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Design and costs benefits of shared anchors and shared mooring lines of floating wind turbines at farm level

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Abstract. This paper focuses on innovative mooring layouts using shared anchors and shared mooring lines. Three studies with the ActiveFloat semi-submersible floater supporting a 15MW wind turbine are presented. Those include two studies of shared anchors layouts, with a semi-taut mooring system at a deep-water site subjected to extreme conditions (Morro Bay) and a catenary mooring at a moderate water depth with gentle environment (Gran Canaria). The third study focuses on shared mooring layout at Morro Bay. The mooring system at this site is semi-taut, made of polyester, with chain close to the sea surface and the anchors. At Gran Canaria, ActiveFloat is featured with a catenary mooring system made of chain lines. Both sites are subjected to irregular sea states and turbulent wind. Time domain simulations in ULS are performed using OrcaFlex models that combine potential flow theory and Morison drag coefficients. Aerodynamic load time series are applied at the tower top. Results show that shared anchor layouts are technically feasible but do not improve the mooring system procurement costs due to the spacing constraint between each turbine. Sharing mooring lines at farm level seems more promising and could help reduce costs, due to the decrease in amount of material use.

1. Introduction

While the offshore wind industry's trend towards floating wind turbines (FOWT) has never been stronger, optimization remains to be performed on the floating systems that support wind turbines, and significant challenges still need to be addressed. One of these challenges lies in reducing the capital cost associated with the construction of floating foundations and their corresponding mooring systems. This high CAPEX must be reduced for floating wind to become competitive. The current mooring and anchoring systems used for floating wind turbines are inherited from the oil and gas industry and are generally composed of a minimum of 3 mooring lines and as many anchors. While deepwater oil and gas terminals are very large single structures using multiple lines, the +1 GW floating wind farm to be installed in the coming years will consist of over 100 floating structures each having a minimum of three mooring lines. This proximity of many floating substructures provides the opportunity to consider mooring and anchoring arrangements where mooring lines and anchors could be shared.

Some studies focus on assessing the behaviour of such layouts. Goldschmidt and Muskulus [1] investigate potential cost savings for a 5MW reference foundation. Their analysis shows large potential cost savings as well as no first-order wave resonance problems. Munir, Lee and Ong [2] investigate shared mooring system dynamics for two different distances between FOWTs, focusing on motion deviation with respect to a single FOWT. Devin and DuPont [3], work on shared anchor reliability by proposing an innovative methodology to strengthen the most important anchors in the layout. The approach involves optimization analysis to identify the most important anchors. Fontana, Arwade, DeGroot, Myers, Landon and Aubeny [4] analyse the net forces reached by a multiline anchor for a specific layout, showing that these concepts may reduce loads at anchors though directionality issues. Finally, Connolly and Hall [5], investigate shared mooring systems optimization using quasi-static models and a design algorithm to get layouts respecting design criteria.

In the present study, the design feasibility and cost benefits of shared anchors and shared mooring lines at farm level are investigated for the ActiveFloat semi-submersible platform supporting the IEA 15MW turbine from NREL. The shared anchor study is conducted at a moderate water depth site (200 meters) in gentle environment (Gran Canaria) and at a deep water site (870 meters) subjected to extreme wind and waves (Morro Bay). The shared mooring lines study is conducted only for the latter. The mooring system of ActiveFloat at Gran Canaria is a catenary system equipped with chain lines. At Morro Bay, it is a semi-taut system mainly made of polyester mooring line, in-between chain sections close to the anchors and the platform.

The present study compares the procurement costs of these mooring systems for a layout of three floating units, against the costs of three conventional mooring layouts.

Firstly the methodology and the inputs are presented, then the results for shared anchors and shared moorings, followed by conclusions and outlooks.

This research is funded by the Horizon H2020 project Corewind, grant number 815083. The project focuses on cost reduction of floating wind technology through research and optimization of the mooring and anchoring systems, dynamic cables, as well as the improvement of installation, operation and maintenance activities.

2. Methodology

2.1. Modelling

Both sites are subjected to turbulent wind and irregular sea states. Shared anchor and shared mooring line configurations are designed and optimized for ULS. Time domain simulations corresponding to DLCs 6.1 and 6.2 as defined in [6] are performed, using OrcaFlex models that combine potential flow theory with additional drag coefficients, and aerodynamic load time series applied at the tower top. For the conventional mooring systems, models with a single turbine are used. For both shared anchors and shared mooring systems, models with three floating turbines are used. The designs are validated against platform motions criteria, maximum nacelle accelerations and utilisation factor of the mooring lines during the entire life of the system (25 years, according to [7]). At end of life, marine growth and chain corrosion are also considered in the models.

