and downsides of these alternatives were outlined regarding the impact of sensitivities like costs, redundancy, safety, site, environmental conditions, legislation, and asset availability. For example, shared moorings might be an option for the COREWIND reference sites generally leading to a reduced number of anchors and potentially reducing the anchor and mooring prelay campaign duration. However, handling of driven piles with several mooring lines connected to the piles during installation will add complexity to the installation procedure. The overall dimensions of anchors loaded by multiple lines may be significantly larger compared to non-shared anchors which may require larger vessel classes to install them.

General Conclusions

In the following paragraphs general recommendations for LCOE reduction potential from installation techniques perspective are described.

Mooring installation methods were explored from O&G as well as current FOWT demonstrator projects, covering the process from installation engineering to mobilisation and As-built surveys. This includes considerations for different types of mooring, anchors, floating foundation type and other equipment. Early engagement between installation engineering and the foundation and mooring design is critical to the success of the project. At windfarm scale especially, more difficult tasks within each FOWT's installation have the potential to significantly increase the cost and duration of the installation campaign.

Many of the installation friendly components and procedures are inherited from the significant mooring installation experience gained in the O&G industry. Mooring installation for single, O&G type floating structures is already a well optimised process, with costs, equipment, and schedule, minimised where possible. It is important to note however, that although a lot can be taken from this prior experience, some of the drivers behind the mooring design and its installation process are different. The major differences include:

- Anchor radius limitations on mooring design due to windfarm layout and turbine spacing.
- The large number of FOWT and moorings within one project, compared to a single floater O&G type project.

From an installation perspective, the anchor radius limitation can lead to various novel mooring designs including hybrid designs incorporating clump weights, buoyancy modules and other items such as load reduction devices. These additions all make the mooring system more complex, increasing the amount of mooring jewellery required and substantially increasing both the number of potential failure modes and the installation complexity.

The increase in failure modes and installation complexity is then potentially multiplied by both the number of FOWT within the windfarm and the number of mooring lines for each floater. The large number of FOWT places an emphasis on streamlining not just the mooring supply chain, but the installation process. The supply chain optimisation often involves reduction of the number of mooring lines, resulting in larger, heavier lines being proposed. This can benefit the optimisation of the installation process, reducing the numbers of anchors and lines to be installed and hooked-up to the FOWT, however the increased size can make equipment difficult to handle and limit installation vessel selection to larger and more expensive vessels.

9 TANK TESTING

Mooring recommendations for floating wind turbines can be extracted from the testing results, including experimental campaigns conducted in the COCOTSU flume and in the CCOB basin facilities managed by FIHAC, as well as marine growth under real marine conditions in the MCTS El Bocal located in the coastal area of Cantabria (North of Spain).

1. Experimental testing in the COCOTSU flume

Tests for mooring dynamics investigations were conducted in the COCOTSU flume facility managed by FIHAC. It is a wave-current-tsunami flume which has been designed to test the performance of medium and large-scale structures. This facility is 56 m long and 2 m wide, with a maximum operating depth for higher waves of 1.35 m. The flume has a 24 m long see-through midsection with bottom and side walls made of glass for use of optical instruments. In order to obtain reliable results without any truncation method, the experimental test layout was limited to analyse the dynamic performance of 'all chain' and chain-nylon mooring line configurations of the ActiveFloat semisubmersible platform at the 100 m deep West Barra Island location. The scale factor selected to perform the tests campaign was 1:75.

To analyse the effect of the modelling characteristics, a set of experiments with the 'all-chain' configuration in dry were carried out before filling up the flume with water. Firstly, the mooring line was tested without spring and without distributed lead weights. Secondly, the mooring line was tested with the spring, but still without distributed lead weights. Thirdly, the mooring line was tested with both the spring and adding distributed lead weights. After filling up the flume with water, for both 'all chain' and chain-nylon configurations the mooring line was tested under three different seabed conditions to characterize the effect of bathymetry irregularities on the dynamics of contact (Figure 9- 1).

Figure 9- 1: Chain-nylon mooring configuration with gentle slope (left) and with steep slope (right) [17].

More than 360 tests were carried out for the 9 different configurations, include tension-deformation tests, forced oscillations with different mean drifts, amplitudes and periods, and imposed irregular movements at the fairlead. The selection of harmonic excitations in planned tests was based on the resulting surge accelerations of the platform when simulating in OpenFAST the DLCs 1.3, 1.6 and 6.1. A triaxial accelerometer and a draw-wire encoder at the fairlead were used to validate the forced oscillations by the linear actuator mechanism. Simultaneously to the tension measured at both fairlead and anchor points, the dynamic performance of the line was recorded by two overlapped video cameras.

