Design and analysis of a ten-turbine floating wind farm with shared mooring lines

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Abstract. This paper discusses the development and analysis of a novel design for a 10-turbine floating wind farm with shared mooring lines. Shared mooring lines tether adjacent floating platforms together, reducing the number of anchors required but increasing system complexity. We present a systematic, multistage design process for shared mooring systems, involving linearized analysis of array layout options, quasi-static mooring line optimization, and design refinement based on coupled dynamic loads analysis. The design developed from this process is thought to represent one of the most advantageous shared-mooring configurations for this scale of floating wind array. It features perpendicular anchor line pairs and allows shared, multiline anchors, making it an example of a shared-mooring-and-anchor array. Comparing the performance and cost characteristics of the shared-mooring design with more conventional three-line individual mooring systems shows equivalent dynamic response characteristics and stationkeeping system cost savings of 25% when using shared mooring lines and shared anchors. The design is also advantageous in the case of a mooring line failure, with offsets and redundancy characteristics similar to four-line individual mooring systems.

1. Introduction

This paper presents a 10-turbine floating wind turbine array design featuring shared mooring lines—where mooring lines run directly between adjacent turbines—and assesses the design's cost and performance characteristics against a more conventional individual mooring approach.

Stationkeeping system components and associated installation processes are a significant cost and technical challenge to deep-water floating wind farms. In deeper waters, mooring lines need to be longer and anchor installation can be more difficult, increasing stationkeeping costs. Anchor layout can be more challenging due to the potential for interference between adjacent turbines' moorings. As such, a floating wind farm's stationkeeping system cost and design complexity generally increases with water depth.

Shared mooring systems are a technique for reducing mooring system costs in which mooring lines in the interior of the farm run directly between adjacent floating platforms, rather than running to anchors. This reduces the number of mooring lines reaching the seabed, thus reducing total mooring line lengths, and reduces the number of anchors used by the farm. The approach of sharing anchors in floating wind farms [1] is relatively well studied, but there is still a relative lack of literature on shared mooring systems. Goldschmidt and Muskulus [2] simulated three different prototypical shared-mooring farms, each with three to five turbines, and explored how the number of turbines affects the accumulation of thrust loads in the upwind mooring lines of the farm. Connolly and Hall [3] did a simplified parametric design study of three pilot-scale shared-mooring floating wind farm designs over a range of water depths and found cost savings at depths greater than 500 m. Wilson et al. explored shared-mooring array designs more broadly using a linearized approach—developing a new design approach and comparing many array layouts at a single water depth [4].

Other work has looked at the coupled dynamics of shared mooring systems. Hall and Connolly [5] created a preliminary dynamic modeling capability and analyzed an example four-turbine, four-anchor array and found that that using shared mooring lines reduced the relative magnitude of the extreme and fatigue mooring loads. Connolly [6] explored the potential of resonances in shared-mooring arrays. Liang et al. [7] studied the restoring and dynamic response characteristics of a two-spar array with one shared line and four anchor lines. Munir et al. [8] studied the dynamic response of a similar array, but with a semisubmersible platform design.

Shared mooring systems have more design challenges than conventional mooring systems because they introduce inter-platform couplings; one platform's motions and stationkeeping properties affect those of other platforms it is attached to. While previous studies touch on some design and modeling implications of these couplings, none describe a design process for shared-mooring floating wind arrays.

In this paper we present a novel 10-turbine shared-mooring floating wind array, the design process we developed for it, and an evaluation of its performance relative to a conventional mooring design. The description and demonstration of the design process (detailed in Sections 2 and 3, respectively) can guide other shared-mooring design efforts. Section 4 evaluates the design and identifies specific benefits that can contribute to the collective understanding of mooring design possibilities.

2. Design methodology

Designing a shared-mooring floating array involves significantly more variables and considerations than designing conventional, individual mooring systems. We developed a design method that goes through several stages, beginning with a simplified linearized analysis of the array layout options, then a quasi-static optimization of each mooring line within the array, and then an iterative design adjustment process that uses time-domain coupled dynamics modeling of the full system (Figure 1).

