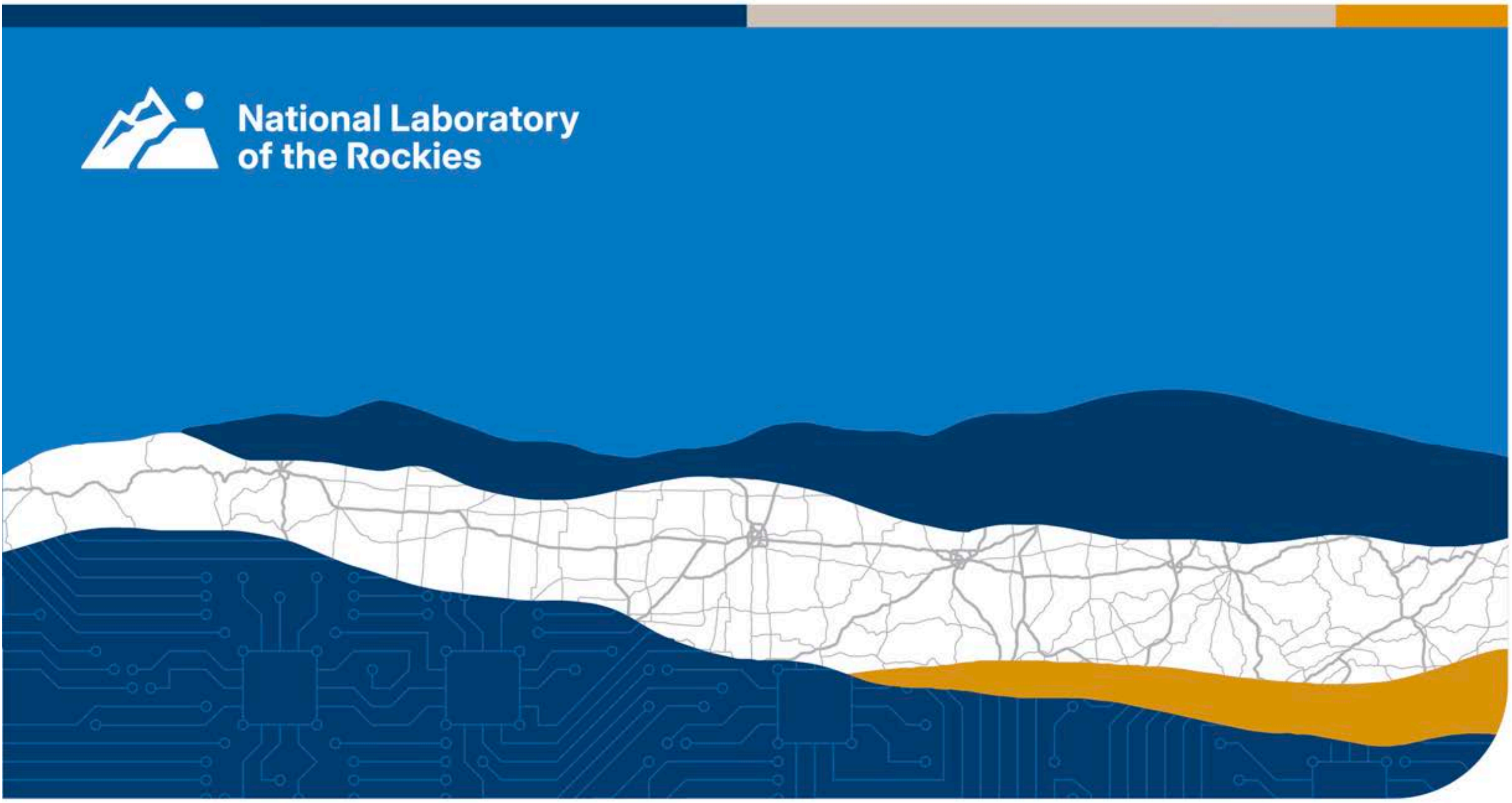

Standardized Scalable Mooring Solutions Optimized for the U.S. Supply Chain

Final Report

Stein Housner[1], Matthew Hall[1], Nicholas Riccobono[1], Felipe Moreno[1], Josiah McVicar[2], and Tristan Flannery[2]

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Produced under direction of National Offshore Wind Research and Development Consortium by NLR under Agreement number FIA-21-21462.

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Strategic Partnership Project Report
NLR/TP-5000-97918
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List of Acronyms and Abbreviations

ABS	American Bureau of Shipping
AEP	annual energy production
API RP	American Petroleum Institute Recommended Practice
CapEx	capital expenditures
D&G	drilled and grouted (pile anchors)
FLORIS	FLOw Redirection and Induction in Steady State
IEA Wind	International Energy Agency Wind Technology Collaboration Programme
LCOE	levelized cost of energy
NOWRDC	National Offshore Wind Research and Development Consortium
NLR	National Laboratory of the Rockies
OpEx	operational expenditures
ORBIT	Offshore Renewables Balance-of-System and Installation Tool
WOMBAT	Windfarm Operations and Maintenance cost-Benefit Analysis Tool

Executive Summary

This report presents a collection of research on mooring solutions for large U.S. West Coast floating offshore wind farms that are standardized to enable serial production and leverage the domestic supply chain. It is the final report of the project *Standardized Scalable Mooring Solutions Optimized for the U.S. Supply Chain*, which was funded by the National Offshore Wind Research and Development Consortium, led by the National Laboratory of the Rockies, and supported by Delmar Systems. The large range of water depths in existing U.S. West Coast offshore wind lease areas may lead to a large variety of mooring designs and component sizes unless standardization methods are developed. The capacity of the domestic supply chain for mooring components is a key constraint on floating wind energy project deployment rates, an effect exacerbated by variation in component types and sizes. This project explores how standardization and careful selection of component types and sizes can lead to more scalable and domestically manufacturable mooring systems under realistic West Coast site conditions with large depth variations. It involves mooring system design at the array level accounting for site bathymetry and integration of a supply chain model within the design loop to enable optimization for supply chain lead time. The findings include estimation of the current and possible future supply chain capacities, engineering of preliminary mooring system designs for California lease areas, and comparison of costs and supply chain impacts across mooring design alternatives.

The first task of the project develops two baseline designs, one in a Humboldt lease area and one in a Morro Bay lease area, that do not use standardization but rather have each mooring line and anchor individually designed for its specific water depth and location in the wind farm. Each farm consists of 40 floating wind turbines arrayed in a rectangular grid layout. The floating wind turbine design is the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) 15-MW reference turbine on the VolturnUS-S reference semisubmersible platform. To suit the deep water, the mooring designs use taut mooring lines of polyester rope with short chain sections at the seabed attaching to suction pile anchors as well as short chain sections near the waterline attaching to the floating platform. In certain seabed areas with rock (rather than mud), drilled-and-grouted pile anchors are used instead. The Humboldt baseline design uses three mooring lines and anchors per turbine. The Morro Bay baseline design uses six mooring lines and anchors per turbine, providing a more redundant mooring option with smaller individual component sizes. An efficient design methodology allows each mooring system to be individually sized to suit the water depth at its anchor's position and meet ultimate and fatigue load design requirements across all 40 turbines in each array without having to run the full loads analysis for every turbine. This design process resulted in baseline mooring system designs with 35 unique chain diameters and 112 unique anchor diameters for the Humboldt site and 29 unique chain diameters and 55 unique anchor diameters for the Morro Bay site. In contrast, only two rope diameters were needed for each site. Each mooring line section had its own length to cater to its local depth and extreme and fatigue loads. This wide variety in component sizes (with the exception of rope diameter) demonstrates the complexity that arises if mooring systems are designed individually, which would require the supply chain to deliver many different component sizes, each in relatively small quantities.

The second task characterizes the domestic supply chain of these mooring system components, using the mooring component volumes from the baseline designs as reference points. We

identified existing domestic suppliers of chain, rope, and anchors that could potentially support the required level of manufacturing and transportation to port for the baseline designs. The domestic supply chain for chain has sufficient workforce but currently can only manufacture chain with nominal diameters up to 127 mm (5 inches), where the nominal diameter is the diameter of the steel rod used to form the chain links. These chains would also require upgrades to meet the necessary offshore grade and certification for permanent floating wind moorings. The domestic supply chain for rope can support the expected mooring rope sizes but production rate is limited by the workforce and processes available for splicing the ends of each rope. The domestic supply chain for anchors has ample suppliers on the Gulf Coast but would require long trips to ship by barge from the Gulf Coast through the Panama Canal to the West Coast. The supply chain and the suppliers' capacities (e.g., throughput, transportation speed) were implemented into the existing Offshore Renewables Balance-of-System and Installation Tool (ORBIT), allowing for full arrays of mooring system designs to be simulated through a supply chain model and enabling calculations of lead time. The total existing supply chain can support the needs of single floating wind projects at the scale studied in this project (600 MW), but some supply chain capacities would be saturated for more than a year. Larger deployment scenarios at the scale of 1 GW per year would therefore not be possible without domestic supply chain expansion. Expansion scenarios were discussed with suppliers of each component type to identify likely expansion steps to support larger amounts of floating wind components. In general, there is an appetite to expand, but demand certainty would be required before investing in expansion.

The third task explores standardization techniques for mooring system design. Different techniques are identified, including homogenizing component types and sizes (like diameters, lengths), sharing components between turbines (like lines and anchors), or other strategies to vary the design or layout to simplify materials or logistics. The techniques are initially studied in isolation using quasi-static mooring design tools and the supply chain model in ORBIT to assess their potential to influence the total mooring system material cost or supply chain lead time. The cost of manufactured and delivered components is calculated only as a function of component mass, in which cost effects of economies of scale, manufacturing setup, or shipping logistics are not considered. These initial studies show that shared anchors provide the largest reduction in supply chain lead time due to a reduction in the total anchor count in the array while marginally increasing anchor sizes to account for multi-line loads. Standardizing mooring line and anchor diameters, by binning diameters to specific standardized sizes, shows a trade-off between increasing component material costs (due to binning and increasing component sizes) and decreasing supply chain lead time (due to decreasing the number of unique sizes to manufacture). Other standardization techniques can provide additional benefits to a project related to staging and installation logistics, but these aspects are not yet quantified.

The fourth task develops and describes new standardized designs for the two sites, improving on the baseline designs using the most effective standardization strategies in combination. These designs use multiple standardized chain diameters and anchor diameters within new shared anchor layouts. The anchors were resized to account for the shared anchor loads before the component size standardization. The choices of standardized sizes are selected following a multi-objective study using the new ORBIT supply chain model within the design loop that aimed to minimize both cost and lead time. The standardized designs increased component material costs relative to the baseline designs by 9% for Humboldt and 20% for Morro Bay but provided reductions in supply chain lead time of 4.5 months and 8 months, respectively. The supply chain modeling assumptions factor into the lead time results considerably. For example, the anchor supply chain modeling assumes two parallel assembly lines, but additional lines could be used.

The fifth task performs a levelized cost of energy (LCOE) analysis between the baseline and standardized designs for the two sites, using the most updated LCOE modeling tools available with many assumptions such as turbine costs, platform costs, and port fees. The results found an increase in LCOE of 1.0% between the standardized and baseline designs for the Humboldt site and a decrease in LCOE of 1.0% for the Morro Bay site. Even though the mooring system material cost is larger in the standardized designs for each site, the changes in annual energy production due to the new shared anchor layouts and the inclusion of higher failure rates of the shared anchors have a larger effect on LCOE.

The overall finding from the project is that standardization of mooring system components for deep-water floating wind farms reduces logistical complexity, improves supply chain efficiencies, and has mixed effects on costs. Standardization reduces supply chain lead times and increases total mooring system material weights, which can result in increased component costs unless countered by savings from economies of scale. The existing domestic supply chain has the capacity to supply a single project, but supplying multiple large-scale project deployments would require significant expansion. Standardization of chain and anchor diameters and the use of shared anchors have the greatest potential for supply chain lead time reductions and can either increase or decrease LCOE on the order of 1% depending on the specific site and design characteristics. Additional aspects of standardization, such as mooring line interchangeability or port storage and handling, can also provide benefits but have yet to be quantified.

General conclusions from the design process are that (1) rope size standardization can be achieved with little change to the design characteristics, (2) standardization of chain and anchor diameters involves a balance between material cost and manufacturing considerations, and (3) shared anchors help reduce both cost and lead time. For continued investigation, development of higher-fidelity supply chain models could provide more comprehensive results and help identify new supply chain strategies to support varying levels of deployment. Specific improvements include accounting for port handling and installation processes and the manufacturing and transportation cost impacts of different component quantities and sizes. Overall, this work set up a new supply chain model, identified different mooring standardization strategies, and applied them to two floating wind farms with individually sized mooring system components, finding that including the supply chain (and other total project processes) in the design process yields different results than conventional design studies.

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1 Introduction

Large arrays of floating wind turbines would require unprecedented quantities of mooring lines and anchors compared to existing offshore projects. Water depths in existing U.S. West Coast offshore wind lease areas range from 500 m to 1,300 m, entailing large variations in mooring system dimensions. If conventional design approaches are applied for each mooring system on an individual basis, the designs for a single 600-MW wind farm would contain a large variety of component sizes that would aim to minimize cost by minimizing material use; however, production of uniquely sized components would be more complicated and increase supply chain lead times. The mooring component demand of one project could also saturate the current capacity of the domestic supply chain. Therefore, harnessing offshore wind energy along the U.S. West Coast would require new stationkeeping solutions that improve economies of scale and use local supply chains more efficiently.

The project *Standardized Scalable Mooring Solutions Optimized for the U.S. Supply Chain*, funded by the National Offshore Wind Research and Development Consortium (NOWRDC) and led by the National Laboratory of the Rockies (NLR), aims to address these challenges. Working with project partner Delmar Systems, our goal is to develop mooring system solutions that use careful selection of configurations and component sizes to maintain cost-effectiveness, support domestic manufacturing, and reduce supply chain lead times and bottlenecks.

1.1 Background on Floating Wind Mooring Supply Chain

Cost-effective stationkeeping for floating wind farms in deep waters is an open design problem, with no floating wind projects yet built in the 500–1,300-m depth range found in existing U.S. West Coast offshore wind lease areas. Deep water generally entails longer mooring lines and therefore higher cost and supply chain demand. Large projects approaching 1 GW capacity would face significant challenges in sourcing the required quantities and sizes of stationkeeping components, which include chain, rope, anchors, and accessories such as connectors and buoys (Figure 1). A single project of this scale would currently impact the entire global stationkeeping supply chain, and hence, the capacities of the stationkeeping supply chain will be a key limiting factor on floating wind deployment timeframes.

Figure 1. Illustration of stationkeeping components staged at port, including anchors, chain, spools of rope, and various accessories.

Illustration from Delmar Systems

Two important supply chain challenges with floating wind mooring systems are large component sizes and component size variation. The large size of current offshore turbines (around 15 MW) entails mooring component sizes that are at the upper end of what is typically manufactured, especially when it comes to chain size. In large floating wind farms, especially off the U.S. West Coast, the wide range of water depths within a lease area can lead to a variety of optimal mooring component types and sizes. This variety increases the demands on the supply chain, requiring manufacturers to switch between equipment to produce different component sizes and generally making it more difficult for local suppliers to meet the need. Variety in component sizes also complicates design, installation, and maintenance processes. Without a solution for standardizing stationkeeping components, depth variations will pose a challenge to the deployment of large floating wind projects on the U.S. West Coast.

Sourcing stationkeeping components from the domestic supply chain can increase local economic benefits and reduce shipping emissions while also helping meet possible local content requirements. An NLR analysis estimates that more than 15% of jobs associated with floating wind projects relate to the stationkeeping system (Shields et al., 2021). Therefore, maximizing local content for stationkeeping systems will have a direct effect on realizing local economic benefits.

However, existing domestic suppliers that can produce various stationkeeping components are not currently able to fully meet the quantity or the specifications demanded by large floating wind projects. A previous study found that the domestic supply chain for mooring chain and rope lacks the required equipment or certifications for permanent offshore moorings (Shields et al., 2022). Creating a new specialized mooring chain facility was estimated to cost $500 million and take 4–5 years to build and permit (Shields, Stefek, et al., 2023). Importantly, uncertainty in demand makes it difficult for existing suppliers to restructure their operations to support offshore wind development. These are critical areas of uncertainty on the path to large-scale floating wind projects in the United States.

Port capabilities are another important aspect of the supply chain. Pathways for developing ports on the West Coast were studied in a recent project (Shields, Cooperman, et al., 2023).

Across the floating wind sector, industrialization to streamline manufacturing and leverage local supply chains is widely seen as a top priority for advancing the technology and lowering costs. While technology developers have focused on substructures designed for manufacturability, strategies for industrializing stationkeeping systems have received less attention. The need for standardized and scalable mooring solutions was well documented in the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Topical Experts Meeting 99 (Desmond et al., 2020) and is evidenced by high industry engagement in moorings research projects. Floating wind project developers often face the additional challenge of satisfying local content requirements when sourcing components. As such, the alignment of stationkeeping designs and local supply chain capabilities directly affects the feasibility, timelines, and costs of their projects.

1.2 Floating Wind Mooring System Standardization

One of the general design strategies to minimize supply chain bottlenecks is standardization. In floating wind farms, where hundreds of mooring systems are needed, adopting a small number of standard component types and sizes offers a significant advantage for mass production compared to custom-designing each individual mooring system as is common in the offshore oil and gas industry. Within the floating wind industry, the largest installation as of 2025 is Hywind Tampen, which involved 11 turbines. There, as in other smaller floating wind projects, the mooring systems tended to use the same chain and rope diameters. However, the ability to standardize in larger installations, where conditions vary significantly over the size of the project, raises technical challenges that require investigation.

Standardization in the context of a floating wind project entails making strategic choices to reduce design and deployment complexity across an array with variations in site characteristics, such as water depth (Figure 2). The simplest standardization concept is to choose uniform component diameters for mooring lines or anchors so that the same production equipment can be used to manufacture all components and only line lengths are varied to accommodate changes in water depth. The disadvantage of the uniform diameter approach is that it will require some components to be sized larger than necessary. Mooring line or anchor lengths can also be made uniform to make these components interchangeable and avoid tracking different-length components for different locations in the array.

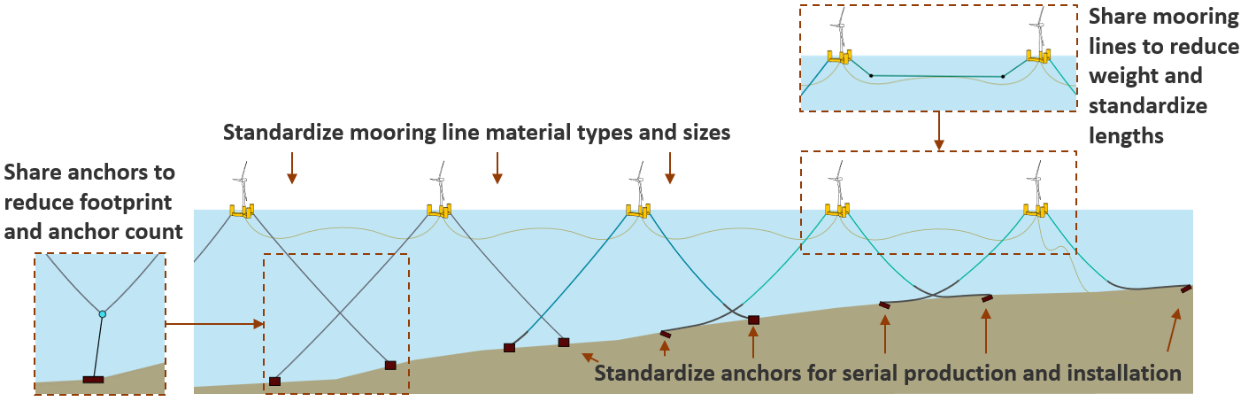


Figure 2. Types of mooring standardization

Another standardization technique is to apply shared stationkeeping configurations to minimize the number of components involved in an array or interacting with the seabed, thereby reducing complexity. Two previous NOWRDC projects looked at shared mooring lines and shared anchors for floating wind farms in deep waters, and the existing Hywind Tampen wind farm demonstrates the use of shared anchors in a commercial project. Shared mooring innovations have technical and supply chain benefits, but dedicated research on standardized and scalable stationkeeping solutions is needed for all configurations.