Procurement cost optimizations are conducted for both conventional mooring systems and shared anchor mooring systems using an in-house optimization screening tool developed for Corewind. It is coded in Python and uses the benderopt library, described in more details in [8]. The optimization tool allows the user to optimize the cost of materials and the cost of anchors of a mooring system, varying mooring parameters such as the line lengths and diameters, and with respect to constraints such as maximum platform motions and mooring lines utilisation factors. At this stage, the tool does not consider installation costs.

Regarding the shared mooring line system investigations, costs optimization are performed iteratively, because of time restrictions on the project and because the optimization tool is not yet suited to such a complex mooring system.

The optimization procedure requires several steps.

For the shared anchor layouts, the line lengths are set at a minimum value while respecting longitudinal and lateral spacings between the floating turbines. Then the optimization screening tool is used to minimize the costs of materials used in the mooring lines, while respecting the design criteria defined. The directionality of the environmental loads enables separate optimization of the upwind lines, positioned along the main environmental loads direction (wind and waves), and the downwind lines, positioned on the other side of the floater. Upwind lines are subjected to higher loads than downwind lines. Therefore, it is possible to reduce the size of the downwind lines when compared to the size of the upwind lines. The results are summarized in section 4.

For shared mooring lines, the first step consists in performing a geometrical optimization as for the shared anchors configuration. The layout minimizing the total line length is found to be the same as for the shared anchors analysis. Depth and buoyancy of a central buoy are introduced as new parameters. However, analysis shows that a surface buoy tends to minimize tension in the lines, so the buoyancy is selected to respect this configuration. The second part of the optimization consists in the optimization of line properties such as diameters and chain grades. As explained before, the optimization tool does not handle such a complex mooring system and improvement is performed iteratively. Results are presented is section 5.

2.2. Cost analysis
The cost of the mooring systems are estimated following recommendations from deliverable D4.6 of DTOcean+ report [9]. The following equations are used for the cost estimations of the polyester and chain:

$$C_{\text{chain}} = (0.055 \cdot MBL - 83.41) \cdot L \tag{1}$$

$$C_{\text{polyester}} = (0.0138 \cdot MBL + 11.281) \cdot L \tag{2}$$

Where MBL is the Minimum Breaking Load of the material (chain or polyester, in kN), and L is the length of the relevant section of the mooring lines (in meters). C_{chain} and $C_{\text{polyester}}$ are respectively the costs in € of the chain and the polyester used in the mooring lines.

The following equation is used to estimate the cost of the drag-embedded anchors:

$$C_{\text{anchor}} = 9.484 \cdot MBL \tag{3}$$

Where MBL is the Minimum Breaking Load of the chain line connected to the anchor and C_{anchor} is the cost of a drag-embedded anchor in €.

In order to properly compute the shared anchor costs, a different method is used. Indeed, cost cannot be estimated by using the MBL of the line, because there is no unique line linked to the anchor. Moreover, the formula used until now is only valid for drag-embedded anchors. Now that forces applied on a shared anchor are multi directional, other anchor types should be considered, such as pile anchors. Consequently, the cost is estimated by the following formula [9]:

$$C_{\text{anchor}} = M \cdot C_{\text{material}} \cdot (1 + CF) \tag{4}$$

Where M is the mass of the anchor (in kg), C_{material} is the mass price of the anchor material (in €/kg) and CF is a complexity factor, usually taken as equal to 1 for a pile anchor.

In order to compute the anchor volume, the American Bureau of Shipping (ABS) [10] method is used. The method enables to estimate the different characteristics of the anchor (length, diameter and thickness) once given the anchor type, the ultimate holding capacity and the soil conditions. The ultimate holding capacity of the shared anchor is defined by the following formula:

$$F_{\text{d}} = \gamma_{\text{mean}} \cdot F_{\text{mean}} + \gamma_{\text{dyn}} \cdot (F_{\text{max}} - F_{\text{mean}}) \tag{5}$$

Where γ_{mean} and γ_{dyn} are safety factors that can be found in [7].