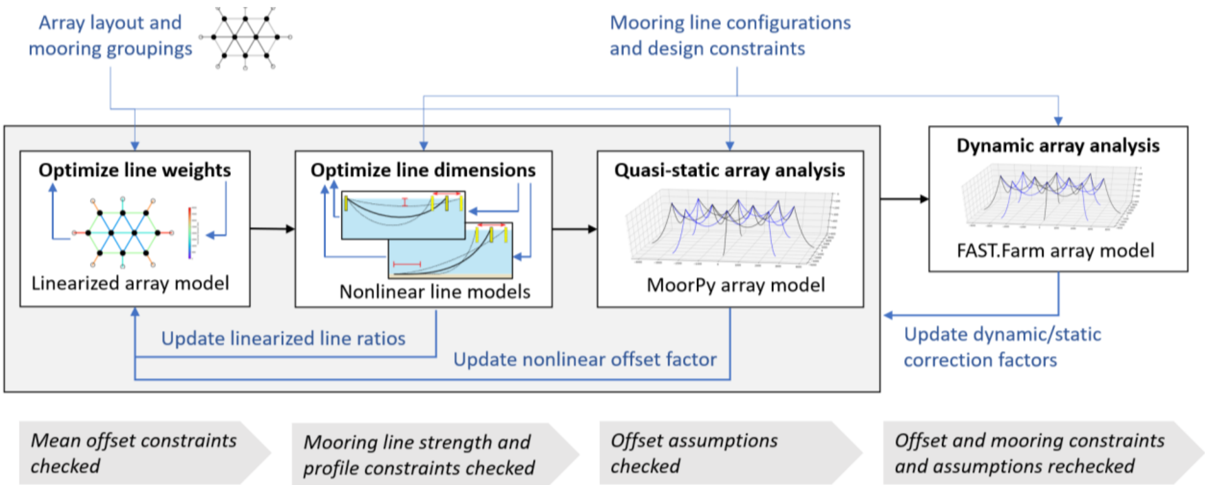

Figure 1. Iterative array-level shared mooring system design process with four stages.

For the design in this paper, we assumed floating wind turbines consisting of the DTU 10-MW reference turbine on appropriately sized spar platforms, with a 600-m water depth, turbine spacing of 1600 m, and an array size of 10 turbines. The following subsections detail the four stages of the design process, and the assumptions and constraints used in each.

2.1. Array layout design

At the first design stage, we consider the turbine and anchor locations, the choice of shared mooring connections between turbines, and the distribution of restoring properties among each mooring line in the system. Our approach was to explore layout options manually, and for each layout use an optimization approach that ensures platforms have the desired equilibrium positions and stay within the desired maximum offset limits.

We consider a shared-mooring array layout to be a two-dimensional definition of the platform and anchor positions, the mooring line attachments between those positions, and the groupings of mooring line types. Mooring lines within a group are set to have identical properties for design practicality. After coming up with a shared-mooring layout, we determine its optimal mooring properties using a simplified method, detailed in [4], that approximates each mooring line's horizontal force-displacement properties as linear. The resulting horizontal tension and effective stiffness of each mooring line is scaled by mooring line weight (a proxy for mooring line cost) to allow simple adjustment of the restoring strengths for each mooring line group. The coupled stationkeeping properties can then be represented by an array-level stiffness matrix. This allows direct computation of each turbine's watch circle (the envelope of maximum offsets in every direction), while accounting for the couplings introduced by the shared mooring lines. It also facilitates a general algorithmic solution for ensuring that the shared mooring system provides "layout equilibrium"—being in equilibrium at the desired positions in the absence of external forcing—which significantly reduces the optimization problem complexity. A full description of the method and its application to various shared-mooring array layouts is given in [4].

In the present design work, we applied the method of [4] to each candidate array layout to optimize the mooring line weights to minimize the overall mooring system weight while satisfying layout equilibrium and keeping each turbine's mean offsets within a limit of 60 m (10% of the water depth). We began by assuming catenary mooring line profiles and an anchor radius of 1,600 m, then revisited those choices in later design stages. Figure 2 shows a sample of the optimized results for different array layouts, with line colors indicating the optimized weights and the gray ellipses showing the watch circles of the turbines. The optimization also gives the optimized total mooring system weight, which we combined with estimates of anchor loads to predict total stationkeeping system cost. From the results, we determined that the main indicator of stationkeeping efficiency (in terms of weight per turbine) is how even and round the watch circles are. This finding guided us to focus on layouts that feature perpendicular anchor line pairs and that avoid long series of shared lines, since inline shared lines result in direct addition of mean tensions. After a layout is selected, the key outputs from this design stage are the target horizontal tensions and effective stiffnesses of each type of mooring line in the array.