The novelties of this work, apart from simulating movements related to irregular waves and recording visual images of the line on plane XZ, were the use of different slopes to model the effect of seabed irregularities and the use of elastic materials to simulate the non-linear axial stiffness of the chain-nylon mooring. Several achievements resulted from the test campaign. Firstly, the importance of the setup and the physical definition of each line was evaluated. Secondly, the snap load cases in the mooring lines as well as the angle measurement at the fairlead at any time was analysed thanks to the visual recordings. The influence of the mean drift in the energy dissipation by a realistic work of the mooring line was assessed as a consequence. Thirdly, the importance of considering the bathymetry when designing the mooring system was demonstrated thanks to the numerical models extrapolation. Finally, a catalogue of elastic materials was generated for further use. The results proved that using elastic materials in a mooring line somehow damp the snap tensions at the fairlead, but implying several issues like having a different axial stiffness as a function of the previous deformation or presenting hysteresis related to the loading velocity [18].

2. Experimental testing in the CCOB basin

Fully coupled experimental tests were conducted in both POLIMI and FIHAC facilities. The hardware-in-the-loop (HIL) methodology try to solve the Froude-Reynolds scaling incompatibility, since the floating platform and the mooring system are governed by gravity-influenced forces, whereas the wind turbine is dominated by the aerodynamic forces. In the real-time hybrid model applied to the CCOB basin facility managed by FIHAC, the hydrodynamic subsystem is emulated by means of a physical scale model and the aerodynamic data is provided numerically using a multi-fan system [19]. The FIHAC's multi-fan system consists of coupling a set of small fans at the aero-rotor interface, and it is calibrated to reproduce accurately the aerodynamic forces previously observed in the POLIMI wind tunnel, including control induced effects and unsteady aerodynamic effects of the IEA-15MW.

A set of physical experiments were carried out to evaluate the seakeeping of novel concrete-based WINDCRETE and ACTIVEFLOAT floating concepts under different environmental conditions, including waves and current and wind actions, as well as installation conditions at the 200 m deep Gran Canaria location. The CCOB facility is a multidirectional wave basin, 30 m long and 44 m wide, with a maximum operating depth for higher waves of 3.7 m. Considering the dimensions of the basin, as well as the wave actuator and current generator capabilities, it was concluded that 1:55 for WINDCRETE and 1:40 for ACTIVEFLOAT were the most suitable test scales to carry out the experimental testing campaign. The mock-ups were designed to be able to reproduce the external geometry of the platforms, as well as their mass properties (centre of gravity and inertia moments). The mock-ups were made of steel, except for the lower hemisphere of the WINDCRETE platform which was made of ABS by means of a 3D printer and the tower of the ACTIVEFLOAT which was made of aluminium.

With a truncated version of the physical model that correctly captures the influence of mooring loads on the structure, the size of the tests can be maximized and the potential effects of using small scale factors can be reduced [20]. Physical experiments were conducted at 165 meters of water depth in WINDCRETE case and at 120 m in ACTIVEFLOAT case (3 m at model scale). Because of the limits of the basin dimensions, mooring lines were truncated in both water depth and footprint size. The methodology for single mooring lines static truncation based in the catenary equations and evolutionary optimization algorithms were applied. The truncated mooring system was designed as simple as possible, to reduce uncertainties and simplify numerical models validation. The mooring system was designed based on tested commercial wires, chains and springs able to reproduce the weight and the axial stiffness of each mooring system. Extra clump weights were added to capture properly the original line pretension (Figure 9- 2).

Figure 9- 2: Manufactured mooring lines for WINDCRETE (left) and ACTIVEFLOAT (right) [21].

An extensive test programme was designed to evaluate the dynamic performance of the floating concepts. The physical experiments were divided into seven groups of tests, namely: (1) Dry Characterization tests, (2) Wet Characterization Tests, (3) Wave Tests, (4) Current Tests, (5) Wind Tests, (6) Coupled Tests: Wave + Current + Wind Tests, (7) Installation Tests. A total number of more than 120 tests were conducted. All the tests were carried out according to DNV recommendations. With the aim of recording the expected physical processes, different instrumentation was used during the physical experiments, namely: free surface transducers for water level measurements, acoustic doppler velocimetries, track motion system to measure the floating platform motions, accelerometer to record accelerations at the nacelle, tri-axial load cell beneath FIHAC multi-fan to records the generated aerodynamic loads axial, and load cells to measure forces on mooring lines.