1.3 Project Objectives and Scope

The objective of this project is to develop highly scalable stationkeeping solutions for U.S. West Coast wind farms that are standardized to enable serial production and leverage the domestic supply chain. Through these designs, we aim to determine whether the benefits from standardization and the inclusion of a supply chain model in the design process can outweigh the benefits of individual component cost-optimization as seen in conventional design approaches.

We focus specifically on the supply chain for stationkeeping system components for the West Coast because these areas are the most developed lease areas for floating systems. These areas are also distinguished by having much deeper water than existing floating wind projects, which means they require longer mooring lines and therefore place a higher demand on the supply chain.

There are many standardization options, ranging from simply finding a small set of component types and sizes that work across diverse conditions to applying shared stationkeeping configurations that minimize how many components interact with the seabed. We consider this range of possible strategies before focusing on those that appear most effective.

The project's approach is to (1) perform stationkeeping design at the array level to identify the most effective standardization opportunities across a range of water depths and (2) integrate a supply chain model in the design loop to enable optimization for supply chain capabilities (Figure 3). These activities make use of the open-source models OpenFAST (for coupled dynamics analysis of floating wind systems) and ORBIT (the Offshore Renewables Balance-of-system and Installation Tool). By standardizing and maximizing use of the local supply chain, the project’s solutions will mitigate supply chain obstacles to the deployment of floating wind projects while lowering project risks and increasing local benefits.

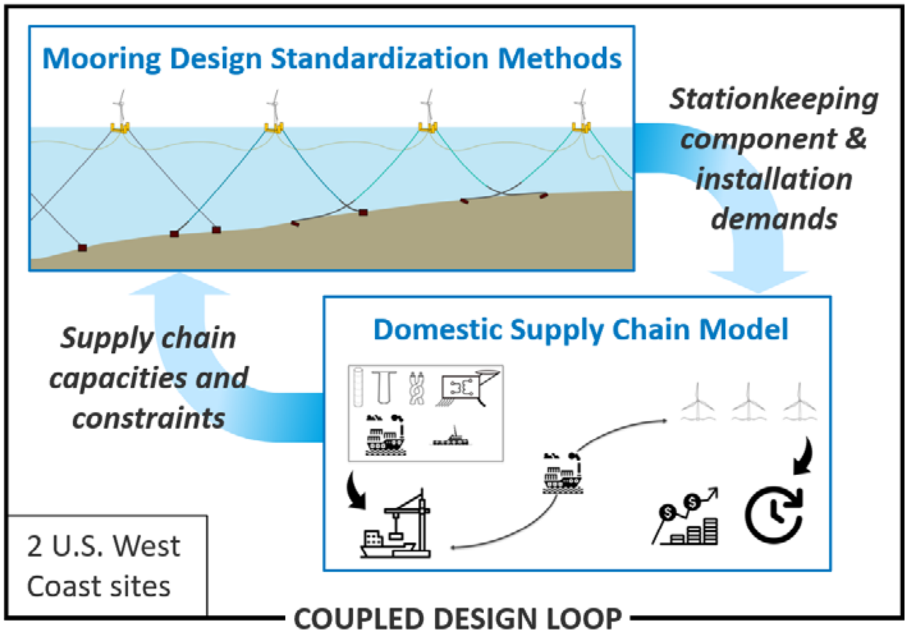


Figure 3. Coupled mooring design loop that includes the supply chain model

Evaluating the effectiveness of different standardization approaches requires developing viable mooring system designs following each approach and then evaluating the change in supply chain demand relative to baseline designs. We developed two 600-MW floating wind farm mooring system designs for two California lease areas and then standardized their mooring system components to compare the impacts on the supply chain. To align with current turbine sizes and technologies being considered in both research and commercial projects, we use the IEA Wind 15-MW reference turbine (Gaertner et al., 2020) and the VolturnUS-S semisubmersible platform design (Allen et al., 2020). Power cables throughout the array are not in the project scope, since dynamic cable designs for the variable water depths in question are a research topic of their own. However, maximum offset constraints in the mooring design process will ensure that the mooring designs are suitable for typical dynamic power cable designs that would be used at these sites.

This approach is in contrast with a more engineering-optimal approach in which each mooring line in a floating wind farm could be individually optimized, resulting in less material use but a wide variety of component sizes across a wind farm. This project uses both approaches to design array-level mooring systems and then compares the resulting designs in terms of component sizes, costs, and supply chain lead times.

To model the supply chain, we take real-world supply chain capacities of mooring system components and integrate them into a new supply chain discrete-event simulator. We consider the manufacturing time, manufacturing limits, transportation times, and capacities, but we do not quantitatively consider the installation of the components at a site. We also consider the design of mooring system components and how they impact the manufacturing process and transportation from manufacturing facility to port or staging area.

The resulting standardized designs will identify stationkeeping solutions for U.S. West Coast floating wind farms that can enable serial production using components and methods suitable for the domestic supply chain. By standardizing and maximizing use of the local supply chain, the project's solutions will mitigate supply chain obstacles to the deployment of floating wind projects while lowering costs and increasing local benefits.

The project's research scope was organized into four tasks. Task 1 developed two representative 600-MW floating wind farm designs for two different U.S. West Coast lease areas. These designs feature stationkeeping systems that follow existing design approaches to serve as baselines against which to compare innovative solutions. Task 2 developed characterizations of the domestic stationkeeping supply chain. This included expanding the ORBIT cost and logistics model to include supply chain details and developing scenarios for the potential future domestic supply chain. Task 3 developed design techniques for standardizing stationkeeping system configurations that are compatible with a range of water depths while using components that are well suited to serial production. Task 4 integrated the expanded ORBIT model of potential domestic stationkeeping capabilities with the developed stationkeeping system standardization methods to perform a holistic design optimization of stationkeeping systems. This coupled optimization yielded standardized stationkeeping solutions that balance cost reduction, scalability, and maximum compatibility with the domestic supply chain.

2 Site Conditions and Baseline Designs

We selected two representative sites in existing California lease areas to use as case studies for the project. By accounting for realistic meteorological and oceanographic (metocean) and seabed characteristics at each site, we can explore the mooring design options in a realistic way. We accounted for the following aspects in the mooring designs, each of which has an impact on the mooring component sizes or design variations across the array:

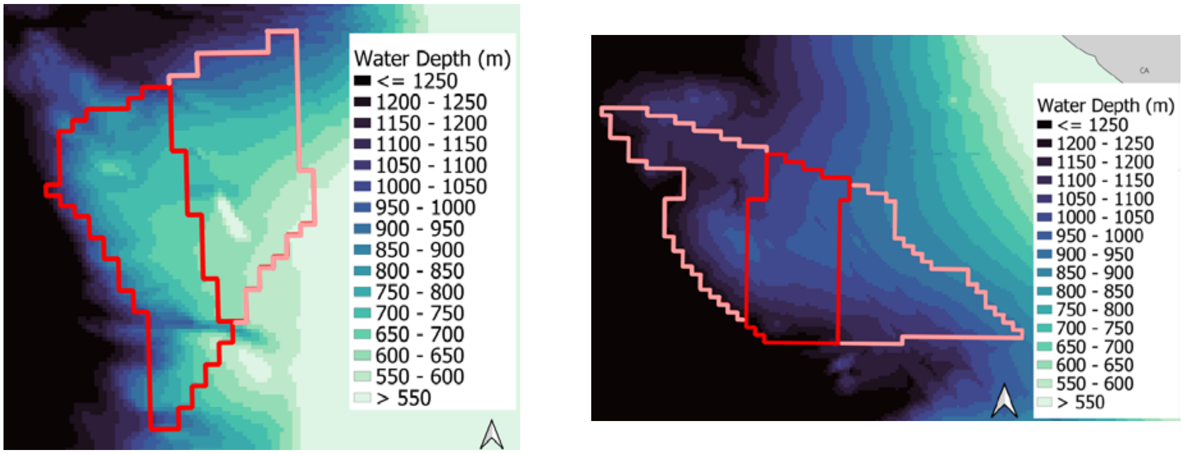
- Seabed bathymetry and variable soil conditions
- Omnidirectional metocean conditions for extreme loads analysis
- Directional metocean conditions for fatigue analysis
- Anchor sizing based on soil characteristics
- Marine growth and corrosion allowances.

To provide a baseline against which to evaluate different mooring system standardization options, we developed a “baseline design” for each of the two sites. They are intended to be representative floating wind farm designs for comparison with standardized mooring system designs. They are designed so that each mooring line section and anchor is individually sized for its specific water depth, orientation to environmental loads, and location within the wind farm.

We first highlight the initial design decisions taken in developing the baseline designs, including the site conditions, the mooring configurations, the anchor types, and the array layouts. Then we describe the methodology taken to create the designs and the actual baseline mooring system design results.

2.1 Site Conditions

We selected two sites in which the baseline and standardized designs were to be set, with the goal of including a wide range of site conditions—including variable bathymetry, soil conditions, and lease area shape. As such, we chose the southwest lease area of Humboldt (OCS-P0562) and the central lease area of Morro Bay (OCS-P064) as the two sites to design floating wind farms. The bathymetry of the two sites is shown in Figure 4.



(a) (b)

Figure 4. Site bathymetry of the (a) Humboldt and (b) Morro Bay lease areas

Seabed and metocean (wind, wave, and current) data for these two sites are further detailed in an NLR technical report (Biglu et al., 2024). The water depth of the selected Humboldt lease area ranges from 600 to 1,000 m, and the water depth of the selected Morro Bay lease area ranges from 950 to 1,150 m. From the data available on soil conditions of these sites, we can identify areas that contain either “mud” soils or “hard” soils, where hard soils could be exposed bedrock, for example. The Humboldt site contains some hard seabeds, and the Morro Bay site contains only mud. Soil maps are shown in figures in later sections.

To represent realistic variability in the seabed soil properties despite the lack of seabed data resolution, we assume that the muddy areas of the lease areas can be separated into two types of clay: very soft clay and medium clay, with shear strength parameters based on American Bureau of Shipping (ABS) recommendations (ABS, 2013). To divide the Humboldt site area roughly equally to include both types of clay, we assumed muddy locations deeper than 800 m are defined as very soft clay, and locations shallower than 800 m are defined as medium clay. For the Morro Bay site, we use the same logic but with a transition water depth of 1,000 m to divide the area roughly equally. The harder, rockier areas of the Humboldt site are assigned strength and stiffness values derived from Vryhof recommendations (Delmar Systems, 2018). Morro Bay does not include any hard soil types (to our knowledge based on the available data). Table 1 tabulates the soil parameters used for each site.

Table 1. Assumed Seabed Geotechnical Parameters

Site	**Mud**				**Rock**	
	Very Soft Clay		**Medium Clay**		**Weak Rock**	
	Undrained Shear Strength at Mud Level, S_{u0} (kPa)	**Undrained Shear Strength Gradient, k (kPa)**	**Undrained Shear Strength at Mud Level, S_{u0} (kPa)**	**Undrained Shear Strength Gradient, k (kPa)**	**Unconfined Compressive Strength, UCS (MPa)**	**Rock Mass Stiffness, E_m (MPa)**
Humboldt	2.39	1.41	23.94	2.67	7	50
Morro Bay	2.39	1.41	23.94	2.67	-	-

2.2 Mooring Configurations

Of the three conventional mooring system configurations (catenary, taut, and semi-taut), we decided to use taut mooring configurations for both the Humboldt and Morro Bay designs. For deep-water floating wind applications, taut systems make the most practical sense as they have lower weights and cost of materials compared to other configurations and allow for reduced seabed footprints. We assume our taut mooring lines have three mooring line sections: a chain section at the anchor attached to polyester rope throughout most of the water column, and another chain section attached to the floating platform. With this configuration, we can include multiple mooring component types (i.e., chain and rope) in the supply chain analysis. Material properties, such as mass, minimum breaking load (MBL), and axial stiffness (EA), for each line type have been previously defined (Hall et al., 2021, 2024).

We also decided to vary the number of lines attached to each platform in each design. In the Humboldt design, we use three mooring lines per platform (Figure 5a), but in the Morro Bay design we use six mooring lines per platform (Figure 5b). The use of the VolturnUS-S platform lends itself to mooring lines in multiples of threes given the platform geometry. Because the majority of existing floating wind turbines use three lines, this is the most logical baseline arrangement. However, doubling or tripling the mooring lines presents a significant design change in that it allows mooring system redundancy and substantially reduces the individual mooring line loads, allowing for smaller components that may be more readily available from existing supply chain capacities.

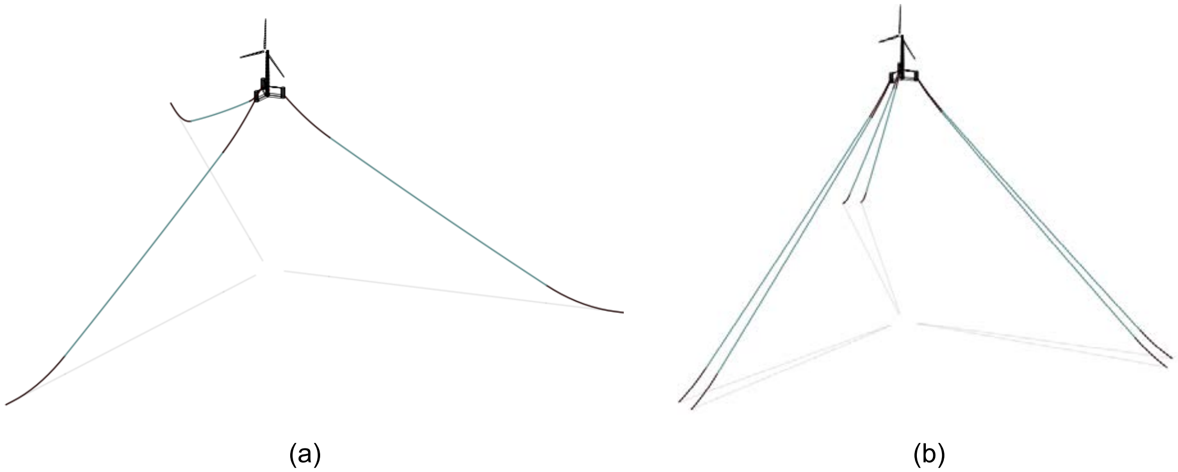

(a) (b)

Figure 5. Baseline design taut mooring line configurations for (a) Humboldt and (b) Morro Bay

Additionally, we decided to use suction pile anchors for any anchor point located in mud and drilled-and-grouted (D&G) piles for any anchor point located in rock. Only the Humboldt design will have D&G pile anchors since that is the only site where rock is present (that we know of). Suction piles are one of the most common anchor types and can function in a variety of soil types—from soft clays to stiff sands. They would also be the most practical to model through the supply chain process as it is a frequently manufactured product. D&G piles have been used in the offshore industry for soils described as weak rock (between 5 MPa and 200 MPa of unconfined compressive strength) and would be one of the most feasible anchor types to drill into these soil conditions.

Other mooring system components, referred to as auxiliary components, are required to connect mooring line sections, tension different mooring lines, and provide efficient hook-up to anchors and platforms. These components include fairlead or articulation mechanisms at the platform attachment point, subsea connectors, thimbles, shackles, H-links, and tensioning devices. These components are not included as part of the mooring designs because they are not consequential to the mooring line design and sizing process; however, they should be included in more detailed design descriptions.

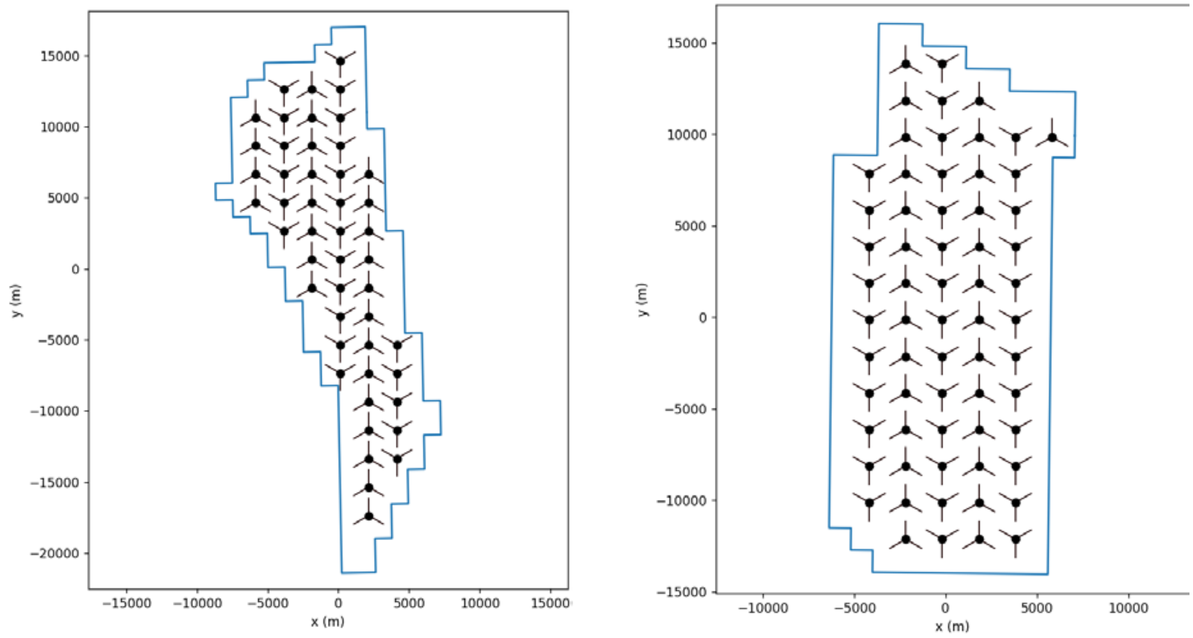
2.3 Array Layout

The array layout defines the turbine positions and mooring system orientations within the lease area. To keep a regular array layout and reduce complexity, we use consistent mooring line positions and headings through the array rather than customizing the layout turbine-by-turbine.

We adhere to regular rectangular layouts to be consistent with most existing wind farms and to avoid irregular geometries that could complicate navigation. We allow for different mooring orientations across rows or columns of the array to avoid mooring overlaps, as long as the orientations follow a consistent pattern. The layout is constrained such that mooring lines and anchors must maintain a minimum separation of 100 m from the lease area boundary and 80 m from each other. We analyze these constraints using estimated anchoring radii to begin with and then confirm if the layout is still suitable once the final anchoring radii are known.