The force F is given by:

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{6}$$

With

$$F_x = \sum_{i=1}^{3} F_{x_i}, \quad F_y = \sum_{i=1}^{3} F_{y_i}, \quad F_z = \sum_{i=1}^{3} F_{z_i} \tag{7}$$

Where F_{x_i}, F_{y_i} and F_{z_i} are the x, y and z component of the force applied by the i^{th} line on the anchor.

In both cases, costs of the shared anchors or shared mooring lines layouts are compared to three time the costs of an optimized FOWT mooring system obtained in the Corewind project for a single floating unit. Indeed, when neither anchors nor mooring lines are shared in a layout composed of three FOWTs, each floating unit is anchored to the seabed with a conventional mooring system. Consequently, the cost of the mooring system of the shared anchors or shared mooring lines layout is equivalent to the cost of three conventional mooring systems.

3. Case studies

The following table summarizes the principal characteristics of the sites of Morro Bay and Gran Canaria, as defined in the Design Basis of Corewind [7], and as used in the models of this study.

Table 1. Main characteristics of the sites of Morro Bay and Gran Canaria.

Site	Gran Canaria	Morro Bay
Water depth (m)	200	870
Extreme wind (m/s) [1]	28.7	37.15
Hs (m) [2]	5.11	9.9
Minimum Tp (s) [2]	9.0	16.0
Maximum Tp (s) [2]	11.0	18.0
Extreme current (m/s) [3]	1.06	0.0

[1] Extreme wind speed at hub height for a 50-years return period.
[2] Extreme sea-state for a 50-years return period.
[3] Extreme current at sea surface for a 50-years return period.

Gran Canaria and Morro Bay are characterised by their different ranges of water depths, significant wave heights (Hs) and peak periods (Tp). Gran Canaria has a moderate water depth and (Hs, Tp), whereas Morro Bay is in deep water and has extreme wave conditions (Hs, Tp). Further in the document, the Gran Canaria site will be named a ‘moderate site’, and Morro Bay a ‘deep water site’.

In the models, the irregular sea states are modelled with a JONSWAP spectrum defined by values of Hs, Tp, peak shape parameter gamma, main direction and wave seed number. Current loads are modelled using a current speed profile as per [7]. The wind loads are applied at the tower top as time series from OpenFast aero-elastic simulations described in [11].
The floater used for this study is the semi-submersible platform ActiveFloat developed by Cobra [7]. Its design is composed of three external columns connected to a central column with submerged pontoons. It supports the IEA 15MW wind turbine from NREL [12].

4. Results for shared anchors

In this section the results are presented from the investigations regarding shared anchor mooring systems at farm level.

4.1. Layouts

The layout for the simulations and comparison with the conventional mooring at farm level is composed of three FOWTs, anchored to the seabed through a common anchor, as illustrated in Figure 1.

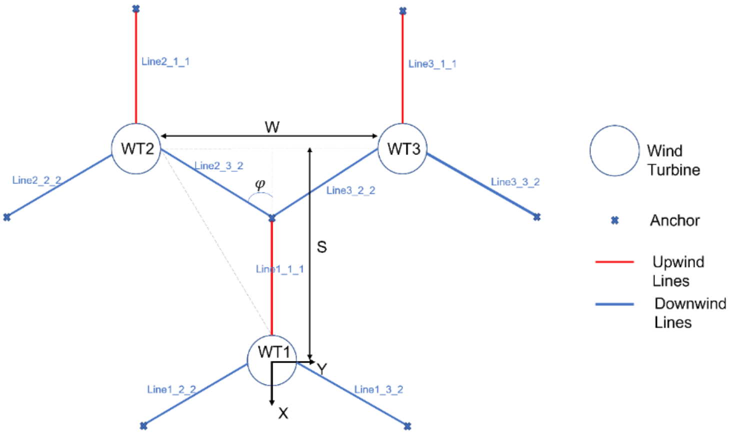

Figure 1. Shared anchors layout.

For the moderate site, the mooring lines are catenary, composed of chain from the fairleads to the anchors. For the deep-water site, the mooring is semi-taut, with lines mainly composed of polyester, except for short chain sections close to the fairleads and the anchors, respectively for installation purposes and abrasion issues. Mooring buoys are attached to the top chain sections of the semi-taut mooring lines to increase the yaw mooring stiffness. Costs of shared anchors are always calculated considering pile anchors, while the others are considered as drag-embedded.