The experimental testing campaign served to analyse the dynamic response of the floaters, including motions at CoG, Nacelle and MSL, and accelerations at Nacelle. Comparing both platforms, WINDCRETE was prone to have larger mean pitch with constant rated wind without or with regular wave with low periods ≤11 s, and larger maximum pitch with operational conditions under turbulent rated or below rated wind than the ACTIVEFLOAT due to the absence of an active ballast system. The rotor of WINDCRETE suffered higher forces than that of ACTIVEFLOAT since in the extreme wind-current-sea state of Hs=5.11 m, Tp=9 s, γ=1.2 with current and rated wind with Normal Turbulence Model, the maximum acceleration at the Nacelle reached 1.74 m/s2 in surge.

Moreover, the experimental testing campaign helped to understand and deep into the mooring dynamics, including line tensions. The mooring system of WINDCRETE was more strained than that of ACTIVEFLOAT, reaching the main line 1 a maximum tension equal to 816 tonnes in this extreme wind-current-sea state. However, the limit of ACTIVEFLOAT was reached for maximum yaw with current, for mean excursion with regular wave with a height of 5.11 m and a period of 7.5 s, as well as for mean and maximum excursion with constant rated wind without or with regular wave and with operational conditions under turbulent rated wind.

3. Chain lines degradation in marine environment for floating applications

Different mooring chain materials were exposed to biological and physicochemical elements of the marine environment in the MCTS El Bocal, located in the coastal area of Cantabria (North of Spain). The test was carried out at two depth levels: at the intertidal zone and at the submerged zone. At each of these levels, steel coating plates of 75x150mm were deployed to be exposed to the elements during 12 and 24 months. The test plates used for the mooring chain included replicates of bare steel, replicates of steel coated with an unmodified reference hempadur 15570 paint (Type 0), replicates of steel coated with a functionalized paint (HDK18+NP Cu) 23% SIO2 + 6%CuO (Type 1), and replicates of steel coated with a functionalized paint (HDK18+NP Cu) 28% SIO2 + 6%CuO (Type 2).

During the experiment, a photographic survey was carried out, taking photographs of the plates on a monthly basis, when possible. After the first extraction, a replicate of each of the plates were carried out to the FIHAC's laboratory for their biotic assessment of the biofouling communities (Figure 9- 3). Afterwards, a visual inspection of the corrosion applying the UNE-EN ISO 4628:2016 standard [22] was conducted for the assessments of degree of blistering, degree of rusting, degree of cracking, degree of flaking and degree of chalking by tape method.

The most abundant species colonizing the plates were the green filamentous opportunistic species Ulva sp. and the red foliose Porphyra sp., with percentage coverages between 10%-70%. The bare steel plate (Figure 9- 3) showed a similar composition of biota but with slightly lower coverage values. In addition, it showed the presence of some small filaments of the brown algae Scytosiphon sp. (2%), giving to this plate the highest species richness overall. Regarding Type 1 plates, the more altered one R2 (Figure 9- 5) showed higher coverages of Ulva sp. (70%) and Porphyra sp. (20%), in addition to a small specimen of the brown algae Taonia sp. (1%) and some individuals of Chthamalus sp. (1%), while the less altered one R1 (Figure 9- 4) showed the lowest values of species coverage and richness among all the plates.