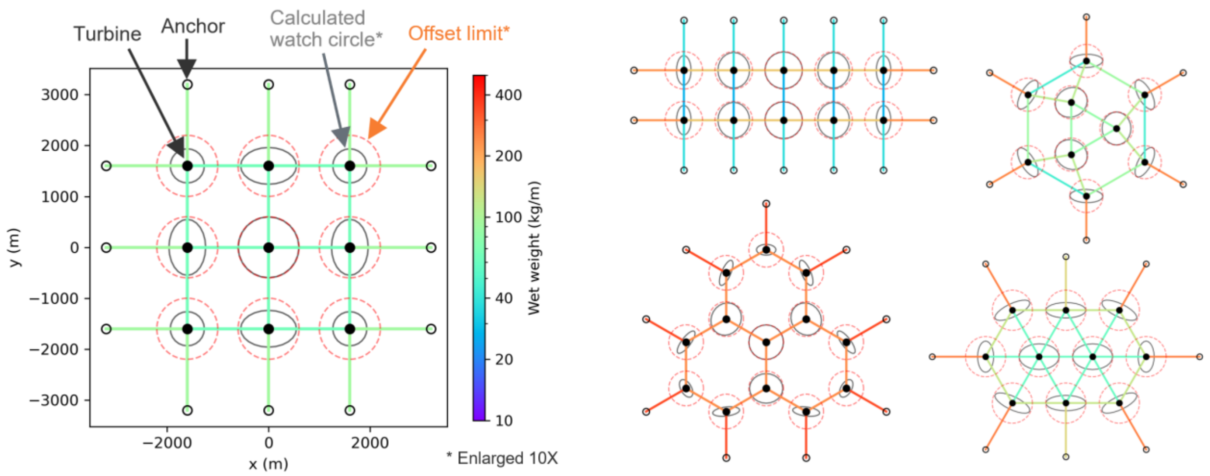

Figure 2. Example array layouts analyzed using the linear method.

2.2. *Individual mooring line design*

Once the array layout and its optimal linearized mooring line characteristics are set, the mooring lines themselves need to be designed. This involves choosing the mooring line segment materials, sizes, and lengths to meet the target tension and stiffness characteristics while also satisfying design constraints related to mooring line strength, anchor uplift loads, and so on. We approach this by developing a mooring line optimization algorithm that uses the quasi-static mooring model MoorPy [9]. This model captures the static, nonlinear behaviors of the individual mooring lines over the range of motion predicted by the linear array analysis. A numerical-gradient-based optimization algorithm finds the design variable values that minimize cost while meeting applicable design constraints.

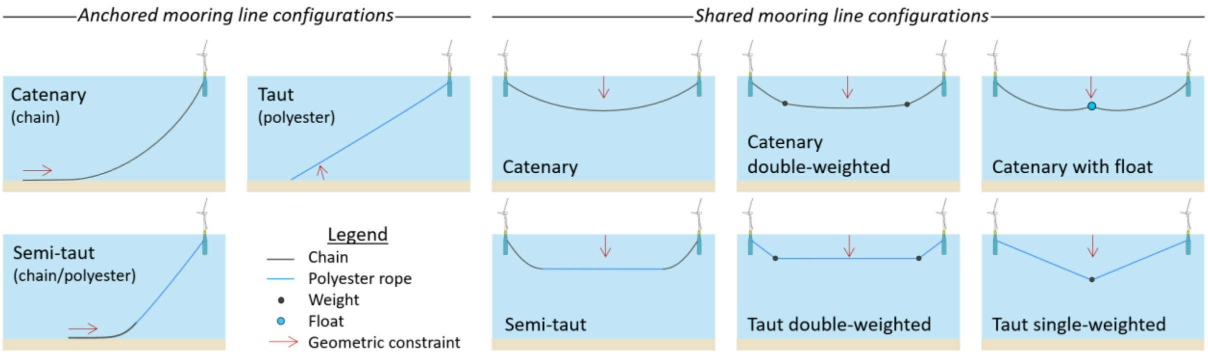

Figure 3. Mooring line configurations considered in the design. Possible design variables include diameter and length for every line segment, anchor position, and the size of weights and floats. Every line segment has a strength constraint. Special geometric constraints are shown by arrows.