4.2. Geometrical constraints

As recommenced in the literature and to be coherent with previous Corewind work [13], the longitudinal distance between two turbines (*S* in figure 1) must be higher than seven times the rotor diameter:

$$S \geq 7D \tag{8}$$

Also, the lateral spacing between two turbines (*W* in figure 1) must be more than four times the diameter of the turbines:

$$W > 4D \tag{9}$$

Finally, the horizontal half-angle between the mooring lines φ is set as:

$$\varphi = 60° \tag{10}$$

4.3. Design and optimization

The following tables summarize the properties of the mooring line materials obtained through optimization. The methodology is described in section 2.

Table 2. Shared anchors layout: mooring properties of upwind lines.

Type of line	Material	Diameter [mm]	Line length [m]
Deep water	Chain R3S	105.0	275.0
	Polyester	169.0	1275.0
Moderate site	Chain R4S	110.0	1275.0

Table 3. Shared anchors layout: mooring properties of downwind lines.

Type of line	Material	Diameter [mm]	Line length [m]
Deep water	Chain R3S	90.0	199.6
	Polyester	146.0	847.5
Moderate site	Chain R4	50.0	840.0

The procurement costs for the optimized shared anchor mooring system are presented and compared to three times the procurement costs of a conventional mooring system. In a conventional mooring, there is an anchor for each mooring line.

The following tables present the cost details for the two solutions and the absolute differences. The methodology is defined in detail in section 2.

Table 4. Detailed optimized costs of a 3 FOWTs layouts of the deep-water site, conventional mooring system vs share anchor mooring system.

Type of mooring	Conventional [k€]	Shared anchor [k€]	Difference [%]
Chain sections cost	829.5	881.9	-2.1
Polyester sections cost	871.3	1049.9	+20.0
Buoys cost	4074.0	4074.0	0.0
Anchors cost	887.4	731.0	-17.6
Total cost	6662.1	6666.9	+0.1

Table 5. Detailed optimized costs of a 3 FOWTs layouts of the moderate site, conventional mooring system vs shared anchor mooring system.

Type of mooring	Conventional [k€]	Shared anchor [k€]	Difference [%]
Chain sections cost	2042.1	2332.3	+14.0
Anchors cost	553.2	396.9	-28.8
Total cost	2595.3	2792.2	+5.1

At both sites, the lengths of the mooring lines connected to the shared anchor in the centre of the layout need to be increased when compared to the lengths used in the conventional mooring system, due to the longitudinal spacing requirement. As a consequence, the cost of polyester used in the mooring of the deep-water site increases by 20% and the cost of chain in the mooring of the moderate site increases by 14%. On the other hand, the use of a shared anchor layout reduces the cost of anchors by almost 18% for the deep-water site and 29% for the moderate site. As the anchor cost represents only 10 to 15% of the procurement cost of the mooring system, the total procurement costs of the shared anchor system are not decreased when compared to a conventional mooring system's procurement costs. The costs are increased by 5% for the moderate site.

The system is verified against several conditions to ensure respect of the design criteria for ULS during the entire lifetime. Main results are summarized in the following tables.

Table 6. DLC6.1 and 6.2, deep water site.

Parameter	Upwind line	Downwind line
UF[1] Chain [-]	0.750	0.987
UF[1] Polyester [-]	0.651	0.848
Platform Offset [m]	44.8	
Platform Pitch [deg]	7.0	
Platform Yaw [deg]	3.4	
Nacelle Horizontal acc. [m/s2]	4.2	
Nacelle Vertical acc. [m/s2]	1.1	

[1]UF utilisation factor

Table 7. DLC6.1 and 6.2, moderate site.

Parameter	Upwind line	Downwind line
UF[1] Chain [-]	0.790	0.998
Platform Offset [m]	56.9	
Platform Pitch [deg]	2.2	
Platform Yaw [deg]	4.4	
Nacelle Horizontal acc. [m/s2]	0.8	
Nacelle Vertical acc. [m/s2]	0.5	

[1]UF utilisation factor

For both sites, utilisation factors UF, defined as the ratio of the design tension and the minimum breaking load of the material, are below 1 as required. UFs of downwind lines are very close to 1, showing that their sizes are well optimized to minimize the costs. UFs of upwind lines are conservative because of the yaw motion criteria, requiring a high yaw mooring stiffness. Motions are also below the criteria defined for the platform (15 degrees pitch and yaw, 104 meters offset), as well as the maximum nacelle acceleration.