The anchoring radius used for the Humboldt design was set to a constant value of 1,200 m, and the anchoring radius used for the Morro Bay design was set to a constant value of 1,000 m. These values were found to produce the lowest cost for mooring line and anchor materials in an initial design study for their respective sites. They also align with sensible values for the horizontal and vertical loading components at the anchor points. We used a spread angle of 4 degrees within each pair of mooring lines for the Morro Bay design to allow 80 m between anchors for installation.

The spacing between turbines was set to 2,000 m in each direction, which allows for wake recovery between turbines to avoid excessive wake losses and leaves a margin of at least 800 m between adjacent turbines' mooring systems. Three-line mooring systems can fit most closely in a rectangular array when the mooring orientations are alternated from one column to the next. Every other column of mooring systems has one of its mooring lines extending northward and the other columns of mooring systems have one of their mooring lines extending southward. The full array layout designs for each site—before selecting the final 40 platforms—are shown in Figure 6. The Humboldt site can initially accommodate 48 platforms using this array layout methodology, and the Morro Bay site can initially accommodate 64 platforms. The soil conditions at each anchor point determines what type of anchor is used.



(a) (b)

Figure 6. Layouts for the (a) Humboldt and (b) Morro Bay designs

2.4 Design Methodology

The baseline design methodology uses an updated and expanded form of the design methods first established in the NOWRDC project *Shared Mooring Systems for Deep-Water Floating Wind Farms* (Hall, Housner, et al., 2022). These methods center on using efficient quasi-static modeling to rapidly optimize individual mooring line designs and then using sophisticated coupled dynamics modeling to evaluate the mooring system designs in various load cases. These methods are used because we aim to individually design 120 different mooring lines and anchors for the Humboldt site and 240 different mooring lines and anchors for the Morro Bay site. Modeling fully coupled simulations for each design iteration of each mooring line would require a significant computational effort. This is why we have strategically combined efficient approximations for the sake of design efficiency with rigorous checks of key scenarios to ensure design robustness.

The overall design approach for the baseline designs has these steps for each site:

- For the shallowest and deepest turbine positions at each site, perform a quasi-static mooring system design optimization at the respective depths.
- Perform an ultimate loads analysis on the quasi-statically optimized design and iterate on the design until constraints pass in the dynamic environment.
- Perform a fatigue loads analysis of the final design that has already passed the ultimate loads analysis.
- Adjust chain diameters and polyester lengths to satisfy fatigue criteria and maintain pretension.
- Parametrically interpolate the design data between the shallowest and deepest designs for the remaining 38 mooring systems in the wind farm.
- Design different anchors for each mooring line based on maximum mooring loads on the anchor points and the soil conditions at each anchor point.

The process of the first four bullets above can be visualized in Figure 7.

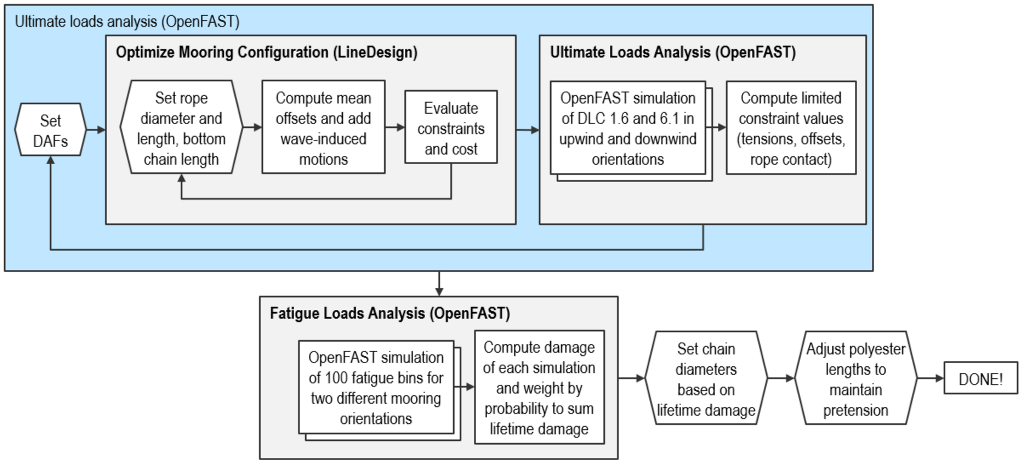


Figure 7. Updated mooring design methodology flowchart to include ultimate limit state and fatigue limit state.

DAF = dynamic application factor; DLC = design load case

2.4.1 Quasi-Static Mooring Design Optimization

The mooring line sizing is initially performed using a quasi-static optimization tool, which we first presented in (Hall, Lozon, et al., 2022), and is based on the mooring system modeling tool MoorPy (Hall et al., 2021). MoorPy can compute floating system mean offsets based on applied steady loads and calculate any mooring system's nonlinear static response. The design tool combines a component-based cost model with quasi-static evaluations of mooring system behavior in key loading conditions in MoorPy. An optimization algorithm adjusts mooring system dimensions and component sizes to minimize the cost while meeting specified constraints.

We fix some design parameters that will be determined later and focus on three design variables: the length of the lower chain and the diameter and length of the polyester rope. The rope length and diameter are most consequential to the restoring behavior and tension response of the mooring system, and the bottom chain length is important for avoiding rope touchdown. Of the parameters that are held constant, the chain diameters are driven by fatigue loads and will therefore be adjusted after fatigue analysis, and the top chain length is set to keep the rope section below the upper 100 m of the water column to avoid marine growth issues. Adjusting the chain diameters after the quasi-static design optimization in an iterative process is effective because the chain diameters play only a minor role in the behavior of a taut mooring system.

Explained in the next subsections, we check the system dynamic response under key load cases using the floating wind turbine dynamic simulation tool OpenFAST, which allows checking of all engineering constraints used in this study. We then update a number of parameters in the quasi-static design tool based on the OpenFAST results and rerun the quasi-static optimization using better dynamic inputs (e.g., wave-induced motion amplitudes of the floating platform, maximum mooring line tensions). This iterative process is performed until the results converge, balancing a thorough loads analysis and quick design optimization.

The optimization objective is to minimize the mooring system cost while meeting key technical constraints for the system's feasibility. These constraints are

- Maximum surge offset: 10% of water depth
- Mooring line tension safety factor (non-redundant): 2.0
- Rope minimum height from seabed: 5 m
- Fatigue life factor for mooring chain: 3 (fatigue life is at least 3 times the design life)
- Suction pile load safety factor: 1.6 for lateral loads, 2.0 for vertical loads (from American Petroleum Institute Recommended Practice [API-RP] 2GEO)
- D&G pile maximum displacements: 10% of the pile diameter in lateral deflection, and 0.25° of pile head rotation.

2.4.2 Ultimate Loads Analysis

The analysis of ultimate loads on the mooring system considers two design load cases (DLCs): DLCs 1.6 and 6.1. These two were found to be the most design-driving for mooring systems in previous studies. We specifically focus on DLC 1.6 at the rated wind speed, since that involves the rated thrust force from the wind combined with 50-year waves. DLC 6.1 includes 50-year wind and wave parameters and 5-year currents and represents another extreme loading case, though it often has lower extreme tensions than DLC 1.6. These DLC selections are in alignment with the recommendations developed in the IEA Wind Task 49 design basis (Hall et al., 2024, p. 49), which can be referred to for more explanation. We evaluate each DLC in two worst-case orientations: (1) when wind, wave, and current are aligned with a mooring line being upwind and (2) when they are aligned with a mooring line being downwind. The former generally results in the largest tensions while the latter generally results in the largest offsets and most risk of rope contact with the seabed. Table 2 and Table 3 show the environmental conditions involved in each load case at each site.

Table 2. Load Case Environmental Return Periods

Environmental Condition	DLC 1.6 Operating	DLC 6.1 Parked
Wind	Rated	50-year
Waves	Joint 50-year	50-year
Current	1-year	5-year

Table 3. Load Case Parameters for Humboldt and Morro Bay

Environmental Parameter	Units	Humboldt		Morro Bay	
		DLC 1.6	DLC 6.1	DLC 1.6	DLC 6.1
Wind speed	(m/s)	10.59	39.44	10.59	28.90
Turbulence intensity	(-)	0.06	0.05	0.06	0.05
Shear	(-)	0.14	0.11	0.14	0.11
Wave height	(m)	10.5	11.8	9.2	10.7
Wave period	(s)	18.7	19.8	18.1	19.6
Current speed	(m/s)	0.92	1.09	0.68	0.81
Safety factor	(-)	2	2	1.67	1.67
Yaw misalignment	(°)	0	0	0	0
Turbine status	(-)	Operating	Parked	Operating	Parked

This approach to the ultimate loads analysis results in the mooring system being designed for similar strength for all loading directions rather than differentiating the worst-case loading condition as a function of direction at each site. The limited amount of metocean data at each site makes it difficult to extrapolate directionally dependent extreme metocean values with high precision, making a unidirectional approach safer. This approach is consistent with the choice of maintaining even mooring line spread angles and avoids using multiple rope diameters within the same mooring system. It also provides a degree of conservatism, and it will be kept consistent throughout the project.

Once simulated, the results from the ultimate loads analysis in OpenFAST are iterated through the quasi-static design optimization tool until the mooring design results converge.

2.4.3 Fatigue Loads Analysis

Fatigue analysis is important for mooring design because fatigue is often the design-driving loading for steel mooring system components. The cumulative nature of fatigue loading means that the directional dependence of fatigue loads can be resolved with good precision. Furthermore, the combinations of wind and wave directions have a large impact on overall fatigue loads. We therefore include directionality in the fatigue analysis and consider the sizing of individual mooring lines to satisfy their specific fatigue loads.

We defined 100 fatigue bins for each site, using hourly metocean data (Biglu et al., 2024). These fatigue bins defined 100 separate OpenFAST simulations to simulate the cumulative tensions on each mooring line, and damage on each line was calculated for each fatigue bin and summed based on the fatigue bin probability of occurrence.

Chain diameters were sized iteratively, landing on specific values to satisfy the fatigue damage constraint of cumulative damage less than 0.33, aligning with a T-N curve slope of 3 for studless chain, based on ABS and API standards and the IEA Wind Task 49 design basis (Hall et al., 2024, p. 49). As discussed in the next section, we performed fatigue analyses for the mooring systems at the shallowest and deepest locations in each lease area and considered multiple mooring system orientations in these analyses, giving us fatigue load results that we could then interpolate from to estimate the fatigue loads on other intermediate-depth mooring system designs in each lease area.

2.4.4 Design Iteration and Parametric Interpolation

Because this project uses the bathymetry from real locations, the depth of every anchor point is inevitably different. This variability requires a systematic method to design the mooring systems in a way that accounts for the depth variation while maintaining consistent assumptions and methods. Furthermore, because the spread of mooring line headings is uniform, each mooring line in a mooring system must have the same horizontal pretension in order for the unloaded equilibrium turbine position to be as intended.

A key challenge is how to adjust for each unique anchor depth without rerunning a fatigue analysis for each specific depth (which would entail running the 100 fatigue bins for each turbine in the array, meaning a minimum of 4,000 simulations per site). Our approach is to instead run fatigue analyses on the shallowest and deepest mooring systems in the array and then interpolate the fatigue damage predictions for the other mooring systems based on a linear interpolation with water depth. This method accounts for the first-order variation of mooring system fatigue with water depth, which we expect is a good approximation based on the linear trends we use in the mooring design parameters. The specific properties that are interpolated are:

- Top and bottom chain diameters (based on sizing for fatigue life)

- Rope length, rope diameter, and bottom chain length (based on optimization subject to ultimate load constraints)
- Assumed wave-induced motion amplitudes and dynamic amplification factors used in the quasi-static design tool (as determined from OpenFAST results).

After the interpolation process, every mooring line diameter is rounded up to an actual diameter provided in mooring line catalogs. Chain diameter values are rounded up to the nearest millimeter (Intermoor, n.d.) and polyester rope diameter values are rounded up to values listed in public polyester rope catalogs (BEXCO, 2004; Lankhorst Offshore, n.d.). Every mooring line length is individually tuned by adjusting the rope length to ensure the desired horizontal pretension so that each turbine is in equilibrium at its desired position in the array.

Lastly, once each mooring design is tuned, its ultimate anchor loads are also estimated based on interpolation between the OpenFAST simulation of the shallowest and deepest cases; these loads are then used as input to sizing algorithms that determine the anchor size. The anchor type is chosen based on the local soil conditions, and the sizing algorithms account for the quantitative soil parameters to size the anchors to meet the specified safety factors.

The full design process for the baseline mooring systems is as follows:

- Quasi-static optimization of mooring lines for shallowest and deepest mooring systems under DLC 1.6 loading (using averaged anchor depths)
- OpenFAST ultimate loads analysis (DLCs 1.6 and 6.1) of mooring lines for shallowest and deepest mooring systems with both upwind and downwind mooring line orientations
- Adjust quasi-static dynamic amplification factors and repeat optimization until convergence with OpenFAST results
- OpenFAST fatigue loads analysis of shallowest and deepest mooring systems in both original and flipped orientations (4 × 100 simulations)
- Update all chain diameters individually to achieve target fatigue factor of 3 (lifetime damage of 0.33) for each chain section based on saved tension time series (2 chain sections × 3 mooring lines × 2 mooring orientations × 2 depths)
- Adjust polyester rope length in each mooring line to restore previously optimized pretension (3 mooring lines × 2 mooring orientations × 2 depths)
- OpenFAST ultimate loads analysis for each mooring line under upwind DLC 1.6 loading (3 mooring lines × 2 mooring orientations × 2 depths) to get peak anchor loads
- Interpolate (based on anchor depth) mooring design parameters and peak anchor loads for every mooring line in the array
- Design each anchor based on interpolated peak anchor loads and local ground conditions
- Adjust polyester rope length in each mooring line for change in anchor depth from the average depth (which has been used in all processes up until now) to the actual, bathymetric depth.

2.4.5 Anchor Sizing

For designing the anchors in the baseline designs, sizing is based on the maximum horizontal and vertical anchor loads calculated from the mooring design process and the local soil conditions of the anchor point. The anchor type is set to suction piles for muddy soil types and D&G piles for hard ground conditions, here addressed as weak rock.

For suction pile sizing, we use the vertical-horizontal failure envelope to characterize the interaction of the vertical and horizontal maximum capacities for different pile sizes (Figure 8). The vertical capacity is primarily determined by the skin friction between the anchor material and the surrounding soil, as well as the reverse end bearing that occurs predominantly in clay soils. The horizontal capacity of suction piles depends on the depth of the padeye. The interaction of vertical and horizontal capacities at different load angles can be modeled using an elliptical relationship characterized by Equations 1, 2, and 3:

$$UC = \left(\frac{H}{H_{max}}\right)^{a_{VH}} + \left(\frac{V}{V_{max}}\right)^{b_{VH}} \leq 1 \tag{1}$$

$$a_{VH} = L/D + 0.5 \tag{2}$$

$$b_{VH} = L/3D + 4.5 \tag{3}$$

where H_{max} is the maximum horizontal capacity at an inclined loading angle of zero, V_{max} is the maximum vertical capacity at an inclined loading angle of zero, H is the horizontal load component, V is the vertical load component, L is the embedded length of the pile, D is the pile outer diameter, and a_{VH} and b_{VH} are the proposed factors for the vertical-horizontal capacity elliptical shape of the failure envelope. The maximum horizontal capacity (H_{max}), in the case where the padeye depth is two-thirds of the embedment depth, is obtained assuming the pile acts as a fixed head body that translates laterally with no significant rotation. For anchors with embedded length to diameter ratios greater than three, we assume a lateral bearing factor ($N_{p_{fixed}}$) of 10.5. The vertical capacity is calculated as one of the following three sources of vertical loading resistance: friction between the outer and inner surfaces of the pile and the soil, weight of the soil inside the pile and outer pile friction with the soil, and reverse end bearing resistance. The maximum vertical pull-out capacity of the suction pile anchor (V_{max}) is found assuming the top plate vent of the pile is permanently sealed and the reverse end-bearing capacity can be calculated, such as during peak pull-out loads during a storm.

Baseline design anchor diameters are iterated upon, with lengths corresponding to length-to-diameter (L/D) ratios of 5, 6, and 7. Design iterations converge when the maximum mooring lines—including safety factors of 1.6 in the horizontal direction and 2.0 in the vertical direction (API, 2005)—lie along the boundary defined by the capacity envelope, as illustrated in Figure 8.

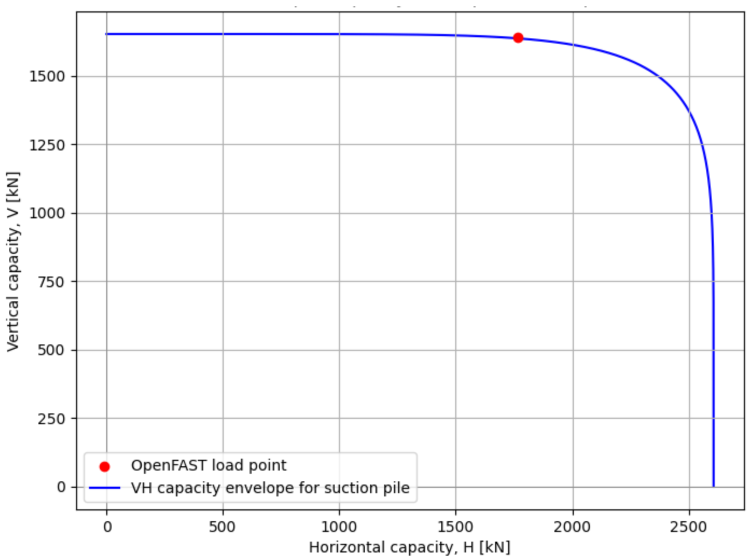


Figure 8. Vertical-horizontal capacity envelope solution for a suction pile

For sizing D&G piles, the holding capacity is normally limited by the horizontal capacity, which can be characterized by the P-y curves method (Reese, 1997). We have implemented an analytical formulation for D&G piles in weak rock. We assume a D&G pile diameter based on a drill head dimension of 64 inches (1.625 m) with a marginal amount of grout between the steel pile and the rocky seabed that does not interfere with the anchor sizing. We then iterate on the length of the pile so that the pile head lateral displacements stay within 10% of the pile diameter and there is less than 0.25 degrees of rotation of the pile. Figure 9 shows the unloaded (black) and loaded (red) deflections of a pile in weak rock, as computed by the model used in the sizing process.

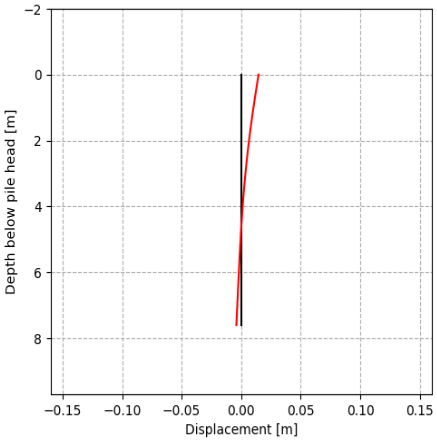


Figure 9. Unloaded (black) and loaded (red) head displacement of a D&G pile

The thicknesses of each suction and D&G pile are calculated as a function of pile diameter (Equation 4) from API RP2A-WSD standards, with D and t both shown in units of meters.

$$t = (6.35 + 20D)/1000 \tag{4}$$

The padeye location for suction piles is always assumed to be two-thirds of the length of the pile below the mudline and at the mudline for D&G piles.