We considered a variety of mooring line configurations, shown in Figure 3. Anchored mooring line configuration options were catenary, semi-taut, and taut configurations, assuming drag-embedment anchors for the first two and suction piles for the taut configuration to allow vertical anchor load. For the shared mooring lines, with minimal examples available in the literature, we identified six profile options: three that use chain with optional weights or floats, and three that use polyester rope with either chain or clump weights to ensure the necessary depth below the waterline while maintaining adequate stiffness. Because this design stage is focused on general stationkeeping behavior, short chain segments used for tensioning or anchor attachment, and bridle configurations to attach to the spars, are not included in the mooring line configurations.

The configurations in Figure 3 have corresponding design variables that dictate the length and diameter of each line segment and the size of any clump weights or floats. We use component-based cost modeling at this stage so that the optimizer can minimize cost. Table 1 shows the cost assumptions, which we chose to be in line with estimates received from industry advisors and coefficients used in other studies. We also size the anchors at this stage so that their costs can be included in the optimization. The sizing is based on the predicted maximum load on the anchor multiplied by the appropriate safety factors from API RP-2SK. For suction piles, the safety factors are 1.6 in the vertical direction and 2.0 in the horizontal direction.

Table 1. Assumed coefficients used in stationkeeping cost estimates.

Stationkeeping cost component	Cost coefficient
Chain	$2,585 per tonne weight
Polyester Rope	$0.162 per tonne break strength
Clump Weight or Float	$1,000 per tonne weight
Suction Pile	$1,080 per tonne anchor capacity
Suction Pile Installation and Removal	$360 k per anchor

Each configuration also has specific design constraints. We specified that anchored lines with drag-embedment anchors must maintain at least 30 m of mooring line on the seabed even in the most extreme offsets. In the semi-taut configuration, the polyester rope segment must never come within 30 m of the seabed, to avoid abrasion risks. The taut configuration must maintain a nonzero departure angle at the anchor so that there is no risk of rope contacting the seabed (in practice, a short chain segment would take any seabed contact near the anchor). To allow vessel navigation over the shared mooring lines, we specified that the line midpoints must maintain a depth of at least 60 m. In all cases, each mooring line segment must maintain a safety factor of 2.0 under the largest tension predicted using the quasi-static analysis, in accordance with API RP-2SK [10]. The optimization algorithm evaluates each constraint at the most challenging offset within the watch circles calculated from the linear analysis.

For each mooring group in the array, an applicable mooring line configuration can be optimized to determine the design parameters that minimize cost while satisfying the applicable constraints and the horizontal tension and effective stiffness requirements from the previous design stage. Multiple configuration options can be tried for each mooring group, then the preferred configurations can be selected from the results.

2.3. Nonlinear quasi-static array analysis

The third design stage combines the layout information and individual mooring line descriptions from the prior two stages, iterating between the linear system optimization and the nonlinear mooring sizing processes in a higher-level design loop to ensure internally consistent assumptions (Figure 1). We then use an iteration step to correct for any discrepancies between the assumptions used in the linear system optimization and the properties of the optimized nonlinear mooring line designs. The design stage begins by assembling a full nonlinear description of the array by assigning the individually optimized mooring line profiles into their locations within the array. This full array description is then analyzed in MoorPy to assess the nonlinear offsets and compare them with the linearized watch circle estimates provided from the first stage. The results are used to update the offset assumptions used in Stage 2 and adjust a factor in the first stage that represents the nonlinearity of the system response, making the offset assumptions in both stages up-to-date with a nonlinear array-level quasi-static analysis.

Additionally, the properties of each mooring line optimized in Stage 2 are linearized and used to update the assumptions in the linear system optimizer. This ensures the linearized models are a good approximation of the nonlinear force-displacement response of the selected anchored and shared mooring line configurations. The first and second design stages are rerun with their updated values, and this iterative process is repeated until the optimal design results converge.

2.4. Dynamic analysis and design refinement

The final design stage takes the array-level mooring system design that has been optimized using quasi-static models and adjusts it based on the results of coupled dynamic loads analyses. We used the simulation tool FAST.Farm, which is a variation of OpenFAST that allows simulation of multiple turbines in an array while accounting for wake effects and, in the latest version, shared mooring lines. We set up a FAST.Farm model of the array-level mooring design from the previous design stage, along with the chosen spar floating platform and the DTU 10-MW reference turbine. The array model can then be run through select design-driving load cases to check the platform offset and mooring line constraints from previous design stages under realistic dynamic conditions.