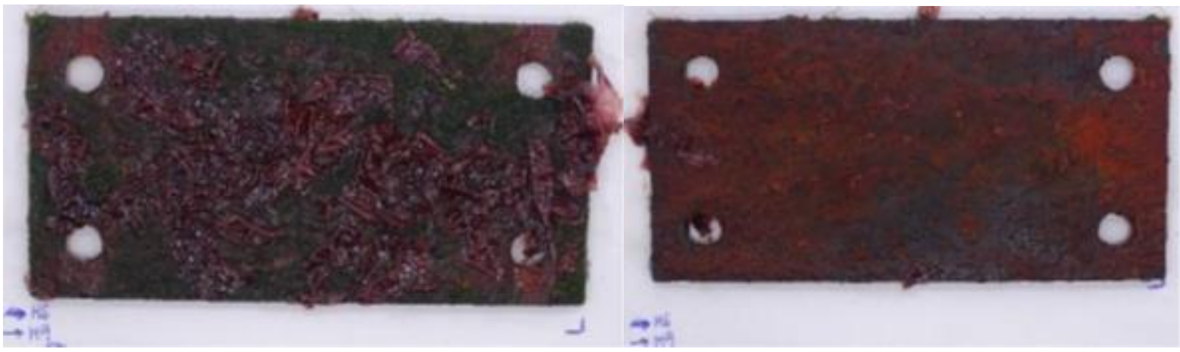


Figure 9- 3: Bare steel at Tidal area. Face A (left) and Face B (right) [23]

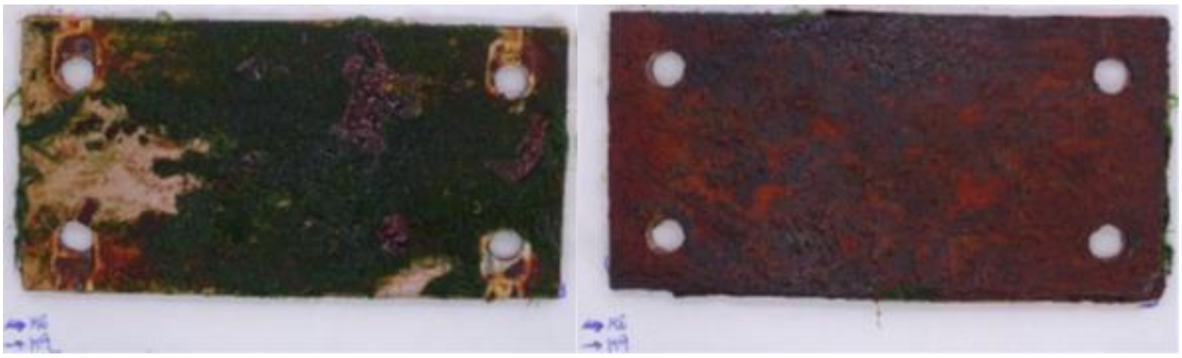


Figure 9- 4: Steel coated of Type 1 R1 at Tidal area. Face A (left) and Face B (right) [23]

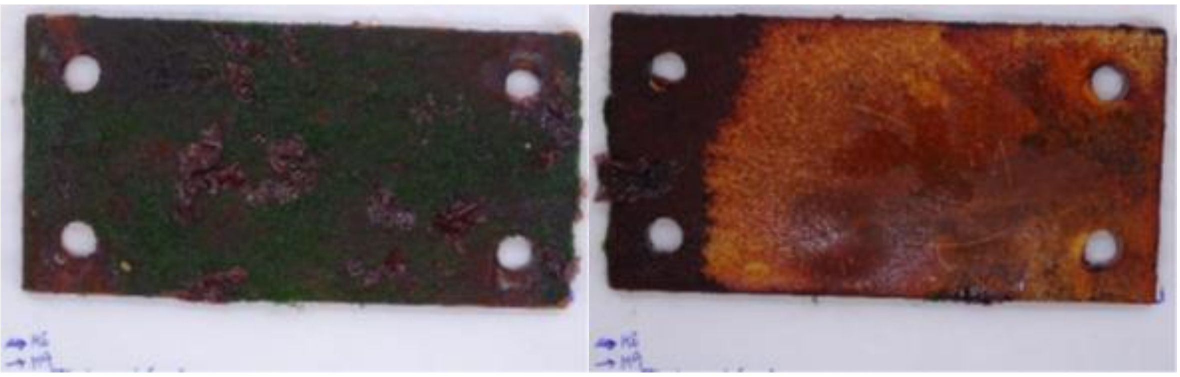


Figure 9- 5: Steel coated of Type 1 R2 at Tidal area. Face A (left) and Face B (right) [23]

10 CONCLUSION AND OUTLOOK

This report highlights the main outcomes of WP2 of COREWIND project. It provides a summary of each topic addressed during the project to perform optimization of mooring and anchoring systems design. In addition, it highlights guidelines and recommendations concluded from results as well as proposes perspectives for future works. The covered subjects refer to several aspects of mooring and anchoring optimization.