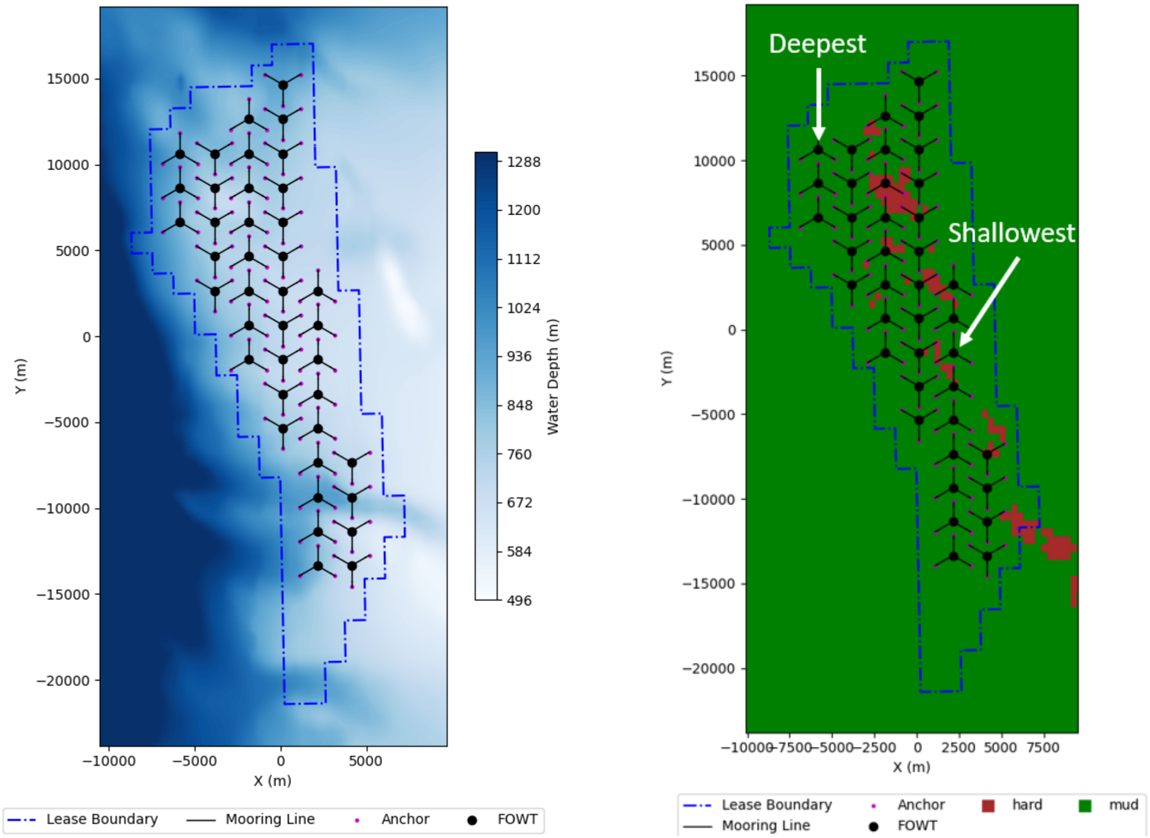
Other anchor design aspects are not included in this study but should be considered for more in-depth anchor designs: sediment mobility, scour assessment, preparation work, geohazards, installation, and cyclic degradation.

2.5 Baseline Design Results

Using the design methodology and assumptions in the previous sections, we present the final baseline designs where each chain, rope, and anchor for each site is individually designed for its specific water depth in the wind farm and its orientation relative to the environmental loads, considering extreme and fatigue loads.

2.5.1 Humboldt

The final array layout of the baseline Humboldt design was iterated on until 40 wind turbines with mooring systems having an anchoring radius of 1,200 m could fit inside the lease area boundaries with sufficient space between systems. The array layout is shown in Figure 10, and the details on the water depth, mooring orientation, and anchor types are provided in Appendix A.



(a) (b)

Figure 10. Layout for the baseline Humboldt design: (a) layout over water depth and (b) layout over seabed type

The water depths at Humboldt range from roughly 650 to 950 m with each anchor of each mooring line having a depth somewhere in between. Figure 11 gives the spread of anchor depths.

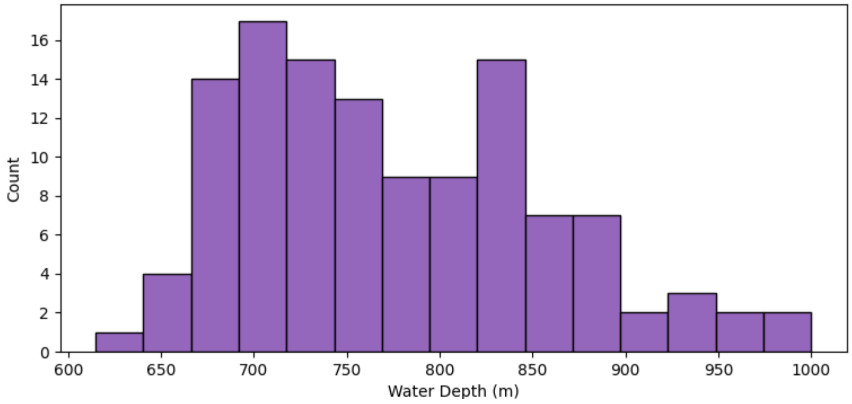


Figure 11. Water depth distribution at each anchor point for the baseline Humboldt design

Out of the 120 anchors in the design, eight of them lie in hard or rocky soils. These eight anchor points are designed to be D&G pile anchors. The remaining 112 are designed to be suction piles.

Using these anchor points, mooring system orientations, and water depths, we follow the mooring system design methodology, starting with the shallowest and deepest mooring systems of the array. The average water depth across the three anchor points for the shallowest design is 667.7 m, and the average water depth across the three anchor points for the deepest design is 922.0 m. We assume that seabed locations with high seabed slopes would not influence the design process. The quasi-static design optimization process using MoorPy was run for these depths and iterated on with ultimate limit state results from OpenFAST. Fatigue simulations were then run to ensure the chain diameters satisfied design criteria, resulting in specific sizes of each mooring line based on their orientation. The data were then parametrically interpolated across all the other water depths, and the maximum anchor loads were used to design the anchors. The design data for each mooring line and anchor are provided in Appendix B and Appendix C.

The chain diameters range from 104 mm to 165 mm. The polyester rope diameters happened to have very little variation; there were only two diameters, 205 mm and 207 mm, after rounding to commercially available sizes. The metocean directions at Humboldt primarily travel from north to south with some directionality from northwest to southeast. This means that the mooring lines and anchors pointed north and northwest experience the highest fatigue loads and therefore require larger sizes.

The complete mooring system designs are visualized in Figure 12.

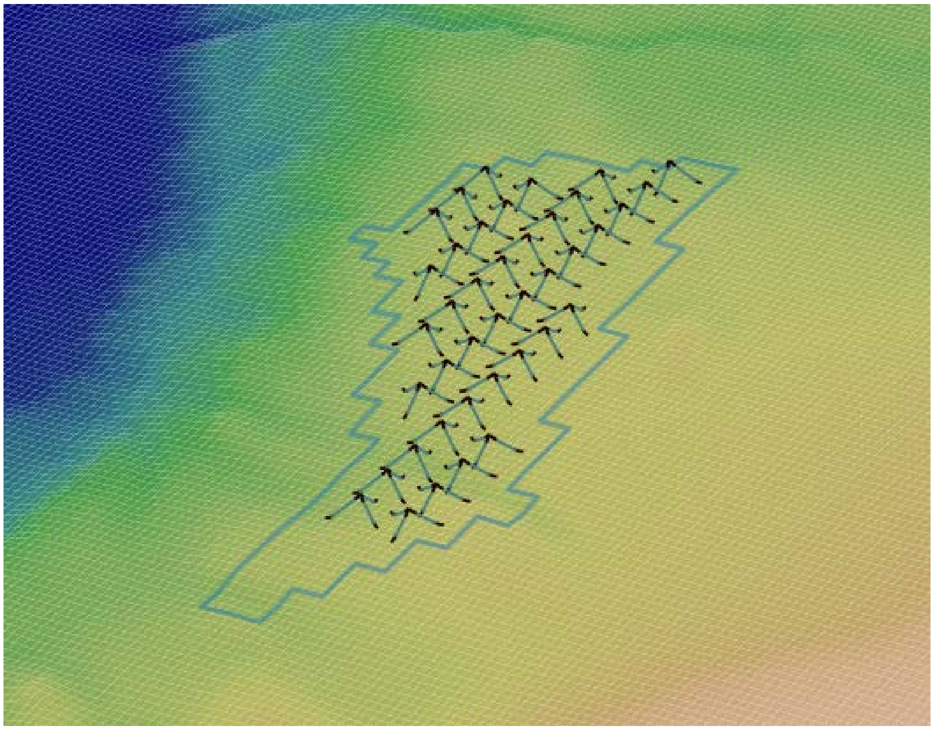
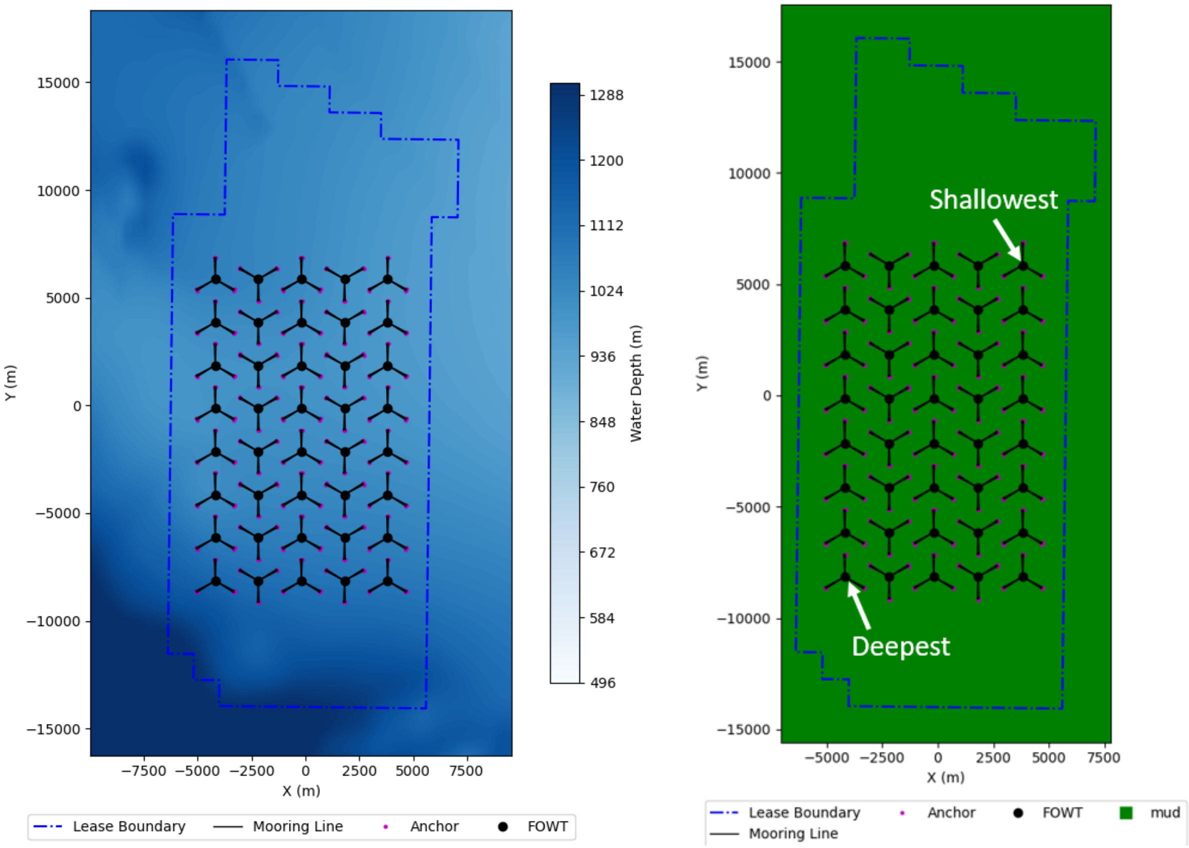


Figure 12. A perspective view of the fully designed 40-turbine wind farm in the Humboldt lease area

2.5.2 Morro Bay

The final array layout of the baseline Morro Bay design was iterated on until 40 wind turbines with mooring systems having an anchoring radius of 1,000 m could fit inside the lease area boundaries with sufficient space between systems. The array layout is shown in Figure 13, and the details on the water depth, mooring orientation, and anchor types are provided in Appendix D.



(a) (b)

Figure 13. Layout for the baseline Morro Bay design (a) over water depth and (b) over seabed type

The water depths at Morro Bay range from roughly 950 to 1,150 m, with each anchor of each mooring line having a depth somewhere in between. The spread of anchor depths is shown in Figure 14.

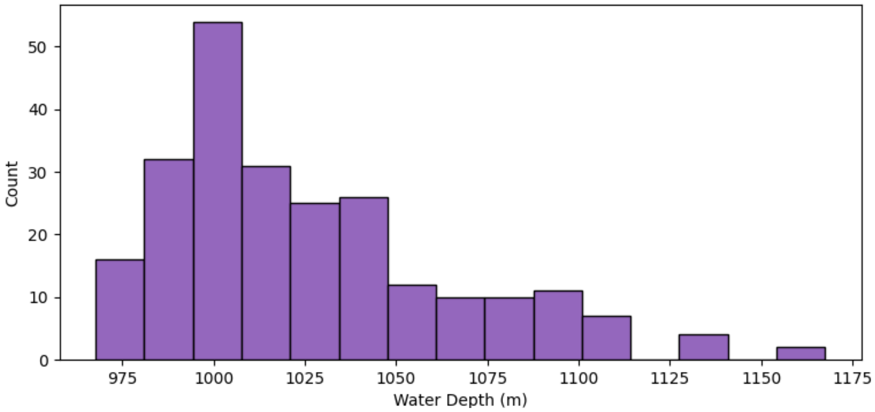


Figure 14. Water depth distribution at each anchor point for the baseline Morro Bay design

Since there is no soil type variation at Morro Bay, all 240 anchors are to be suction piles in mud.

Using these anchor points, mooring system orientations, and water depths, we followed the mooring system design methodology, starting with the shallowest and deepest mooring systems of the array. The average water depth across the three anchor points for the shallowest design is 974.2 m, and the average water depth across the three anchor points for the deepest design is 1,131.5 m. The quasi-static design optimization process using MoorPy was run for these depths and iterated on with ultimate limit state results from OpenFAST. Fatigue simulations were then run to ensure the chain diameters satisfied design criteria, resulting in specific sizes of each mooring line based on their orientation. This data was then parametrically interpolated across all the other water depths, and the maximum anchor loads were used to design the anchors. The design data for each mooring line and anchor are provided in Appendix E and Appendix F.

The chain diameters are much smaller in Morro Bay, ranging from 67 mm to 98 mm. The polyester rope diameters again had little variation; there were two distinct diameters of 117 and 123 mm after rounding to commercially available sizes. Given the doubling of the number of lines and the decrease in safety factors due to redundancy, smaller component sizes satisfy the design criteria in the Morro Bay site compared to the Humboldt site. There is also less environmental directionality at Morro Bay, so fatigue loads are more evenly distributed among the mooring lines and there is less variation in chain sizes. The effect of directionality is not seen in extreme loads because we take an omnidirectional approach to extreme metocean conditions.

The complete mooring system designs are visualized in Figure 15.

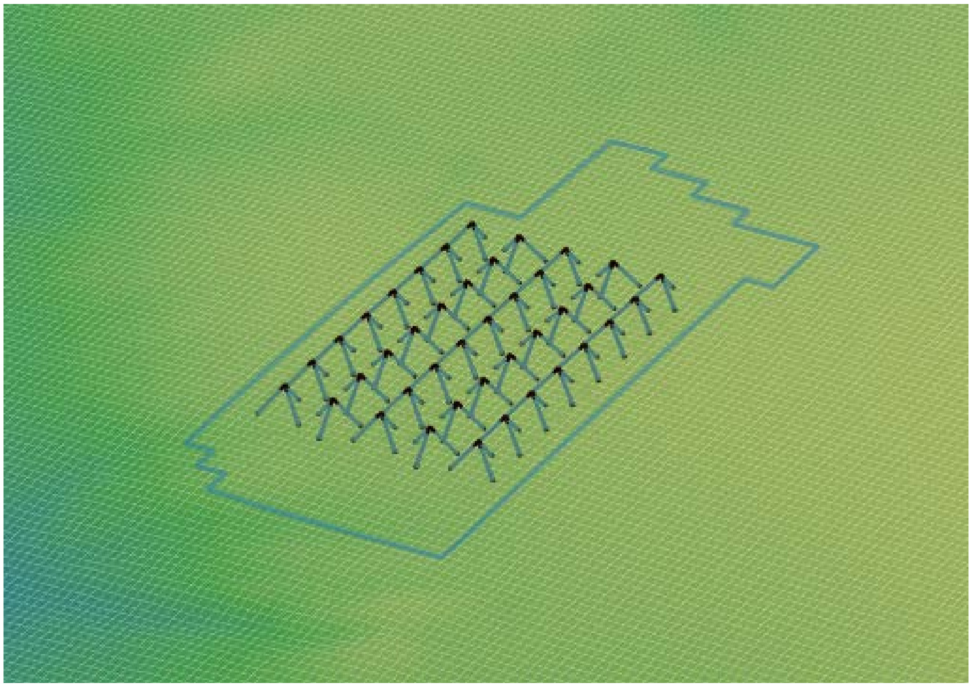


Figure 15. A perspective view of the fully designed 40-turbine wind farm in the Morro Bay lease area

2.5.3 Supply Chain Demands

A summary of the total mooring components between the two designs is summarized in Table 4.

Table 4. Overview of Component Parameters of the Baseline Designs

Component	Parameter	Humboldt (3-line)	Morro Bay (6-line)
Chain	Number of units	240	480
	Total Length (m)	51,657	42,904
	Total Mass (t)	16,462	6,241
Polyester Rope	Number of units	120	240
	Total Length (m)	113,957	285,392
	Total Mass (t)	3,297	2,914
Suction Piles	Number of units	112	240
	Total Mass (t)	5,902	7,712
D&G Piles	Number of units	8	0
	Total Mass (t)	48	0
Auxiliary Components	Shackles	360	720
	Thimbles	240	480
	Subsea Connectors	120	240
	Fairlead Tensioners	120	240

Figure 16 plots the distribution of chain demand of the baseline designs organized by chain nominal diameter. We used 1-mm chain size increments, which are technically available in the global supply chain, though coarser increments would be more likely in practice.