Depending on whether the dynamic simulation results show constraint violations or excess margin, the mooring design parameters (e.g., line diameters) can be sized up or down to satisfy all constraints at minimum cost. We made these design adjustments by inserting dynamic/static ratios (similar to dynamic amplification factors) into the quasi-static constraint calculations in Stage 2, and tuning these factors in proportion to how much each mooring line group's constraint values were off. After the adjustment, the entire sequence of design stages can be rerun. If the updated FAST.Farm simulations still show a constraint offset, further iterations can be performed until the desired margin is achieved for all constraints. In practice, we typically performed around 20 iterations to arrive at a converged design. This iterative, multistage approach balances the computational efficiency of quasi-static design algorithms with the thoroughness of checking constraints in coupled dynamic array simulations.

3. The design

This section describes how we developed the 10-turbine shared-mooring array design using the methodology laid out in the previous section.

3.1. *Array layout*

After comparing the linearized optimization results of over 40 shared-mooring array layouts, we selected the layout shown in Figure 4, which features two staggered rows of turbines with shared mooring lines that cross back and forth between the rows. This layout had one of the lowest estimated costs of all arrays considered at the scale of 10 turbines. We attribute this to its unique staggered arrangement of shared mooring lines and its use of perpendicular anchor line pairs. Staggering the shared mooring lines at right angles effectively minimizes couplings across the array; while one turbine is coupled by shared lines to its two neighbors, there is very little coupling between the two neighbors. The pairs of perpendicular anchor lines ensure each turbine individually has omnidirectional stationkeeping properties (in a linear approximation). Together, these features result in round watch circles for 8 out of 10 turbines, meaning the mooring system is very efficient. Results of the initial linearized optimization using catenary profiles from [4] yield target horizontal tensions of all mooring lines of 3.8 MN and target effective stiffnesses of 38.1 kN/m for the anchored lines and 16.7 kN/m for the shared lines.

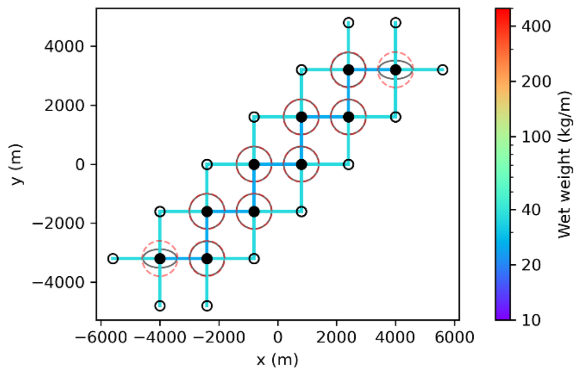

Figure 4. Selected shared-mooring array layout featuring staggered shared line and perpendicular anchor line pairs.

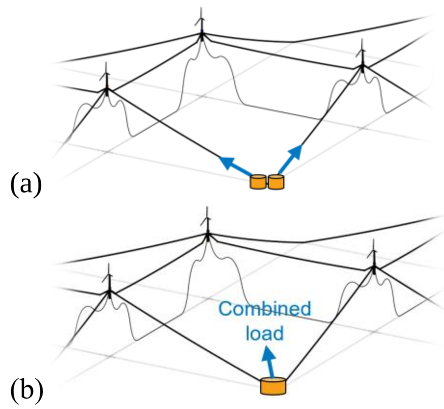

Figure 5. Illustration of anchoring options: (a) individual anchors and (b) replacing anchor pairs with shared anchors.

3.2. *Individual mooring lines*

The selected layout has two mooring line groups: one for the anchored lines and one for the shared lines. We applied the nonlinear mooring line optimization approach to each of these groups, testing all applicable mooring line configurations from Figure 3 for each. The taut polyester rope was the lowest-cost anchored mooring line configuration, and the polyester rope with two clump weights was the lowest-cost shared line configuration. At this stage, we also varied the anchor spacing and confirmed that spacing anchors around 1,600 m gave the lowest cost. This spacing also locates pairs of anchors in the same position, raising the possibility of using shared anchors, as illustrated in Figure 5. Figure 6 shows the resulting optimized mooring line profiles in the undisplaced and most-offset conditions.