5. Results for shared mooring lines

This section presents results for shared mooring lines at farm level.

5.1. Layouts

For this analysis, the layout is composed of three FOWTs. The analysis focuses on the deep water site only. Each turbine is connected through a horizontal line to a shared central buoy, which is attached to the seabed by a vertical line. Figure 2 below illustrates the layout. The lines are composed of a mix of polyester and chains. For lines connecting platforms directly to the seabed, buoys are used to increase yaw mooring stiffness.

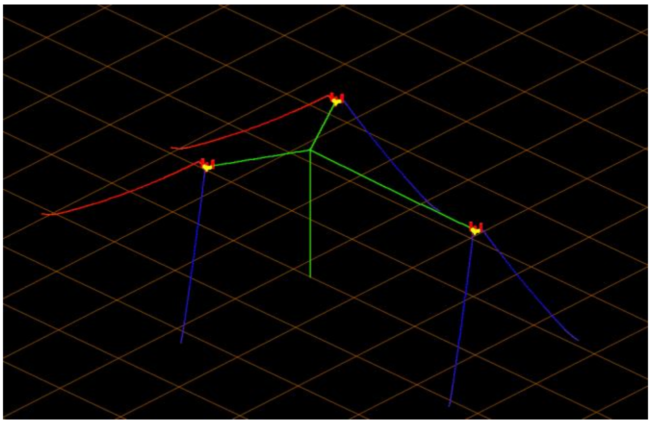

Figure 2. Shared mooring lines layout.

5.2. Geometrical constraints

The geometrical constraints used for this analysis are those described in section 4.2

5.3. Design and optimization

The iterative optimization described in section 2 is applied to optimize the line properties. The tables below summarize properties of material for upwind lines, downwind lines, and the vertical line.

Table 8. Shared mooring lines layout: mooring properties upwind lines.

Type of line	Material	Diameter [mm]	Line length [m]
Shared	Chain R4S	92.0	10
	Polyester	126.0	1235
Classic	Chain R4	128.0	200
	Polyester	190.0	1376

Table 9. Shared mooring lines layout: mooring properties downwind lines.

Type of line	Material	Diameter [mm]	Line length [m]
Shared	Chain R4S	92.0	10

	Polyester	126.0	535
Classic	Chain R4S	97.0	181
	Polyester	166.0	860

Table 10. Shared mooring lines layout: mooring properties vertical common line

Type of line	Material	Diameter [mm]	Line length [m]
Vertical	Chain R4S	92.0	10
	Polyester	126.0	840

Procurement costs for the optimized mooring system are presented below. Costs are compared to the costs of a conventional mooring system for 1 FOWT obtained during the Corewind project. For comparison purposes, these costs are multiplied by 3.

Table 11. Detailed optimized costs of a 3 FOWTs layouts at Morro Bay, conventional mooring system vs shared mooring lines system.

Type of mooring	Conventional [k€]	Shared anchor [k€]	Difference [%]
Chain sections costs	829.5	668.4	-19.4
Polyester sections costs	871.3	1178.6	+35
Buoys cost	4074.0	887.3	-78.2
Anchors cost	887.4	695.7	-21.6
Total cost	6662.1	3425.0	-48.6

The costs of the polyester sections increase significantly between conventional and shared anchor because of the increase in polyester length to allow connection between FOWTs. A significant reduction is achieved for anchor cost, due to the reduction of the number of anchors. The most significant decrease is obtained in the number of buoys used. This reduction is achieved thanks to the natural increase in yaw mooring stiffness obtained with the use of horizontal shared lines. During the design of the conventional mooring system a lack of yaw mooring stiffness was observed, leading to large yaw motions. This problem was solved by adding buoys. The cost reduction for chain is mainly due to the reduction of chain length thanks to shared mooring lines.

The design is validated by running DLC 6.1 and DLC 6.2 cases as defined in [7]. Both start-of-life and end-of-life analysis, accounting for marine growth and corrosion are assessed. The table below summarizes maximum values obtained for parameters of interest.