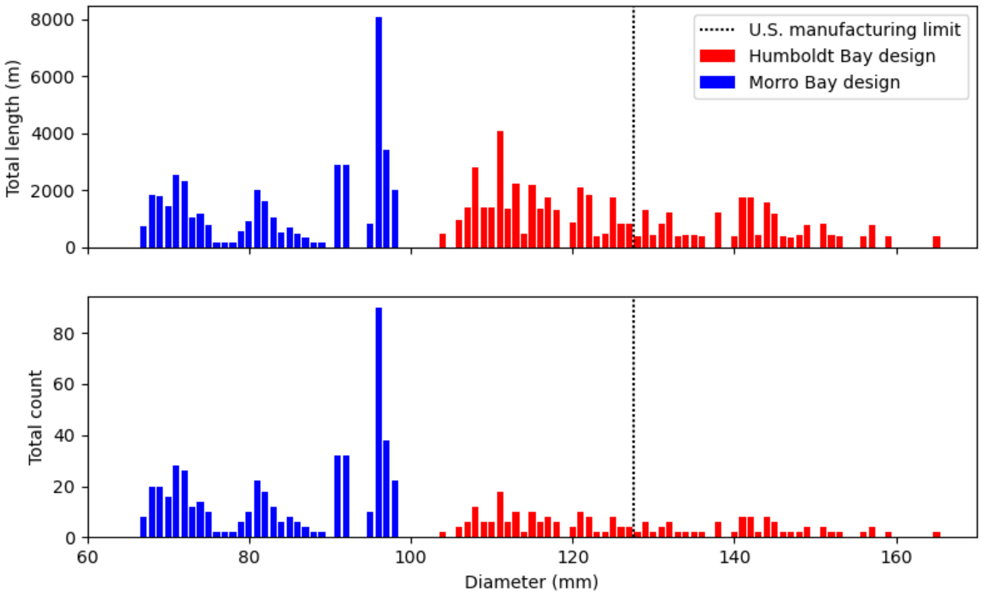


Figure 16. Baseline design chain demand

Figure 17 shows the demand for polyester rope of the baseline designs organized by rope diameter. Each design only uses two rope diameters because a large distribution was not needed. These specific diameters were derived from commercially available diameters. Figure 18 shows the demand for anchor piles in terms of pile diameter, pile weight, and quantity.

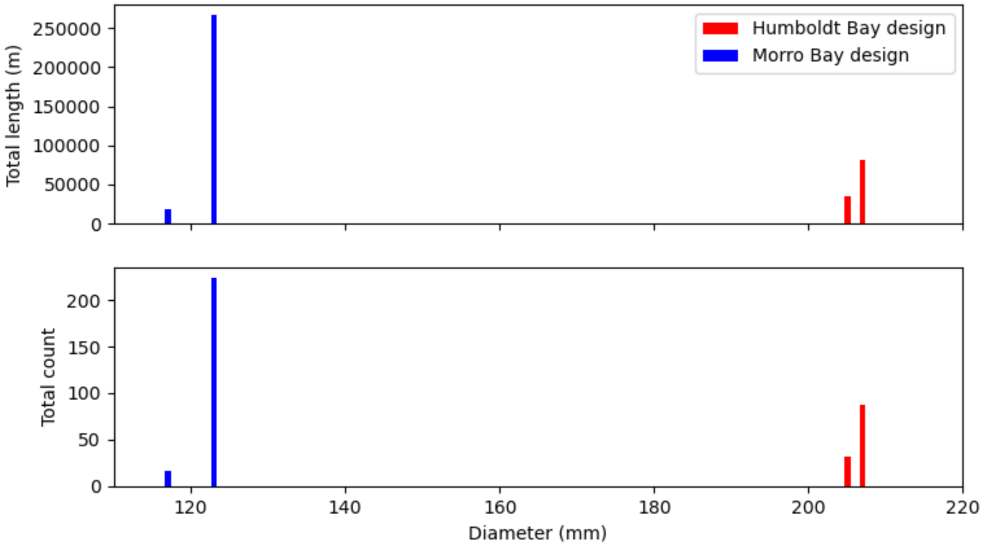


Figure 17. Baseline design polyester rope demand

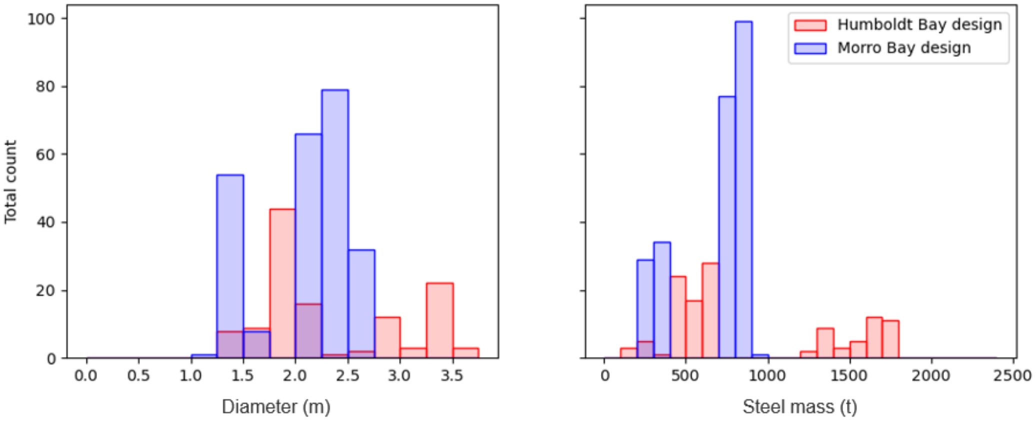


Figure 18. Baseline design pile demand

3 Domestic Supply Chain

A separate but related goal of this study is to characterize the domestic supply chain and update our modeling tools to support supply chain processes. By doing so, we can develop standardized mooring system designs that include supply chain considerations and evaluate the effects on system cost and lead time.

We begin with a characterization of the current domestic supply chain, including factors for manufacturing each mooring component and other transportation logistics, the potential growth of the supply chain to meet floating wind deployment goals, and a description of the new supply chain modeling capabilities.

3.1 Existing Supply Chain

We describe the existing supply chain in terms of different suppliers and manufacturers, associated throughputs, transportation requirements, and other storage and installation considerations for the three main mooring components present in the baseline designs: chain, rope, and anchors. We have found that all stationkeeping components have bottlenecks in their respective supply chains. The current status is summarized as follows:

- **Chain:** There is one potential supplier in the United States that can produce a moderate size of chain, and no new announced facilities as of 2022, meaning the ability to supply chain domestically for West Coast floating wind projects is limited and depends on the chain designs. Larger sizes would need to be sourced internationally.
- **Rope:** One domestic supplier can produce large enough rope, but their ability to meet the demand of the two baseline designs is a bottleneck. Other domestic polyester rope suppliers are not currently set up for the required production, so sourcing internationally may be necessary depending on the installation schedule.
- **Anchors:** There are a number of domestic suppliers capable of suction pile or D&G pile anchors. Anchor manufacturers are concentrated on the Gulf Coast, so both manufacturing throughput and transit time are constraints on installation schedule. Other anchor types available domestically are limited.
- **Connectors:** There are several domestic suppliers of common mooring connectors and specialized fairlead components. Most domestic connector suppliers are not offshore certified, but that is not expected to be a large barrier. Numerous international suppliers exist. The small size of these connectors makes them less of a bottleneck than other components.

In general, domestic manufacturing of these mooring components would not be adequate and would require many new certifications necessary for offshore wind applications. Chain, rope, anchors, and connectors generally need to be graded for permanent installation, which differs from the grade and certification required for other applications like temporary moorings. Offshore-grade components therefore generally entail a higher cost due to higher quality and lifetime requirements and additional required supplier certifications, which also makes for a smaller market and fewer suppliers.

Classification societies, such as ABS and Det Norske Veritas (DNV), require that offshore mooring chain and accessories be manufactured in accordance with their specific guidelines for certification. The material, testing, and manufacturer certifications required to manufacture components are quite different between the categories, as described in the ABS guide (ABS, 2022):

- **Offshore Grade:** Considered grade R3, R4, R5 steel. This grade is used for permanent or long-term offshore structures such as oil and gas platforms. The type of steel and processes used to manufacture components must endure fatigue loads and sustained exposure to seawater and marine growth over a long service life.
- **Marine/Ship Grade:** Considered grade 2/3/3a steel. These chain grades are commonly used as anchor chain for a wide range of vessels. The chain spends some time under water and some time stowed onboard a vessel. While these chains must endure high loads, they can be inspected and maintained more easily throughout their lives.

Certification to produce offshore-grade components would be required for existing domestic suppliers that do not yet produce components with those grades. More detailed descriptions of existing domestic supply chain capacities for each component type are provided in the subsections below. Addition supply chain information is provided in Appendix G.

3.1.1 Chain

Currently, the primary domestic consumer of large marine anchor chain is the U.S. Navy. This concentrated demand is handled by one domestic manufacturer. Two domestic manufacturers previously supplied the U.S. Navy, but due to a limited market there is now only one manufacturer with the capability for large marine anchor chain. Global suppliers also exist with larger production capabilities. Table 5 summarizes domestic chain manufacturing capabilities.

Table 5. Mooring Chain Manufacturer Spotlight

Manufacturing Facilities	Product	Annual Throughput	Capacity
1	4 in. (102 mm), 5 in. (127 mm)*	16,200 t (47,000 m)	34%–40%

*5-in. chain is possible, but there is currently little demand.

The domestic supplier is equipped to produce 5-in. offshore-rated chain, but they would need to seek ABS certification to do so, and there is no domestic demand. Currently, they produce 4-in. Grade 2, 3, and 3a chain. Their facility possesses two machining lines that make the chain (chain makers), each of which can manufacture bar stock diameters within ±6 mm (1/4 in.) of an initial diameter. Manufacturing chain diameters outside of this range relative to an initial diameter requires stopping production and retooling the machinery, which can take up to one week. The chain makers have a combined throughput of 47,000 m of chain per year. That throughput is accomplished at a reported 35%–40% utilization. Based on these numbers, they could theoretically produce 134,000 m of chain at maximum capacity, but this is likely not realistic assuming they retain their existing orders.

Per U.S. Navy specifications, marine anchor chains are made in 90-ft segments called shots. Each shot weighs approximately 9.5 t. Those segment lengths and weights would vary for offshore-grade chain. A domestic offshore wind market would likely generate enough demand for offshore-rated mooring chain such that the manufacturer could expand and certify their processes beyond marine anchor chain.

3.1.2 Fiber Rope

Domestically produced polyester rope has a larger market than large mooring chain, and as a result there are more potential suppliers. One of the largest suppliers can produce polyester rope up to a size of 55 kg/m, as measured by mass per length. This limit is set because their test equipment reaches a maximum break force of 2,500 t. Thicker polyester rope can be manufactured, but larger test equipment is required to certify their products. Based on the baseline designs, the required polyester rope sizes are up to 207 mm in diameter, which equates to 29 kg/m, meaning these sizes can be manufactured easily. Other domestic rope suppliers (compiled in Appendix G) do not currently make large enough rope but could expand their facilities and certify their processes to meet future demand. Table 6 summarizes the manufacturing capabilities for domestic rope.

Table 6. Polyester Rope Manufacturer Spotlight

Manufacturing Facilities	Product	Annual Throughput
1	55 kg/m	100 ropes (46,800 m)

The primary rope manufacturing facility can produce roughly 46,800 m of rope per year by length but only produce 100 ropes per year by splice. Splicing is a highly specialized “art-like” skill in which a trained worker manually sews in a loop at each end of the rope. This metric determines the throughput of the facility for our purposes. Splicing involves a qualification program for the workforce that can take up to 2 years, so throughput can increase with an increase in workforce. The baseline designs involve a total of 360 ropes.

Other synthetic fiber rope types that could be considered for floating wind applications include high-modulus polyethylene (HMPE) and nylon. Manufacturing capabilities for ropes of these other materials are expected to be similar to polyester.

3.1.3 Anchors

We focus mainly on suction pile anchors, which are similar to other pile anchors, and are one of the most established anchor types in the United States. States like Louisiana and Texas have become the central locations for suction pile anchor manufacturing. Manipulating large plate steel and rolling it into pile sections requires specialized equipment. Suppliers have grown their operations over the years to support the offshore oil and gas industry in the Gulf. The area’s river systems have been crucial for transporting large, heavy structures by barge.

Anchor manufacturers use a manufacturing apparatus, referred to as a jig, to assemble a number of anchor “cans” together to complete an entire anchor (Figure 19). Anchor cans are portions of a suction pile that are typically manufactured in lengths of 10 ft and welded together to form the complete suction pile. Jigs are typically set up for one specific anchor diameter, and any other anchor diameter would require downtime to reset the equipment or a separate assembly line or facility. The concept of individually sized suction piles—as in the baseline designs—is not common practice in the current offshore industry.

Figure 19. Suction pile manufacturing and assembly of cans and supporting jigs.

Photos from Delmar Systems

One manufacturing facility on the Gulf Coast can manufacture two to four piles per month. They have a plate roller capable of turning plate steel into a can up to 25 ft (7.6 m) in diameter. From there, two assembly lines allow welders to seam-weld the cans and reinforce them prior to staging cans together to form the pile. Each can is welded to another can, capped on one end, and fitted with valves and ports. Table 7 summarizes the manufacturing capabilities of one anchor manufacturing facility.

Table 7. Suction Pile Anchor Manufacturer Spotlight

Manufacturing Facilities	Product	Annual Throughput
1	Up to 20–25 ft (6–7.5 m) diameter	24–48 piles

Appendix G provides compiled information including eight other domestic suppliers that are ready to manufacture suction pile anchors. D&G piles can be produced by the same facilities using similar methods since they are typically smaller than suction piles. Other than driven piles, which have similar manufacturing processes, domestic production of other anchor types for floating wind projects is not well established at present.

3.1.4 Connectors

Other stationkeeping components such as shackles, tensioners, pivots, and quick releases are generally less of a supply chain constraint because of their smaller size and material use. The nature of these components varies widely; they can be used to provide simple connections and load transfer functions (e.g., shackles), provide mobility in specific planes, reduce chain fatigue, or provide tensioning ability without requiring divers.

Shackles are the most prevalent connector for attaching chain to anchors or other mooring line sections. Thimbles are used to attach the loop of a rope to a connector, such as the pin of a shackle. Shackles and thimbles are currently available from several domestic suppliers at an estimated combined rate of 70 units per month, although they are not currently offshore certified. Numerous international suppliers exist. H-links are a more specialized connector for connecting mooring line sections and are available from many of the same suppliers, though they are not necessary for mooring systems like the ones in the baseline designs.

Various quick connect/disconnect products exist to make it easy to detach and reattach mooring lines for maintenance or emergencies without requiring complex marine operations. One domestic has an estimated throughput of 40 quick release devices per year.

A range of products are on the market for attaching mooring lines to floating platforms. A practical option for deep-water mooring systems are devices that combine three functions: a chain stopper to lock the mooring chain at the desired length, a universal joint system that allows the mooring line to pivot horizontally and vertically to minimize out-of-plane bending loads on the chain links, and an off-vessel tensioner that allows the free end of the chain to be pulled by a service vessel to adjust the mooring line tension. This is the most economical way to tension mooring lines in deep water, especially for taut mooring lines that require retensioning to counter slow creep of their fiber ropes. We provide more information for different connector categories in Appendix G.

3.1.5 Transportation and Storage

After mooring components are manufactured, they need to be transported to the integration port, where they are stored until installation. This transportation is typically done as freight from the supplier to the integration port by either rail or marine vessel, though smaller components like shackles could be transported by air or truck.

Figure 20 is a map of North America with representative locations of current suppliers of the mooring components needed for the baseline designs. The dots represent suppliers and stars represent the two baseline design locations. ArcGIS railway and marine highway paths show the possible routes the components may use prior to reaching the staging and integration port. These large distances show that different components will have vastly different transportation times.

Figure 20. Map of North America with stationkeeping suppliers and major transportation routes.

Source: arcgis.com referencing national railroad network and marine highway map

Transport by rail is limited by the capacity of the railcars. A common 50-ft railcar has a carrying capacity of 60 t. Transporting chain by rail is routine. Chain manufacturers can transport shots of chain as piles that take up 7 m^2 and weigh roughly 9.5 t each by railcar. There is a claim that long chain segments that exceed the capacity of a single railcar can be draped across two railcars to distribute that weight, but it has not yet been demonstrated to our knowledge. One railcar can also transport up to five reels each with 450 m of rope. Chain can be transported by rail from Washington to California, and rope can be transported by rail from the East Coast to California.

Marine vessel transportation avoids the space and weight constraints of railcars, but they are subject to weather delays, availability, and longer transit times. Shipping components like suction pile anchors on cargo vessels may be more economical than by rail. Anchor manufacturers on the Gulf Coast employ barges along the river systems to move these large, fabricated structures. A common 300-ft barge can transport up to six suction piles per trip. This approach is feasible for nearby, one-off projects in the Gulf that may only need 6 or 12 piles. However, transporting that barge from the Gulf Coast to the West Coast via the Panama Canal can take 14–18 days one-way. For all anchors in the baseline designs, this would take 60 back-and-forth trips for one barge to deliver all anchors. More efficient solutions or vessels could be developed.

Table 8 shows typical space requirements of the main mooring components. Chain is stored and shipped in piles that require a certain area per chain quantity, which we estimate at 7.5 m^2 per 90 ft (1 shot) of chain length. Polyester rope can be containerized or spooled, then transported by railcar to port. A conventional 450 m polyester rope is stored on a spool that takes up 6.75 m^2 and is transported by rail. A challenge might be that the volume of a long, large-diameter rope may exceed the volume of a spool or container.

Suction piles can be shipped in horizontal and vertical orientations. They require 10 ft of clearance on all sides to give deck space for workers and crane operations. Most suction pile anchors will exceed a railcar's capacity and would either need to be shipped in pieces and assembled at the port or transported by a cargo vessel. These storage requirements need to be considered in the capacities of transportation railcars and vessels, as well as at port.

Table 8. Component Space Requirements

Stationkeeping Component	Existing Storage Requirement
Mooring Chain	7.5 m^2 pile per 90-ft chain
Polyester Rope	6.75 m^2 spool per 450-m rope or 53-ft container
Suction Pile Anchor	(Length + 10 ft) × (Width + 10 ft)
D&G Pile Anchor	(Length + 10 ft) × (Width + 10 ft)

The staging and integration port where all the stationkeeping components are delivered is also important. Port studies performed by Moffatt & Nichols for Humboldt Bay (Humboldt Bay Harbor Recreation & Conservation District, 2023) and Port of Long Beach (Moffatt & Nichol, 2023) provide engineering drawings that show wharf areas between 40 and 80 acres. The drawings in both reports show large components like blades and nacelles being staged, but they lack reference to stationkeeping components. A 2022 NLR report showed that 10 acres of space with 150 m of wharf length would provide some intermediate staging of mooring chains and anchors (Shields et al., 2022). However, it is estimated that 40 acres would be needed to store all mooring components for one design at a time while accounting for loading equipment and maneuverability. Large port investments are needed to ensure that a steady flow of manufactured products can be stored, organized, inspected, and then loaded onto installation vessels. Space availability at the integration port is location-specific and currently in flux, with port areas under development. We therefore do not characterize the current staging area capacities in detail.

Mooring system installation primarily requires vessels for installing anchors, lowering and attaching mooring lines, and tensioning mooring lines. There are two main vessel types for these purposes: anchor handling vessels and multipurpose support vessels. Anchor handling vessels store chain below deck in chain lockers while rope is stored above deck on reels. Winches and other equipment exist to feed anchors, chain, and rope off the stern roller. The deck is large enough to stow multiple anchors, typically in rows along either side. Anchor handling vessels are typically outfitted with Karm Forks to lay out chain on the vessel before installation, and they are typically only designed for specific chain sizes. Multipurpose support vessels typically have large cranes but less specialized equipment or storage for mooring components than anchor handling vessels. The deck of a multipurpose support vessel is adaptable so it can be fitted with storage for rope or chain or equipment for working with mooring lines. Finding capable vessels that can install certain mooring system component sizes while meeting Jones Act requirements is another problem to be addressed.

The port and vessel considerations for stationkeeping systems extend well beyond the scope of the present project, and there are open questions within each topic.