First, an innovative optimization process is described together with its application on the two reference foundations, ActiveFloat and WindCrete, and the three reference sites of the COREWIND project, West of Barra, Gran Canaria and Morro Bay. This optimization process shows encouraging results, allowing to automatically optimize mooring system based on ULS cases for most of the configurations. Some limits are reached for harsh environment and for design driven by FLS. However, perspectives for future projects are proposed such as the improvement of optimization algorithm, use of artificial intelligence, or optimization in the frequency domain. A summary of ULS and FLS reliability of optimized mooing systems performed with coupled analysis is provided as well.

The report also gives results and recommendations offer by innovative solutions for mooring systems. It starts by analysing the use of peak load reduction systems for the two platforms and three sites. Analysis reveals promising results, with significant load reductions achieved. For semi-taut mooring systems, the benefits seem less evident, probably due to the use of synthetic lines. Regarding costs, the optimization is not significant, mainly due to procurement costs of the devices, which should drop as the technology matures. USTUTT presents their study on the use of clump weight and the role of pretension is investigated to allow mooring footprint reduction together with costs of the mooring system. It is observed that clump weights can be a key element to achieve costs savings. Investigations on the controller are assessed, to quantify benefits of tunning of the controller to extend lifetime of the mooring system. Study covers tunning of Ki and Kp gain, as well as including nacelle fore-aft velocity. The analysis shows promising results opening door for future work to be done carrying a thorough investigation. Eventually, innovative mooring system layout, with shared anchors and shared mooring lines layout are investigated. Several outcomes are drawn from the studies. DTU underlines how means of surrogate models are suitable for shared mooring lines optimization. In addition, modal analysis is performed to highlight benefices and changes implied by connecting several floating wind turbines. INNOSEA also presents their work on technical feasibility of such system through time-domain based optimization, showing that sharing the anchors is feasible, however its potential should be confirmed with further studies including longitudinal spacing refinement and installation costs considerations, while shared mooring lines configurations already provide costs savings, thanks to natural yaw stiffness provided by the system. UPC and COBRA summarize their work on design of mooring connections to concrete structures. They provide an original design associated to optimized mooring systems, contributing to de-risking this sensitive part of the design. The innovative design is stiff, reliable and make compatible the concrete floater with the moorings. These aspects participate to overall system costs reductions.

DTU also worked on modelling improvement, proposing an accelerated method scales with O(n) cost compared to the O(n2) cost of the double sum method used to get second order wave loads. This opens the door towards an improvement of floating offshore wind loads assessment. A second topic, the effect of second-order wave forcing on the low-frequency modes and response calculation for a floating offshore wind farm with shared mooring line, is analysed, showing that second order does not significantly affect mooring line tension, that surge is increased in a shared configuration compared to a single FOWT and that second order provides larger offsets than first order ones, especially for surge. Eventually, an analysis shows the applicability and benefices of vortex solvers for the loads and energy yield assessment.

Ramboll presents their works on qualitative LCOE reduction potential from installation techniques. Techniques from O&G industry as well as current FOWT demonstrator projects are investigated, and the common procedures are listed. They show how mooring installation procedures are well documented from O&G, though pointing some differences with FOWTs, such as a constrained mooring footprint, potentially leading to complex systems. Ramboll investigates different scenarios, reducing procedures and risks, leading to costs optimization. In addition, they show how reducing mooring lines and anchors numbers can be beneficial for installation costs, as for supply chain, though mentioning that some limits can be achieved because of required installation vessels.

Eventually, FIHAC summarizes their works related to the three tests campaigns performed during the project. These tests campaigns include mooring and dynamic cable tests in the COCOTSU flume, fully coupled tests in the CCOB basin facilities and marine growth analysis under real conditions in the MCTS El Bocal. From those tests, FIHAC offer a large panel of results from which researchers and industries can pick conclusions to achieve costs savings. Those results cover several topics such as, importance of set up and physical definition prior to tests, snap loads a fairlead angle analysis, influence of mean drift and bathymetry, dynamic analysis of two platforms or efficiencies of different coating on marine growth.