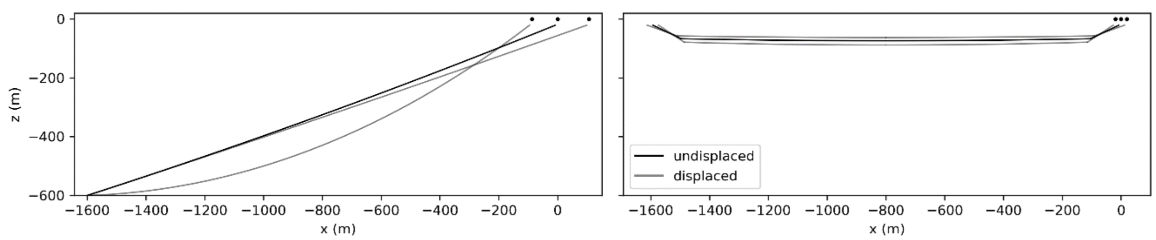

Figure 6. Optimized anchored and shared line profiles in undisplaced and displaced states.

The anchored line takes some curvature in its slackest condition but still maintains an angle off the seabed, as required by the constraint. The shared mooring line relies heavily on clump weights for achieving the target tension and stiffness while maintaining adequate depth below the surface. A 100-m length between the clump weight and the platform eliminates any collision hazard in the case of the shared line failing.

3.3. Assembled shared-mooring array

Inserting the optimized mooring line profiles from Section 3.2 into the array layout of Section 3.1 and adding in the floating wind turbines gives the array design pictured in Figure 7(a). The fairleads are located at a depth of 21 m and radius of 10.6 m. At this stage, we also inserted a bridle arrangement into the top 45 m of each mooring line to provide sufficient yaw stiffness on the spars. This system was then evaluated in MoorPy to check its mean offsets to the rated turbine thrust force across all wind directions, while accounting for the nonlinear mooring line response and shared-mooring couplings. Results showed that the largest offsets were 8% greater than predicted by the linear analysis. We applied this factor to the constraint evaluation in the linear analysis and then repeated the prior design steps so that the constraints would be properly met.

We also developed a simpler individual mooring system with three taut mooring lines for each turbine to serve as a baseline for comparing the shared-mooring array against, Figure 7(b). After optimizing the mooring lines, we found 175-mm polyester lines with 1,300-m anchor spacing to meet constraints at the lowest cost.

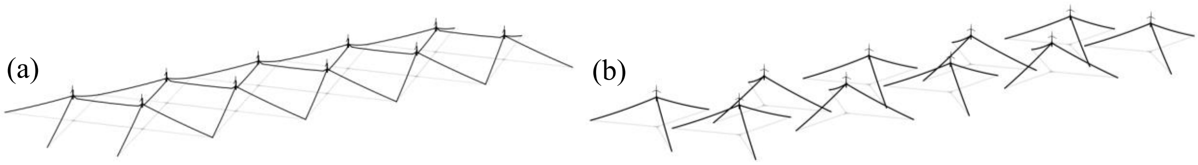

Figure 7. The quasi-static-optimized (a) shared-mooring and (b) baseline array designs.

3.4. Dynamic analysis and refined array design

For the final design stage, we set up FAST.Farm simulations of the baseline and shared-mooring array designs. We initially used nine different load cases, which combined rated and 50-year wind speeds with typical and 50-year wave conditions, at three different wind-wave headings to load the array in different directions. We ran each case in FAST.Farm for 1 hour plus an initial 10 minutes for start-up transients. Figure 8 shows a sample of the shared-mooring array's simulated mooring line tensions for a case with 11.4 m/s wind and mild waves at a 0° heading. The anchor line tensions are clearly separated into three groups depending on whether the lines are oriented upwind (greatest tension), crosswind, or downwind. The shared-line tensions all have similar mean values, but lines along the wave propagation direction have much larger amplitudes because they are excited by the platform surge motions. A full description of the simulations and their results will be published separately for space reasons.