3.2 Potential Supply Chain Expansion

We also define the expansion potential of the supply chain to support larger floating wind energy goals. The potential growth depends on an assumed trajectory of floating wind project development. This trajectory is based on a combination of recent publications and recent offshore wind leasing activity, especially on the West Coast.

We use the baseline floating wind deployment scenario from the West Coast Ports Strategy Study (Shields, Cooperman, et al., 2023), which entails 25 GW of floating wind projects deployed by 2045, entirely in California lease areas. This scenario matches California state projections. The decision to exclude deployment in Oregon is in current agreement with the recent cancellation of the BOEM auction for that state, and Washington does not currently have offshore wind plans.

Figure 21 shows the West Coast ports baseline deployment scenario in terms of the cumulative capacity deployed between now and 2045. The deployment rate is approximately steady, based on modeled port availability, which is assumed to build up quickly at the beginning and then not change over the time span (Shields, Cooperman, et al., 2023).

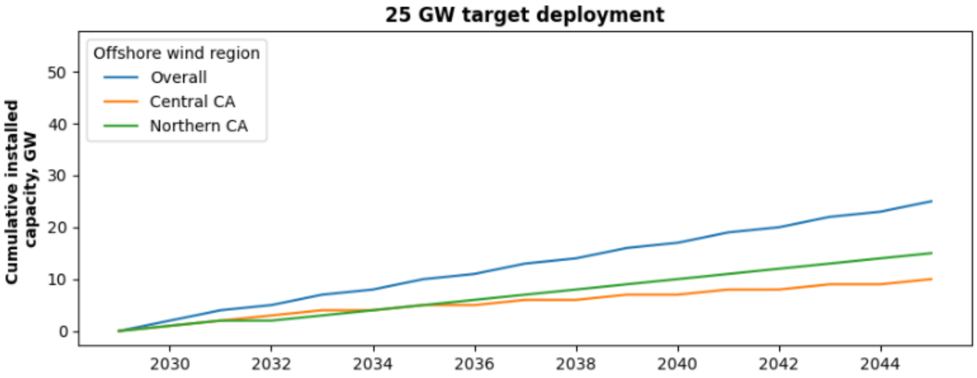


Figure 21. Floating wind deployment scenario adopted from the West Coast Ports Strategy Study

The assumed project deployments by year and region are given in Table 9.

Table 9. Baseline West Coast Floating Wind Deployment Scenario

Year	Added Capacity (GW)			Cumulative Capacity (GW)		
	Central CA	Northern CA	Total	Central CA	Northern CA	Total
2030	1	1	2	1	1	2
2031	1	1	2	2	2	4
2032	1	0	1	3	2	5
2033	1	1	2	4	3	7
2034	0	1	1	4	4	8
2035	1	1	2	5	5	10
2036	0	1	1	5	6	11
2037	1	1	2	6	7	13
2038	0	1	1	6	8	14
2039	1	1	2	7	9	16
2040	0	1	1	7	10	17
2041	1	1	2	8	11	19
2042	0	1	1	8	12	20
2043	1	1	2	9	13	22
2044	0	1	1	9	14	23
2045	0	2	2	9	16	25

We use these projections to estimate the amount of mooring system component material to meet these goals. Extrapolating from our baseline designs, Table 10 lists the material amounts needed for these growth scenarios.

Table 10. Mooring Component Quantities in Deployment Scenarios

Component Quantity	For 1 Line	1 Turbine	1 GW Farm	25 GW Scenario
Chain (ft)	1,350	4,000	272,000	6,800,000
Polyester rope (ft)	3,600	10,000	723,000	18,075,000
Rope splices	2	6	402	10,050
Suction pile anchors	1	3	201	5,025

These material amounts (in units of feet) and deployment scenarios were provided to key suppliers of mooring system components. The suppliers were then asked to comment on how their company would adapt to the resulting demand. Based on these discussions, it is possible for the demand of major stationkeeping components to be sourced domestically, as follows:

- **Chain:** To meet the projected demand, the current capacity of two chain makers (chain manufacturing machines) capable of making 4-in. chain could be expanded through another facility with at least three new chain makers. This would take roughly 3 years. There is a local capable workforce that can be trained to support growth, so labor is not an expected limitation in most regions.

- **Rope:** The current rope supplier capable of making large enough ropes could expand operations in 18–24 months and build an entire new facility in 5 years to meet the full demand. A cost-effective expansion plan could include final assembly at the port where sub-ropes are braided and finished, allowing the current facility to increase production on sub-ropes. Workforce is a significant factor; a fivefold increase would be required, as would significant training time for splicing work.
- **Anchors:** Existing suppliers could foreseeably double their facility capacities to meet the required demand. Workforce could be a limiting factor, but with size standardization and investment in automation, workforce bottlenecks could be reduced. Shipping from the Gulf may pose overflow concerns if not enough vessels are available to ship the piles with the necessary frequency.

Deployment scenario discussions with suppliers indicated that there is generally an appetite for expansion to meet potential offshore wind demand, provided there is sufficient certainty in the business opportunity. Purchase orders would be needed to justify the investment of installing new equipment and building new facilities. Without that certainty, suppliers may be able to meet the demands of individual projects by working over a longer time frame, but this would not support steady year-over-year deployment. This topic warrants further study from a broader perspective. Further details on each mooring component are provided in the next subsections.

3.2.1 Chain

The existing chain production capacity would need to expand considerably to meet the production needs for the deployment scenarios provided. With existing facilities, domestic chain manufacturers can produce up to 4-in. chain with two chain makers/production lines. Although there is no concern with switching between two or three different sizes of chain, retooling the equipment to accommodate a different size requires roughly a week of downtime. Standardizing chain sizes would therefore have a direct supply chain benefit in that it would reduce retooling delays.

To produce chains with a diameter larger than 4 in. in large quantities and at the lengths required for floating wind projects, there would likely be a need for a new facility to accommodate the volume under consideration.

Based on the forecasted demand illustrated in Table 10, three additional chain makers would be needed. To account for maintenance downtime, however, it is assumed that one chain maker will always be inactive for maintenance and repairs. Procuring and installing the equipment needed for expansion would take approximately 3 years.

Workforce availability is not a concern; it is expected that the manufacturer could quickly hire and train new workers to support the projected growth.

3.2.2 Fiber Rope

To meet the production needs for the deployment scenario provided, the rope manufacturer would need to expand their workforce and in-house equipment. Depending on the confirmed business volume, a new facility may be justified near the floating wind ports (such as in Eureka, California) to complete the sub-rope assembly and application of the jacket to the rope.

To complement the current facility, a new closing braider located on the West Coast could help increase production speed with a smaller investment. In this scenario, the sub-ropes would be manufactured at the existing facility and shipped separately for final assembly of the full rope (composed of multiple sub-ropes) using the closing braider on the West Coast. The time to procure and operationalize a new closing braider could span 18–24 months. Combining the sub-ropes, applying the covering braid, and creating the splices would all be completed at the West Coast port.

A longer-term scenario could involve adding a dedicated sub-rope facility on the West Coast as well. Establishing a new facility to execute the full production process would take about 5 years, two of which would be for the physical expansion itself.

The domestic rope manufacturing workforce currently has eight specialists capable of splicing the rope sizes needed. Increasing the workforce would require a ramp-up period, as training to splice rope is extensive and can take several years. One expert can train two apprentices at a time. To meet the requirement for the deployment scenario provided, the current workforce would need to expand by an estimated factor of 5.

Standardizing the rope diameter is not a significant factor for production rate since the rope production process adapts to different sizes by changing the number of sub-ropes to form the required diameter rather than needing to change equipment or retool machinery.

3.2.3 Anchors

Many manufacturers on the Gulf Coast have been manufacturing suction piles for offshore applications. One manufacturer has investigated expanding current capabilities, namely, adding a line that is able to roll 3-in.-thick, 12-ft-wide plate, which is larger than their other line. There is also interest in adding up to two new lines and scaling up the welding workforce, solely for offshore wind work. Although it seems unlikely that this supplier would open any new facilities along the West Coast, they could expand their current physical footprint locally within the Gulf. We assume that other fabricators could consider similar expansion.

While the facilities themselves can keep up with a large portion of the required volume, the workforce in the region may be insufficient. If piles are standardized to two or three sizes, it would be possible to automate part of the manufacturing process, lightening the load on the workforce. Automation has not yet been implemented because it is not needed for the current volume.

Given the current facility capabilities, it is possible to expand production and produce cans for a suction pile every 2–3 days per line. With two lines focused solely on suction piles, a facility could produce 10–12 piles in a month. With enough demand, it is even foreseeable that eight existing major manufacturers could each expand their current output to each produce 20–24 piles per month, which would enable a total throughput of 160–200 piles per month.

Another concern is the rate that the suction piles can be transported from the Gulf Coast to the West Coast versus the rate at which the suction piles are produced. Trucking is less feasible once the pile diameters exceed 12 ft (3.66 m) and would be inefficient with so many vehicles needed for such a large quantity. It would be possible to transport cans individually, but then a facility would need to be established on the West Coast to handle the welding. Barges are thought to be the most effective way to transport piles. In the 6–8 weeks it would take for one barge to drop off a shipment of six piles and return to the Gulf Coast, a facility with two lines at full capacity could produce 20–24 piles, causing an overflow. Therefore, several barges in constant rotation would be needed to keep up with production capabilities.

3.2.4 Connectors

When discussing the deployment scenario, the surveyed connector manufacturer seemed confident that they currently have the capability to handle the output required with a staggered delivery. Many of the forges that would produce connectors would need to be certified by the applicable class society to manufacture "R"-grade mooring equipment to the associated material specifications. Many of the same facilities that make lifting shackles could make offshore mooring shackles.

3.3 Supply Chain Modeling

The supply chain processes are modeled using ORBIT—a discrete event model developed by NLR to analyze the cost and times of offshore wind balance-of-system processes. ORBIT includes many different modules, split into design and installation modules, that can model individual processes within the balance-of-system process. To resolve the manufacturing and transportation aspects of the supply chain, we expanded ORBIT to include two new project modules: a custom mooring system "design" and a mooring system supply chain "process." Previously, mooring system design info was estimated using regression curves based on water depth and turbine rating. Now, the custom mooring system design allows for individual mooring components to be read into ORBIT with full details of the lengths and diameters of specific mooring lines, in addition to the lengths, diameters, and thicknesses of anchors. Using these more detailed design data, ORBIT can now also simulate the supply chain process of manufacturing, storing, and transporting mooring components from manufacturing facilities to port using user inputs such as production takt time, laydown area, and transit time. ORBIT can also consider other logistical aspects such as transportation weather windows, but these are excluded in the supply chain model for simplicity.

Using real-world information from mooring component suppliers, we set up manufacturing and transportation inputs for ORBIT to represent the domestic supply chain of chain, rope, and anchors, shown in Table 11.

Table 11. Supply Chain Parameters

Category	Parameter	Chain	Rope	Anchors
Manufacturing	Assembly Lines	1	1	2
	Takt Time (h)	**0.186 (per m)**	0.187 (per m) **87.6 (per rope)**	**182.5 (per unit)**
	Reset Trigger (mm)	6.35	25.4	200
	Reset Time (h)	168	0.5	168
Transportation	Transit Time (h)	168	168	336
	Maximum Capacity (# per railcar or vessel)	-	2 (5 spools of 450 m)	6 (per 300 ft barge)
	Maximum Cargo Load (t)	600 (60 t/railcar)	-	-
Storage	Space Required (m^2)	7.5 (per 90-ft shot)	6.75 (per 450-m spool)	[(Length + 3) × (Width + 3)]
	Port Laydown Area (m^2)	40,500 (10 acres)		

In the supply chain module, the general process goes through the following steps:

- Set up a custom mooring system design that contains mooring component (e.g., chain, rope, anchors) diameters, lengths, thicknesses, and costs.
- Initialize an ORBIT port object to store manufactured items that have been transported.
- For each mooring component from the custom design, assign storage requirements, manufacturing requirements, and transportation requirements using ORBIT inputs based on supply chain parameters (e.g., Table 11)
- Once setup is complete, run the simulation to begin instances of manufacturing each component and loading each component onto a transportation vessel until all components have been manufactured and transported to port. Component loading pauses until the transportation vessel arrives back from port. Manufacturing does not pause based on the transportation vessel.

In our modeling of the supply chain to create standardized mooring system designs, we use a set of assumptions:

Manufacturing Assumptions

- There is only one assembly line for chain and rope but two assembly lines for anchors.
    - Current chain manufacturing capacities include 47,000 m per year over two chain makers, or two assembly lines, at 35%–40% capacity. Multiple assembly lines can be modeled, but comparisons are easier with only one line. We model one chain maker that can produce 47,000 m per year, which would equate to 70%–80% of annual capacity. We assume the other chain maker would remain available for other manufacturing orders.
    - Anchors of different sizes are typically manufactured by different lines to avoid retooling for different sizes. However, we assume that each assembly line would

roughly manufacture the same number of anchors regardless of diameter to minimize total manufacturing time. We assume two manufacturing lines.

- Anchor manufacturing equipment shuts down for 1 week to accommodate new anchor diameters that are more than 0.2 m from a reference anchor diameter. The first anchor diameter manufactured after each retooling becomes the reference diameter to check for subsequent diameters greater than 0.2 m. This assumes all anchor diameters within 0.2 m from the reference diameter can be manufactured with existing equipment setups.
- Chain manufacturing equipment shuts down to retool for 1 week to accommodate new chain diameters that are greater than 6 mm from a reference chain diameter. The chain manufacturing equipment assumes no significant changes are needed to process bar stock within 6 mm of a reference diameter.
- Rope manufacturing equipment shuts down for 30 minutes to accommodate new rope diameters that are greater than 25.4 mm (1 inch) from a reference rope diameter.
- Manufacturing time for chain is based on length, not diameter. Manufacturing time for ropes and anchors uses the provided takt time per unit. The takt time of rope is based on the current throughput of 100 ropes per year.
- Anchors can be manufactured at any incremental length (as opposed to rolling sheets of steel into 10-ft cans).
- Takt time is based on continuous throughput of actual suppliers (from Section 3.1), which does not consider any realistic facility downtime or other existing customers and work orders.

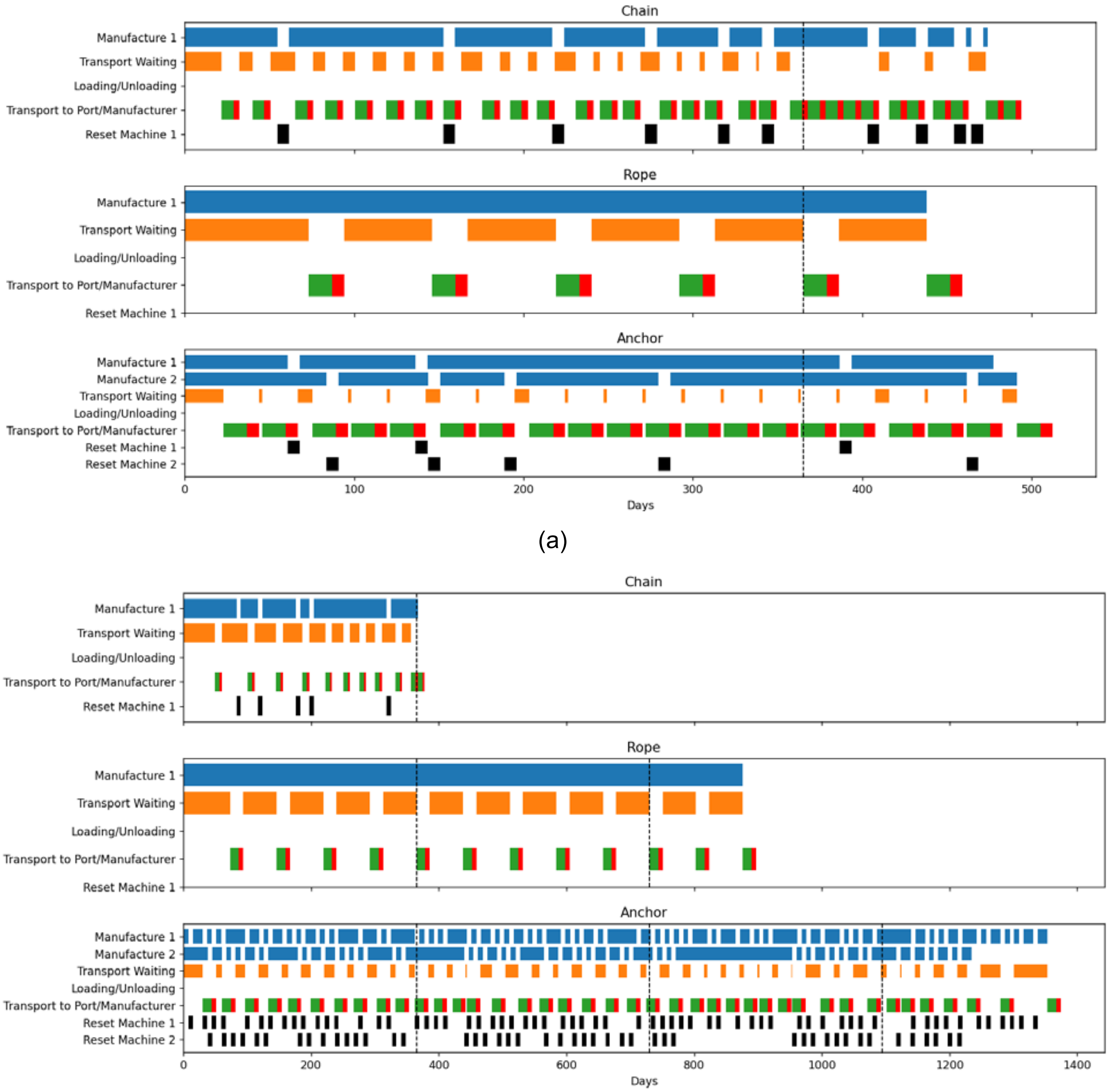
Transportation Assumptions

- The loading and unloading of components takes zero time.
- There is one train to transport chain, which consists of 10 railcars, and each railcar can support up to 60 t of chain.
- There is one train to transport rope, which also consists of 10 railcars; each railcar can support up to two ropes amongst a number of reels. Detailed reel sizes to support rope lengths on the order of 1,000 m for the baseline designs are not included.
- There is only one 300-ft barge, which can carry six anchors at a time. Anchor throughput is based on the existing supply chain, where one manufacturer can produce 48 piles per year. In the 6-8 weeks it would take for one barge to transit to port and back, one manufacturer could produce 5-7 piles, which would not cause an overflow for one barge.
- Trains and vessels take half the time to transit back (unloaded) to the manufacturing facility as they take to transit to port (loaded). In reality, additional vessels or trains can be used while initial vessels or trains are transiting.
- Chain is manufactured in Washington, rope is manufactured in Pennsylvania, and anchors are manufactured on the Gulf Coast; they are all transported to the West Coast. Transporting chain and rope from the manufacturing facility to port takes 1 week, and transporting anchors through the Panama Canal takes 2 weeks.

Storage Assumptions

- The port laydown area of 10 acres is representative of potential land use at the Port of Humboldt (Shields et al., 2022) but it is assumed that any number of mooring components of any size can be delivered to port without laydown space conflicts. Further details to determine whether mooring components can be placed at port will depend on finalized port plans and installation activities, which are not included in this study.

To demonstrate the capabilities and outputs of the supply chain module, we provide a supply chain timeline of the Humboldt and Morro Bay designs in Figure 22, showing how each discrete process happens within ORBIT for each mooring component.