Table 12. DLC6.1 and 6.2

Parameter	Upwind line	Downwind line
UF[1] Chain [-]	0.53	0.94
UF[1] Polyester [-]	0.82	0.86
Offset [m]	29.1	
Pitch [deg]	6.8	
Yaw [deg]	3.2	
Horizontal acc. [m/s2]	4.4	
Vertical acc. [m/s2]	1.2	
Pretension [kN]	2126.7	

[1]UF utilisation factor

Utilisation factor is below 1 as required. Motions are also below expected criteria (15deg pitch and yaw, 104m offset). The maximum horizontal acceleration is significant, almost reaching the design criterion.

For this configuration, a modal analysis is also performed in OrcaFlex. This analysis requires to set the system in its static position. It is possible to include mean environmental conditions, which is not done in the present study. The analysis required a constant added mass matrix, while potential flow theory uses a frequency-dependant one. Hence, three matrices extracted from frequency-dependant matrices are used, to assess the influence of such a parameter on the behaviour of the system. The three frequencies are presented below, and they respectively correspond to approximately the middle of the 1P region, the minimum extreme wave peak period and the lowest frequency available.

Table 13. Added mass matrices used

Line	Added mass frequency used
Bottom green series[1]	0.1102
Middle green series[1]	0.0612
Top green series[1]	0.0159

[1]green series corresponds to modes on figure below

Results are presented on Figure 3. Green markers (three first row from the bottom) correspond to the first 25 modes of the system. The purple markers (top row) correspond to individual FOWT natural periods.

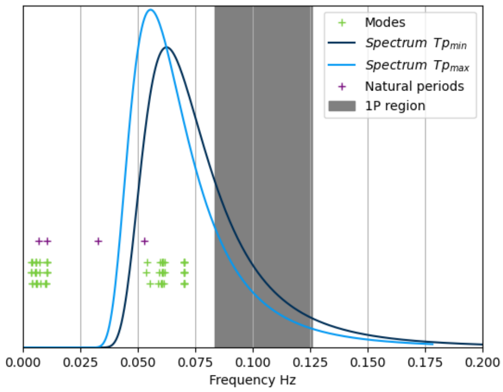

Figure 3. Modal analysis results.

The aim of this analysis is to evaluate if modes resulting from coupling FOWTs can appear in the 1P region of the turbine, which could lead to fatigue issues. First, results show that added mass has a low influence on the floater's modes. This analysis also shows that new coupling modes appear but out of the 1P region. This strategy can be used to screen various shared mooring lines configurations, in order to limit detailed analysis.

6. Conclusions and outlook

In this study the cost benefits of shared anchors and shared mooring lines are assessed for two sites and one floating platform, the ActiveFloat semisubmersible, developed as part of the Corewind H2020 project. The costs of the optimized layouts are compared to a reference single FOWT configuration already optimized in a previous task of the project.

Regarding the shared anchors study, for both sites studied it is possible to find a shared anchor layout that respects the design criteria. However, the costs of such layouts are very similar to the classic layout. As 85% to 90% of the procurement cost of the mooring system is due to the line materials costs, reducing the anchors cost was not enough to compensate the increased lengths of the lines connected to a shared anchor. Nevertheless, several aspects shall be considered to improve these results. First, as mentioned earlier, the installation costs are not considered in this study. Those costs are expected to decrease in a shared anchor layout. The spacing of 7D could be refined and potentially reduced. More advanced studies on wake effect and turbine positions relative to one another could be carried out in order to potentially reduce the spacing, and consequently the line lengths. Finally, it would be interesting to perform a sensitivity analysis on the effect of modelling a farm layout with more than 3 turbines.

The shared mooring line study found a shared mooring line layout that respects the design criteria. Moreover, noteworthy cost reductions (almost 50%) are reached thanks to a decrease in the number of buoys needed. As for a shared anchor layout, installation costs are not taken into account, and could lead to greater cost diminution. Nevertheless, practical aspects such as access and manoeuvrability around the turbines must be taken into account. Indeed, a surface buoy is for now chosen to link the shared lines together, and consequently the lines are close to the sea surface. This could impact the navigability around the turbines and make maintenance operations more complex. It would also be interesting to complete the study with investigations on shared mooring lines layouts on the moderate site (Gran Canaria). As mentioned earlier, the present study has been limited to investigations on the deep-water site since the cost of the mooring design is especially significant at such water depth.

7. Acknowledgements

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