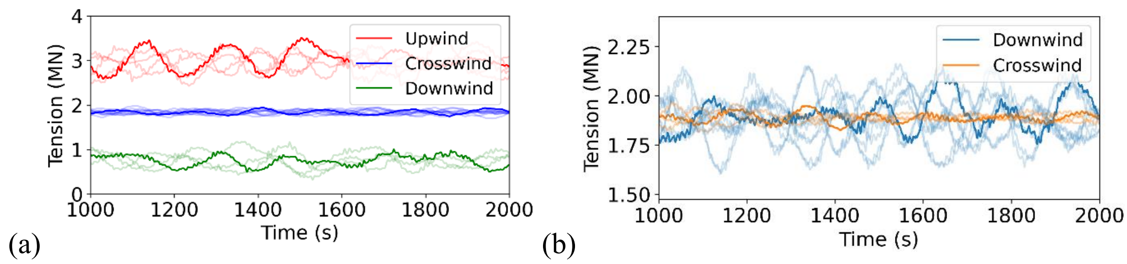

Figure 8. Example tensions at the fairlead of (a) anchored and (b) shared mooring lines in the array for the operating load case with 0° wind and wave heading.

The FAST.Farm results showed that the first design iteration from the quasi-static design process was overly conservative. The mean thrust force was lower than the rated thrust, and the system dynamics in FAST.Farm increased mooring line tensions only a small amount. The lower safety factor of 1.67 meant there was excess margin in the line strengths, which were the design-driving constraints. We updated the assumed factors for extreme offsets and dynamic/static tension ratios in the previous design stages, and then repeated the iterative design and loads analysis process until the most critical safety factors were satisfied by a margin of 5%–10%. We also revised the capacity of each array's anchors at this stage based on the largest anchor loads seen across the FAST.Farm results.

After the iteration process converged, the refined designs showed cost reductions on the order of 15% compared to the original designs based on quasi-static analysis. The changed design parameters and total cost estimates are given in Table 2.

Table 2. Original and refined design parameters for the baseline and shared mooring systems.

	Baseline design		Shared-mooring design	
Design parameter	Original	Refined	Original	Refined
Anchor spacing (m)	1,600	1,300	1,600	1,600
Anchor line diameter (mm)	175	175	213	209
Anchor line length (m)	1,644.1	1,373.5	1,639.7	1,632.1
Anchor holding capacity (t)	516	420	763	578
Shared line diameter (mm)			200	163
Shared line length (m)			1,563.3	1,514.6
Clump weight mass (t)			100	80
Total stationkeeping cost ($k)	32,180	27,950	32,180	27,090

4. Additional considerations and discussion

The shared-mooring array design was made to support shared anchors to realize further cost reductions without altering the rest of the mooring system. The design also has very favorable behavior when a mooring line fails. In this section we discuss those factors and make a final cost comparison. A brief analysis with semisubmersible platforms indicated similar results but is out of scope for this paper.

4.1. Shared anchors

In the shared-anchor variation of the shared-mooring design, 16 anchors along the long sides of the array—which are paired at coincident points—are replaced by 8 multiline anchors. Each of these multiline anchors has two lines attached at perpendicular headings (Figure 5).

To size the shared anchors, we modeled their loads as the vector sum of the tension vectors from each of the two attached mooring lines. The anchor capacity was then based on the largest value in this combined force time series, using the same safety factors as before. The design-driving load case for sizing the shared anchors is with a -45° wind and wave heading, which causes the greatest combined load from the tensions of the attached two lines. The final anchor capacities are 556 t for the six individual anchors and 782 t for the eight multiline anchors. This compares with the required anchor capacity of 590 t for the 22 individual anchors in the original shared-mooring design. The shared-anchor variation reduces the summed anchor capacity by 16% and the number of anchors by 36%.

4.2. Failure considerations

The system behavior when a mooring line fails is an important design consideration, especially when considering floating wind arrays where having multiple floating units increases failure risks. We checked the shared-mooring array under several failure scenarios to ensure that failure of one line will not subsequently cause additional failures in the array. A small set of FAST.Farm simulations confirmed that the mooring line tensions maintained a safety factor above 1.0 during the transient response following a mooring line failure, indicating that the shared-mooring array design is not at risk of cascading mooring failures.