(a)

(b)

Figure 22. Baseline design supply chain process for chain, ropes, and anchors in ORBIT for (a) Humboldt and (b) Morro Bay.

Blue represents manufacturing time; black represents equipment downtime; orange represents transportation wait time; green and red represent transit time to and from port, respectively.

The blue rectangles represent the manufacturing time needed for each component in the mooring system. The black rectangles represent the downtime needed of the manufacturing equipment to account for changes in component sizes. The orange rectangles represent the time that the transportation railcar or vessel waits for the manufacturing processes to be completed and loaded. The green and red rectangles represent the transportation railcar or vessel transiting to and from port, respectively. In this view, we can see a clear timeline of each process that is simulated within the supply chain module of ORBIT.

This supply chain model uses the same architecture and processes as an installation module within ORBIT, meaning it can calculate its own process cost based on times for each activity and the day rates associated with the transportation vessels. However, we do not consider these costs because the number of transportation vessels, amount of products per order, and day rates of vessels or railcars would be project-specific and outside the level of detail for this study.

At the time of publication, the expanded ORBIT model with the supply chain module is publicly available on a feature branch of the main ORBIT GitHub repository titled "Standard_Mooring" (https://github.com/WISDEM/ORBIT/tree/Standard_Mooring).

A working example of the new ORBIT model can be run in a Jupyter Notebook under: https://github.com/WISDEM/ORBIT/tree/Standard_Mooring/examples/Standard_Mooring.

Should this feature branch cease to exist, refer to the ORBIT change log (https://wisdem.github.io/ORBIT/source/changelog.html) to find the version where the feature was integrated.

4 Mooring Standardization Techniques

Mooring systems could be standardized in a variety of ways to better suit local supply chain capacities and to realize practical benefits related to simplifying design, manufacturing, and logistics. This section describes potential benefits from standardization, the mooring standardization techniques considered, and a preliminary evaluation of these techniques before more detailed investigation in later sections.

We define a "standardization technique" here as an array-level strategy to homogenize some aspects of mooring system design to reduce complexity, in contrast to designing individual engineering-optimized mooring systems for each turbine in an array. Standardization can result in over-engineering of some components, but it can improve other aspects of a project outside of the engineering design process, such as fabrication, deployment, and maintenance. In this project, we focus on benefits from design through deployment. We consider four main categories in which standardization strategies could reduce complexity:

- **Design complexity**: the degree of variation in the design that relates to the number of design variables and the difficulty in generating good designs.
- **Supply chain complexity and spread**: the number of different types of suppliers and steps in the supply chain as well as the geographic spread of the supply chain (from regional to national to international), which impacts local economic benefits and control over supply chain dependencies.
- **Manufacturing complexity**: the degree of sophistication or adjustments involved in manufacturing the components, including the demand for retooling to switch to producing different sizes or types of components, which impacts manufacturing cost and time.
- **Logistical (transportation, staging, integration, installation) complexity**: the degree of different infrastructure, sequencing, and tracking needed to accommodate the quantities and variations of component types, sizes, and positions when transporting from suppliers, staging, integrating, and installing.

We highlight various standardization techniques that could be considered in the design process, the ones that are likely to make the largest impact on mooring system material cost and supply chain lead time, and initial case study results to quantify these changes. Once evaluated, we can determine which techniques would be best applied to our baseline designs to create final standardized designs.

4.1 Standardization Techniques

We considered many mooring system standardization options qualitatively before selecting the most promising ones to explore quantitatively. The simplest form of mooring standardization is to choose a single mooring configuration and anchor type for all mooring systems in the array. This reduces the complexity of the supply chain demand in terms of the types of suppliers required. This can also include choices of components that are more available locally.

Standardization of component sizes allows components to be produced with the same manufacturing process without changing the setup of manufacturing equipment. This could include the size of connectors and the diameters of linear components such as chains, ropes, and anchors. Standardization of lengths (of chains, ropes, and anchors) also allows for similar manufacturing processes for the same lengths and may improve storage requirements. Standard component lengths with standard component sizes can be used interchangeably throughout the farm, which avoids the need to pre-allocate each component to a specific location in the farm and allows warehousing and replacement of components with minimal customization. However, accounting for water depth variation across the array would have to be done by other design parameters.

Under the umbrella of standardization, we also consider approaches that can reduce component quantities through shared mooring line or shared anchor configurations and through layout standardization approaches. Layout standardization can include using regular spacing of turbine positions and uniform mooring orientations (both of which were used in the baseline designs), which help reduce variability in the load conditions experienced by mooring components across the array. Positioning choices, such as where anchors are placed, can also provide for more similar seabed conditions for each mooring system and anchor in the array. Beyond these techniques, standardization concepts could consider reduced component quantities, logistics time, or operational burdens with the aim of simplifying processes to which many operators can conform.

Table 12 lists all standardization techniques considered in this study. These do not include techniques applied to processes outside of the design of the mooring system, such as manufacturing, transportation, or installation processes.

Table 12. Standardization Techniques

Technique	Parameter	Description and Impact
Standard Types/Sizes	Line Type	Standardizing line materials in the project allows for less suppliers needed, similar performance, and eases installation complexity.
	Line Diameter and Length	Standardizing the size and/or length of all line sections of one material type eases manufacturing, installation, and storage complexity at port and on the installation vessel.
	Anchor Types	Standardizing anchor types and geometries in the project allows for less suppliers needed, eases transportation and installation logistics, and can account for varying seabeds.
	Anchor Diameter and Length	Standardizing anchor diameters and lengths across the project. Manufacturing can involve the same number of “cans” and steel plate dimensions to avoid fabrication line delays and simplify transportation logistics.
	Connector Components	Standardizing the size, type, and/or location of connector components across the project. Simplifies manufacturing, transportation, and installation logistics.
	Manufacturing Location	Standardizing the location of where mooring components are sourced and manufactured (e.g., California) can reduce supply chain times and complexities if capable of supporting large floating wind projects.
	Shared Mooring Lines	Using shared mooring lines between platforms can standardize length and avoid variation in lengths due to

Technique	Parameter	Description and Impact
		bathymetry while also reducing anchor counts. However, the floating systems become much more coupled and the sizes and tensions of lines likely increase.
Shared Components	Shared Anchors	Decreases the total number of anchors required for a project but would require different sizes to accommodate different loads.
	Hybrid Systems	A combination of shared mooring lines and shared anchors that can use benefits from both ideas.
Simplified Layouts	Gridded Layouts	Simple layouts can ease navigation and/or fishing processes but may not be optimized for maximum AEP.
	Mooring Line Orientations	Consistent mooring line headings can ease installation and navigation processes and can also be oriented to reduce extreme or fatigue loads.
	Anchoring Radii	Setting all anchoring radii in a project can simplify the design and installation processes.
	Soil Conditions	Organizing layouts to avoid unfavorable soil characteristics or seabed slopes can reduce design and installation complexity.

The baseline designs already conform to some of these standardization techniques. They use the same mooring line configuration (consisting of two chain sections and a polyester rope section) across the entire farm. The floating turbines are in a gridded layout with consistent anchoring radii across the entire farm. Further standardization of anchor types can reduce anchor manufacturing and installation complexity but may sacrifice the advantages of a gridded layout or consistent mooring line orientations due to varying seabed soil conditions.

After qualitatively analyzing these standardization techniques, we concentrated our efforts on a subset of standardization techniques that are likely to have the largest impact on the cost of mooring component materials and the demand on the supply chain compared to the baseline designs. These include:

- Standard chain diameters
- Standard chain lengths
- Standard rope diameters
- Standard rope lengths
- Standard anchor dimensions
- Shared anchors.

The rope diameters of each baseline design are only two discrete diameters, but their lengths extend through the majority of the water column over variable bathymetry. The chain diameters have a large distribution across the farm to accommodate different fatigue loads depending on water depths and mooring line headings, but the chain lengths have relatively less distribution. There is also a large distribution in anchor size. These techniques provide an initial assessment of the effect that each has on the baseline designs and how standardized designs can best impact the design of a floating wind farm.

4.2 Initial Standardization Case Studies

To investigate these standardization techniques, we expanded our quasi-static mooring system design tools to apply the standardization techniques to the Humboldt baseline design with 120 individually sized mooring lines and anchors and adjusted the component sizes for each technique separately. We made use of the existing sizings from the baseline design as much as possible to avoid unnecessary reoptimization of each mooring line. As a result, the standardized designs showcase array-wide adjustments to the baseline designs with an emphasis on the supply chain impacts rather than on precise optimization to the original design requirements.

We identify certain array-level parameters and quantities that can easily be used to evaluate each design:

- Total length chain; total length of rope
- Total weight of chain; total weight of rope
- Total procurement cost of chain; total procurement cost of rope
- Total weight of anchors
- Total quantity of mooring line sections
- Supply chain lead time
- Installation complexity factor.

We use the ORBIT supply chain model to calculate lead time, and we formulate an "installation complexity factor" to represent the complexity imposed on the installation process due to variations in components:

$$ICF = \frac{2U_{D,chain}}{N_{chain}} + \frac{U_{D,rope}}{N_{rope}} + \frac{U_{D,anchor} + U_{L,anchor} + U_{T,anchor}}{N_{anchor}} \tag{5}$$

where U indicates the number of unique values for chain diameter, rope diameter, and anchor diameter, length, and thickness and N indicates the total number of chain sections, rope sections, and anchors in the design. Costs are calculated solely as a function of component mass using assumed cost coefficients for each component (Hall et al., 2021), which do not consider other cost effects like economies of scale, manufacturing setup, or shipping logistics.

Table 13 lists the results of each standardization technique individually applied to the Humboldt baseline design using these metrics.

Table 13. Initial Standardization Technique Case Study Results

Parameter	Baseline	Standard Chain Diameter	Standard Rope Diameter	Standard Chain Length	Standard Rope Length	Standard Anchor Size	Shared Anchor
Number of Chain Sections	240	240	240	240	240	240	240
Total Length of Chain (m)	52,148	52,148	52,152	67,742	73,541	52,148	52,148
Total Weight of Chain (t)	16,572	28,395	16,574	21,785	24,355	16,572	16,572
Chain Procurement Cost ($M)	42.8	73.4	42.8	56.3	63.0	42.8	42.8
Number of Rope Sections	120	120	120	120	120	120	120
Total Length of Rope (m)	114,771	118,062	118,062	100,847	97,676	114,771	110,301
Total Weight of Rope (t)	3,320	3,416	3,339	2,918	2,827	3,320	3,191
Rope Procurement Cost ($M)	24.8	25.6	25.0	21.8	21.2	24.8	23.9
Number of Anchors	120	120	120	120	120	120	95
Total Anchor Length (m)	1,615	1,615	1,615	1,615	1,615	2,546	1,458
Total Anchor Weight (t)	5,950	5,950	5,950	5,950	5,950	11,925	5,115
Anchor Procurement Cost ($M)	61.0	61.0	61.0	61.0	61.0	122.2	52.4
Chain Supply Chain Lead Time (years)	1.22	1.07	1.22	1.54	1.65	1.22	1.22
Rope Supply Chain Lead Time (years)	2.51	2.58	2.51	2.21	2.14	2.51	2.41
Anchor Supply Chain Lead Time (years)	2.96	2.96	2.96	2.96	2.96	2.56	2.29
Installation Complexity Factor (-)	6.3	5.9	6.3	4.3	5.3	5.4	6.39

4.2.1 Standard Chain Diameter

The maximum diameter throughout all chain sections in the baseline design (165 mm) was assigned to all 240 chain sections in the standardized design. The polyester rope lengths were then adjusted to ensure the original pretension on the platform was maintained. The results of this standardized design are shown in Table 13 and Figure 23.

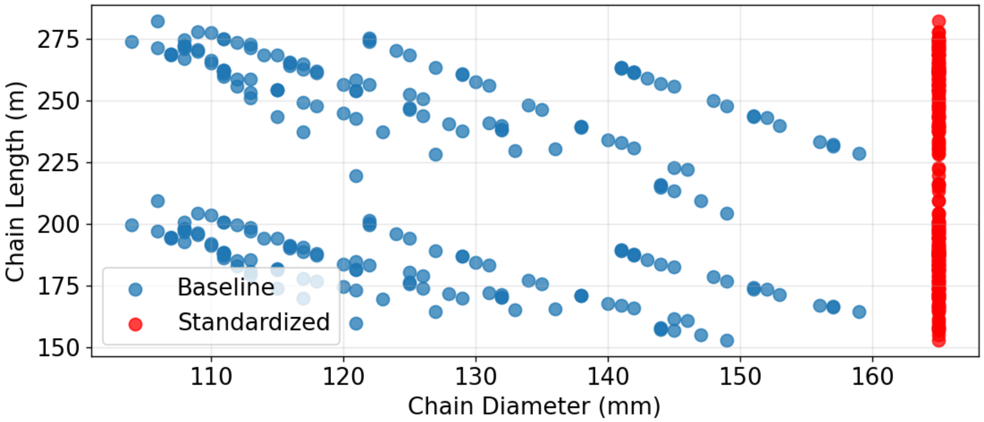


Figure 23. Chain diameter distribution between baseline and standardized designs

Even though the number of mooring line sections stayed constant, the increase in all chain diameters to 165 mm contributed to a 71% increase in both weight and cost of chain. The adjustment of the polyester rope lengths to maintain the original pretension of each line contributed to a 3% increase in the total length, weight, and cost of polyester rope.

The time required to manufacture and transport the chain components to port originally required 1.22 years, but by standardizing all chain sizes to one diameter, the lead time was reduced to 1.07 years (-14%). This reduction happens because the chain makers do not need any downtime to retool for different sizes of chain, which also reduces the time that the transportation railcar waits until it reaches its loading capacity.

The installation complexity of the standardized design decreases by 6.8% due to the reduced ratio of unique chain diameters to total number of chain sections. With only one chain diameter across the entire array, the installation and storage logistics are likely to be more efficient.

4.2.2 Standard Rope Diameter

This standardized design employs a uniform rope diameter. The maximum diameter throughout all rope sections in the baseline design (207 mm) was assigned to all 120 rope sections in the standardized design. The chain lengths were then adjusted to ensure the original pretension on the platform was maintained. The results of this standardized design are shown in Table 13 and Figure 24.

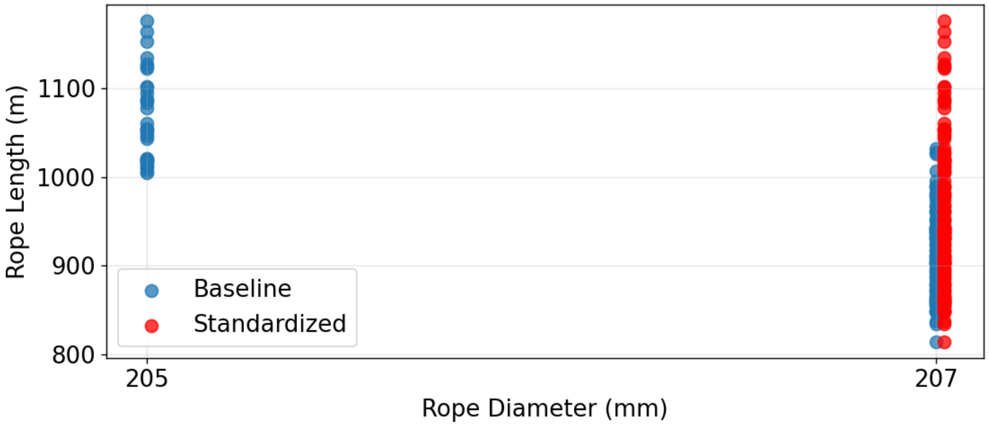


Figure 24. Rope diameter distribution between baseline and standardized designs

The baseline rope diameters happened to be very close at values of 205 and 207 mm, even though each polyester rope section was designed individually for extreme and fatigue loads for different water depths. When all rope diameters were standardized to a value of 207 mm, the total mooring system design, the supply chain lead time, and the installation complexity changed marginally. Since the mooring system designs do not require large distributions in rope size, ropes can likely be standardized to one diameter for ease throughout the floating array development process and simplify the supply chain process.

4.2.3 Standard Chain Length

The maximum chain length throughout all chain sections in the baseline design (282 m) was assigned to all chain sections in the standardized design to avoid the rope contacting the seabed at any depth. The polyester rope lengths were then adjusted to ensure the original pretension on the platform was maintained. The results of this standardized design are shown in Table 13 and Figure 25.

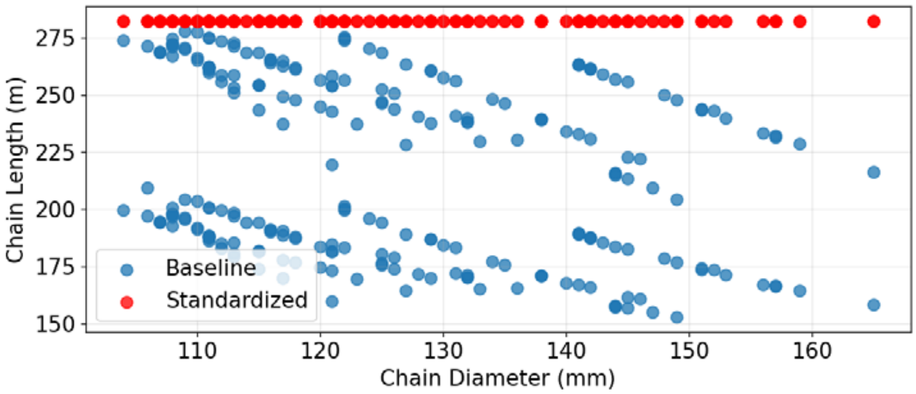


Figure 25. Chain length distribution between baseline and standardized designs

Increasing all 240 chain sections in the array to 282 m increased the total length of chain by 30%; the total weight and cost also increased by 31%. The total polyester rope length (and weight and cost) decreased by 12% because of the increase in chain length and the adjustment in polyester length to maintain the original pretension of each line.

Standardizing chain length to a maximum value increased both the material cost and the supply chain lead time. The time required to manufacture and transport the chain components to port increased by 26% while the supply chain lead time of rope decreased by 12%. The installation complexity factor decreased by 32%, as there are likely advantages of uniform chain lengths during storage, assembly, and installation processes. However, from a mooring system design perspective, standardizing the chain lengths may not be advantageous in terms of cost and time. There could be opportunity to standardize the chain length to a value other than the maximum value or standardize the top and bottom chain sections to separate values, but more design work would be needed to ensure the original criteria of each mooring design could be met.

4.2.4 Standard Rope Length

This standardized design employs uniform rope lengths. The minimum rope length throughout all rope sections in the baseline design (814 m) was assigned to all rope sections in the standardized design, as the minimum would avoid the rope contacting the seabed at any depth. The chain lengths were then adjusted to ensure the original pretension on the platform was maintained. The results of this standardized design are shown in Table 13 and Figure 26.