11 REFERENCES

[1] https://www.nrel.gov/wind/nwtc/openfast.html, NREL

[2] https://github.com/openfast, NREL

[3] L Arsen, T Orben J. & H Ansen, A Nders M. 2020 How 2 Hawc2, The User’s Manual. Tech. Rep..Dtu Wind

[4] Aagaard M Adsen , H Elge , Larsen, T Orben J Uul, P Irrung , G Eorg , L I, A Ng & Z Ahle, F Rederik 2020 Implementation Of The Blade Element Momentum Model On A Polar Grid And Its Aeroelastic Load Impact. Wind Energy Science 5, 1–27

[5] Ramos-García, Néstor, et al. "Investigation of the floating IEA Wind 15 MW RWT using vortex methods Part I: Flow regimes and wake recovery." *Wind Energy* 25.3 (2022): 468-504

[6] D1.2 DESIGN BASIS, COREWIND Consortium, August 202

[7] DNV-ST-0119 Floating Wind Turbine Structures 2021, DNV, June 2021

[8] P. Trubat, A. Herrera, C.Molins, Mooring Optimization Using ML Techniques, 2022, Proc. Of ASME2022, Intern. Off. Wind Tech. Conf. IOWTC 2022.

[9] DNV, "DNV-ST-0119 Floating wind turbine structures," 2021.

[10]R. Huang, M. Zhang, M. Guo, R. Ye, C. Fu and D. Shen, "Study on Mooring Economy and Stability of Floating Wind Turbine," 2020 5th Asia Conference on Power and Electrical Engineering (ACPEE), Chengdu, China, 2020, pp. 308-312, doi: 10.1109/ACPEE48638.2020.9136319.

[11] Z. Wu and Y. Li, "Platform Stabilization of Floating Offshore Wind Turbines by Artificial Muscle based Active Mooring Line Force Control," in IEEE/ASME Transactions on Mechatronics, doi: 10.1109/TMECH.2020.2992711.

[12] Li, Y.; Le, C.; Ding, H.; Zhang, P.; Zhang, J. Dynamic Response for a Submerged Floating Offshore Wind Turbine with Different Mooring Configurations. J. Mar. Sci. Eng. 2019, 7, 115.

[13] T. P. Mazarakos, S. A. Mavrakos and T. H. Soukisian, "Wave Loading and Wind Energy of a Spar Buoy Floating Wind Turbine," 2019 Fourteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte-Carlo, Monaco, 2019, pp. 1-7, doi: 10.1109/EVER.2019.8813555.

[14] Giorgi, G.; Gomes, R.P.F.; Bracco, G.; Mattiazzo, G. The Effect of Mooring Line Parameters in Inducing Parametric Resonance on the Spar-Buoy Oscillating Water Column Wave Energy Converter. J. Mar. Sci. Eng. 2020, 8, 29.

[15]Chemineau, M et al. 2022, COREWIND D2.2 Design analysis and optimization of mooring and anchoring system for floating wind turbines

[16]Mechinaud, L et al. 2022 COREWIND D2.3 Exploration of innovations and breakthroughs of station keeping systems for FOWT

[17]Gözcü, O., Kontos, S., & Bredmose, H. (2022, May). Dynamics Of Two Floating Wind Turbines With Shared Anchor And Mooring Lines. In journal Of Physics: Conference Series (Vol. 2265, No. 4, P. 042026). Iop Publishing.

[18]Bredmose , H Enrik, R Inker , Jennifer , S Krzypinski, Witold , Zahle , Frederik, Meng , Fangzhong , Dykes , Katherine , Gaertner , E Van , Barter, G Arrett, B Ertolotti , Pietro , S Ethuraman , L Atha & S Hields , Matt 2020 Definition Of The 15 Mw Reference Wind Turbine. Tech. Rep. D1.1. Corewind

[19]Arramounet, V. et al., 2021. *COREWIND D5.2: Mooring and cable dynamic testing report*.

[20]Somoano, M., Rodríguez-Luis, A., Blanco, D. & Guanche, R., 2022. *Experimental analysis of mooring and power cable dynamics when using elastic string models*. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE, Volume 8.

[21]Somoano, M., Battistella, T., Fernández-Ruano, S. & Guanche, R., 2021. *Uncertainties assessment in real-time hybrid model for ocean basin testing of a floating offshore wind turbine*. Journal of Physics: Conference Series, Volume 2018.

[22]Facchinetti, A. et al., 2020. *COREWIND D5.1: HIL 15MW development*.

[23]Guanche, R. et al., 2022. *COREWIND D5.3: Integrated FOWT test report*.

*[24]*4628-1:2016, UNE-ENISO 2016, Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance.

*[25]*Guanche, R. et al., 2022. *COREWIND D5.3: Annex I. Chain lines and dynamic cable coating degradation in marine environment for floating applications.*