We also ran quasi-static MoorPy analyses to characterize the steady-state offsets after different mooring line failures. This exploration revealed an unexpected benefit of the shared-mooring design in failure cases: it has significantly smaller offsets than the baseline three-line mooring system. Figure 9 illustrates the system offsets predicted by MoorPy in the worst-case scenario of an upwind anchor line failure. In general, the shared-mooring array offsets less than half as far as the baseline array. In the most extreme case with the turbine still operating at full rated thrust, the upwind turbine is offset by 580 m in the shared-mooring design, whereas it is offset by 1,370 m in the baseline array, coming close to the turbine behind it. This difference means the shared-mooring array could reduce the demands on power cables and could more easily meet redundancy criteria, which allows for reductions in safety factors that could further lower costs.

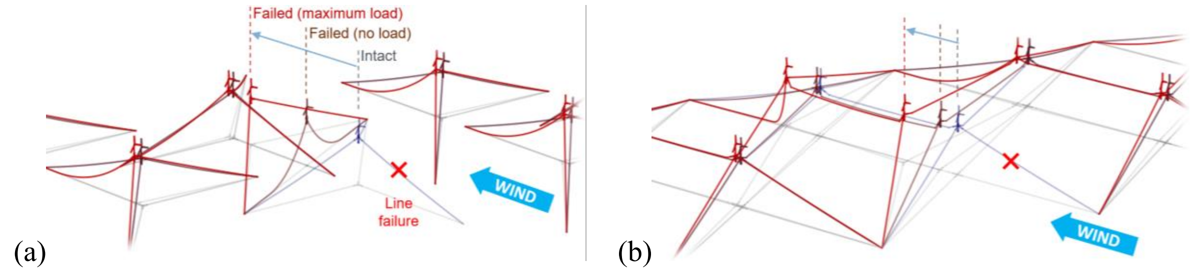

Figure 9. Equilibrium after an upwind anchor line failure for (a) baseline and (b) shared-mooring array designs.

4.3. Final cost breakdown and comparison

Based on the coefficients listed in Table 1, Table 3 shows the stationkeeping cost breakdowns of the four mooring system designs that we considered. This includes the three-line baseline design, the shared-mooring design with individual anchors, the shared-mooring design with shared anchors, and an alternative baseline design with four lines rather than three. We created this last design because having four individual mooring lines per turbine gives similar characteristics after a line failure as the shared-mooring design; it therefore provides a more representative cost comparison. The design is based on adjusting the original baseline design's mooring line strength and anchor capacities by three-quarters, and verifying the suitability through quasi-static model checks.

Table 3. Total array stationkeeping cost breakdown and comparison.

Quantity per 10-turbine array	Baseline	Shared mooring	Shared mooring shared anchor	Four-line baseline
Anchors (quantity x capacity)	30 x 420 t	22 x 578 t	6 x 556 t 8 x 782 t	40 x 315 t
Shared line cost ($k)	0	1,020	1,020	0
Anchor line cost ($k)	3,540	4,420	4,420	3,080
Anchor cost ($k)	13,610	13,730	10,190	13,610
Install and removal cost ($k)	10,800	7,910	5,040	14,400
Total stationkeeping cost ($k)	27,950	27,090	20,670	31,090

For all designs, the anchor and its associated installation and removal is the largest cost component. Comparing the designs in Table 3 in terms of anchors and total stationkeeping cost shows that the shared-mooring-shared-anchor array design shows significant cost reductions because of its reduction in the anchor count. Relative to the three-line baseline, the shared-mooring design has minimal cost reduction, but the shared-mooring-shared-anchor design gives a reduction of 24%. If we consider the value of the shared mooring system's beneficial behavior in line failures by comparing with the four-line baseline, the cost reductions increase to 13% with individual anchors and 34% with shared anchors.

5. Conclusions

We developed a systematic design process for shared mooring systems and applied it to design a 10-turbine shared-mooring floating wind array. The selected staggered shared-mooring design with perpendicular anchor line pairs and shared line pairs met the performance requirements under both quasi-static and dynamic simulations. It also showed significantly smaller excursions after a mooring line failure than a conventional three-line mooring system. In the conditions studied, the shared-mooring array design can reduce mooring-system installed cost by 3% relative to a three-line conventional design, and by 13% relative to a four-line conventional design. The use of shared mooring lines combined with shared anchors can reduce mooring system installed cost by 26% relative to a three-line conventional design, and by 34% relative to a four-line conventional design

These conclusions shed light on the design of shared mooring systems and provide an early demonstration of how shared stationkeeping components can reduce overall stationkeeping system material and installation costs, offering a way to lower the cost of wind farms in deep waters.

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