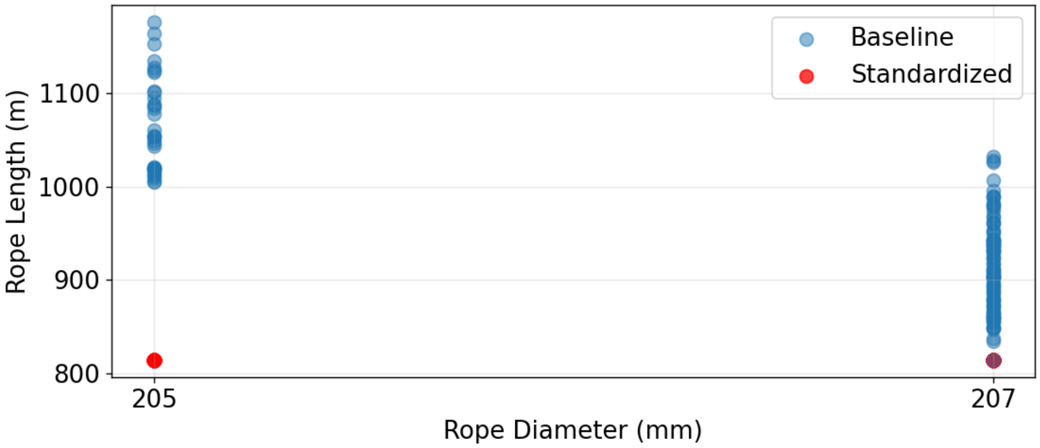


Figure 26. Rope length distribution between baseline and standardized designs

Standardizing all 120 rope sections in the array to 814 m decreased the total polyester length by 15%, which is a notably larger decrease than the standardized design with uniform chain lengths. The total chain length increased by 41%, and the total chain weight and cost increased by 47%. Both standardization techniques of uniform lengths increased the chain section lengths to ensure the rope contact constraint on the seabed would still be satisfied, but other standard lengths may prove to be beneficial.

The time required to manufacture and transport the rope components to port decreased by 15% while the supply chain lead time for chain increased by 35%. Regardless of whether the chain or rope sections are standardized, the supply chain lead time for chain increases by 4–5 months, and the supply chain lead time for rope decreases by 3–4 months. The installation complexity decreases by 16% with a uniform rope length.

4.2.5 Standard Anchor Dimensions

This standardized design employs uniform anchor diameters and lengths to analyze the effect of making all anchors the same size. Pile diameters and lengths play critical roles in the holding capacity of the anchor in both the vertical and horizontal directions. Standardizing only pile diameters or lengths may improve supply chain lead time but could result in new holding capacities that is not designed specifically for the maximum load each anchor will experience. In this design, we standardize both the diameter and length of all 112 suction piles to the maximum diameter and length of the baseline design, which should maintain the required holding capacity for all mooring lines in the array. The D&G pile anchors are not altered. The results of this standardized design are shown in Table 13 and Figure 27.

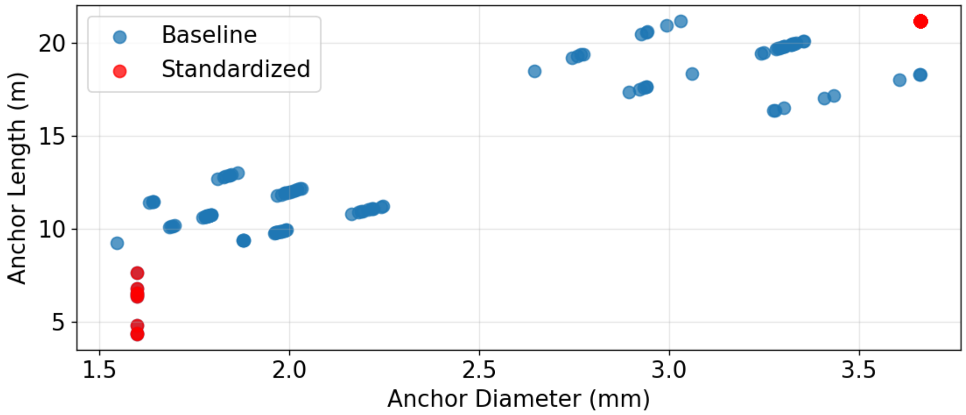


Figure 27. Anchor diameter and length distribution of uniform anchor dimensions between baseline and standardized designs

All suction pile diameters were standardized to the value of 3.66 m, and all suction pile lengths were standardized to the value of 21.2 m. This resulted in a 58% increase in the total weight of anchor material and a 100% increase in the total sum of anchor length. The time required to manufacture and transport all anchors decreased by 14%, which equates to almost 5 months. This decrease is attributable to less time being needed to retool the manufacturing equipment for different sizes, which also reduces the time that the transportation vessel is waiting to load its maximum capacity. This standardization method can help reduce the total time required to supply anchors for a floating project but may significantly increase material costs compared to individually sized anchors.

4.2.6 Shared Anchors

This standardized design approach reduces the total number of anchors in the array by sharing anchors between adjacent mooring lines for different floating platforms. When designing shared anchor systems, the main goals are to minimize material use and reduce procurement costs and installation time while maintaining the structural integrity and functionality of the mooring system. To evaluate shared anchors as a standardization technique, the baseline array layout requires adjustment for proper anchor sharing. The number of shared anchors is primarily driven by the shape of the lease area and the number of platforms in the lease area. To demonstrate and evaluate this standardization technique, Figure 28 shows a shared anchor layout derived from the Humboldt baseline design by shifting every other column of turbines and slightly adjusting the anchoring radius of each mooring system. This layout was chosen as it requires the least amount of change from the baseline design to preserve existing sizing while still achieving good anchor-sharing efficiency.

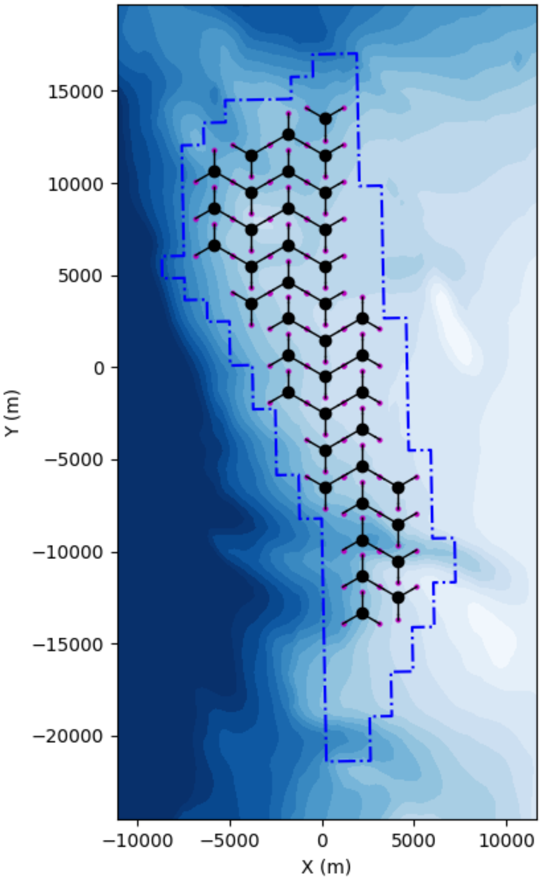


Figure 28. A shared anchor layout based on the Humboldt baseline design

This design shares some anchors between two platforms and reduces the number of anchors by 26% from 120 to 95. Twenty-five anchors are shared, and there are now six D&G anchors (instead of eight in the baseline design), four of which are shared anchors. There is potential to reduce the number of anchors even more with other shared anchor layouts, but these would require greater changes to the array layout and mooring line designs.

Using the shared anchor design methodology, we use interpolated mooring loads based on water depth to design new anchors. In operational conditions, the shared anchors experience partial compensation of the horizontal component of adjacent mooring line loads but summation of vertical and torsional loads of adjacent mooring lines. Considering the new loads and new soil properties, we resized the diameters and lengths of all anchors. A distribution of the anchor sizes compared to the baseline designs is shown in Figure 29, and the results of this standardized design are shown in Table 13.

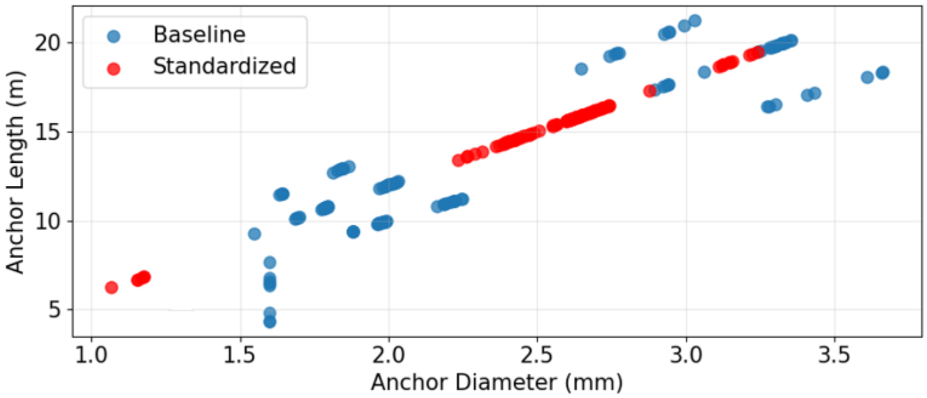


Figure 29. Anchor diameter and length distribution of the shared anchor layout between baseline and standardized designs

The anchor sizing methods found new dimensions of individual and shared anchors with similar length-to-diameter ratios of 6. The primary advantage of this standardization method is the reduction in number of anchors. The total weight of anchor material decreases by 14%, which is due to a combination of the reduction in anchor count as well as the resizing of anchor dimensions. The total length of all anchors decreases by 10%. The time required to manufacture all anchors decreases by 23% for the same reasons.

The installation complexity is slightly higher than the baseline design, meaning that there are more specific anchor dimensions as a result of the shared anchor resizing process. These anchor sizes can likely be further standardized to yield design properties similar to the baseline design but avoid the significant increases in anchor weight as discussed in Section 4.2.5. Continued iterations using different layout geometries and the inclusion of anchor reliability parameters would also increase confidence in shared anchor designs.

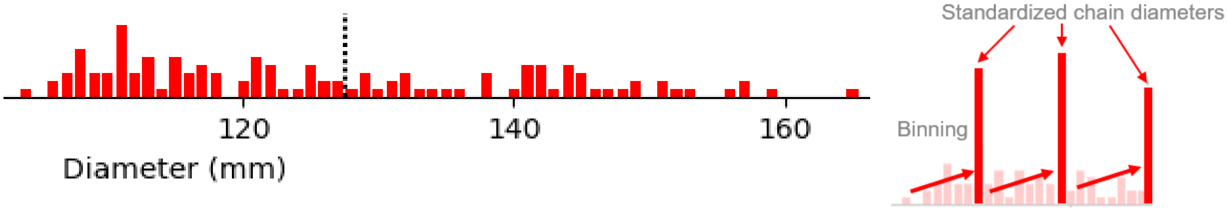
5 Standardized Designs

After developing individually sized baseline designs, characterizing the domestic supply chain, and identifying standardization techniques to apply to the baseline designs, we can develop more robust standardized designs from the baseline designs using specific techniques and results from the supply chain model. We have taken three standardization techniques from Section 4—standard chain diameters, standard anchor dimensions, and shared anchors—and have adapted them for different amounts of standardization. We also use the same shared anchor layout used in Section 4.2.6. To implement the logic for different amounts of standardization, we first introduce a new methodology to allow component sizes to conform to the existing domestic supply chain. We then present the final standardized designs for both the Humboldt and Morro Bay sites.

5.1 Methodology

For the standardization of component sizes (chain diameters and anchor diameters), our approach "bins" the range of component sizes according to selected standardized sizes, where each diameter within a bin is rounded up to the corresponding standardized size (Figure 30). We use these standardized size values—and the discrete number of sizes—as design variables in our standardization design process to find the assortment of standardized sizes that can minimize both supply chain lead time as well as component material cost.

We assume that if we bin component sizes of the baseline designs to standardized sizes, then all design criteria originally met by the baseline designs can still be satisfied, since increasing size (diameter) only increases component strengths and stiffnesses. This concept is shown in Figure 30 using the baseline Humboldt design chain diameters. This concept is suited for standardizing chain and anchor diameters, as opposed to chain and anchor lengths, since increasing component lengths may result in designs that do not meet design criteria.



(a) (b)

Figure 30. (a) The spread of chain diameters in the Humboldt baseline design and (b) the binning standardization approach

Some of the baseline design chain diameters in the Humboldt design are greater than the maximum chain diameter that can be manufactured domestically (127 mm). To represent realistic domestic supply chain scenarios that include this manufacturing limit, we assume that the mooring lines that contain these larger chain sections will be "doubled up," meaning that they will consist of two chain sections near the fairlead and two chain sections near the anchor with reduced chain diameters by a factor of $\sqrt{2}$ to ensure the mooring line properties (like mass and stiffness) are maintained. These new mooring lines now have four total chain sections but still contain only one rope section and one anchor (Figure 31). We assume that the more detailed auxiliary components of the mooring line will be able to support these doubled-up connections without affecting the behavior of the mooring line or anchor.

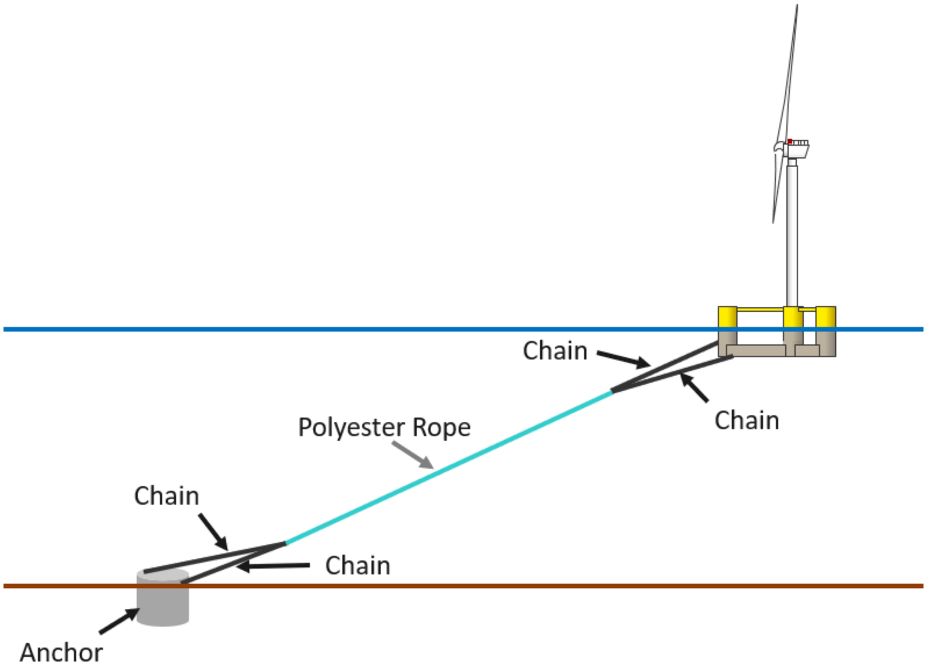


Figure 31. Depiction of "doubled up" chain sections to reduce chain diameters below 127 mm

The maximum chain diameter of the Humboldt baseline design is 165 mm, which, when doubled up, creates two additional chain sections and updates all four chain diameters to 117 mm. Throughout our standardization optimization of chain diameters, we ensure that there is always at least one bin of at least a diameter of 117 mm to ensure that these large chains never have to be tripled up. When comparing supply chain results between the baseline and standardized designs, we employ this strategy for both designs.

We assume the same binning technique for other component sizes, like anchor diameters, where we can analyze different numbers of anchor diameter bins and bin values to determine what assortment of sizes can minimize supply chain lead time and component costs. To ensure anchor design criteria are met, we ensure that at least one standardized size is at least the size of the maximum anchor diameter in the array. We also employ a process to recalculate a new length of the anchor to maintain the original horizontal and vertical holding capacities while assuming the padeye location always remains at two-thirds of the length below the mudline for suction piles. The anchor thicknesses (t) are also adjusted as a function of the new standardized diameters (D), based on Equation 4.

For the standardization technique of using shared anchors, our standardization approach is to develop a shared anchor layout similar to the baseline layout, redesign the anchors based on new multi-line loads and water depths, and analyze the supply chain effects of the new component designs. We do this by first manually identifying attractive shared anchor layouts where we can vary the floating platform positions, the mooring line anchoring radii (distance from platform centerline to anchor), the mooring line orientations, or a combination of all three to achieve desirable shared anchor layouts. We then find the new anchor location depths and interpolate the baseline anchor time series of the two orientations of the shallowest and deepest baseline mooring system designs (using a single wave seed for computational efficiency) to calculate the new loads on the anchors. These new loads are then summed based on the directionality of mooring lines attached to shared anchors (which typically reduces horizontal loads but increases vertical loads) and are used as input to design new anchor dimensions. New diameters, lengths, and thicknesses of suction piles and D&G piles are derived using the new multi-line loads and the soil properties from the baseline design process.

We assume that the new anchoring radii of the shared anchor layouts, the baseline mooring line sizes, and an adjustment of the polyester rope lengths to maintain the original horizontal pretension will still satisfy the baseline design criteria. We do not account for a difference in shared anchor design considering shared anchor reliability or installation logistics relative to individual anchors. Additionally, we assume that the supply chain model for D&G piles is the same for suction piles, whether they are individual anchors or shared anchors.

Outside of our standardization methodology, we also make assumptions about the logistics of the supply chain. We assume that the components can be ordered in bulk, meaning that the manufacturers will produce and transport the entire array of components in an order based on the component sizes and not based on the order in which they are scheduled to be installed in the array. For example, in Figure 30, the chain manufacturer will first manufacture all chain diameters of the lowest size and then manufacture all subsequent chain sections in order of increasing diameter. We call this “sorting.” Sorting provides more efficient manufacturing by minimizing the amount of retooling required for different sizes, but the delivery of different sizes also depends on the available space at port and how efficient the installation process is considering all the other aspects of a floating wind array installation (i.e., substructures, turbines, cables). Sorting strategies based on unique installation schedules are not considered in this study. Additionally, when using two assembly lines for anchors in the supply chain, we ensure the anchors are sorted between the two lines so that they have roughly the same number of anchors to manufacture, regardless of anchor size differences.

Using this methodology and assumptions, we have developed standardized designs of both the Humboldt and Morro Bay designs using the three selected standardization techniques. Our objective was to minimize the material cost of the components as well as the supply chain lead time of manufacturing and delivering those components. This multi-objective optimization created Pareto fronts in which we looked at the trade-off between these two objectives.

5.2 Humboldt

The baseline and standardized Humboldt designs use three mooring lines per turbine. We applied the binning approach to the Humboldt baseline chain diameters and anchor diameters, after the anchors had been redesigned for shared anchor loads. This section covers the standardization process and decisions for each of the three techniques—chain diameter, shared anchor, and anchor diameter—and then combines them all into one standardized design.

5.2.1 Chain Diameter

Our binning approach created sets of standardized chain diameters, where each set represents a farm-level mooring system design that has a total mooring system material cost and a supply chain lead time evaluated with our cost models and ORBIT. The full range of feasible diameter sets was generated between diameters of 91 mm and 127 mm using increments of 6 mm while ensuring at least one bin was greater than or equal to 117 mm, for combinations of up to seven standardized sizes. The value of 6 mm increments was selected because any diameters within a 6 mm tolerance would all be manufactured by the same machinery setup. Each chain section with a diameter greater than 127 mm was doubled up, which reduced its diameter and corresponding properties by a factor of $\sqrt{2}$. These designs are represented by each dot on the scatter plot of Figure 32, where each color represents a different number of standardized chain diameter bins. Multiple dots of the same color represent the same number of bins, but have different standardized diameter values, resulting in different costs and lead times. The chain material cost, which is calculated as a function of diameter using a single cost coefficient and is assumed to be independent of manufacturing time and number of bins, is shown on the *y*-axis, and the supply chain lead time of chain is shown on the *x*-axis.

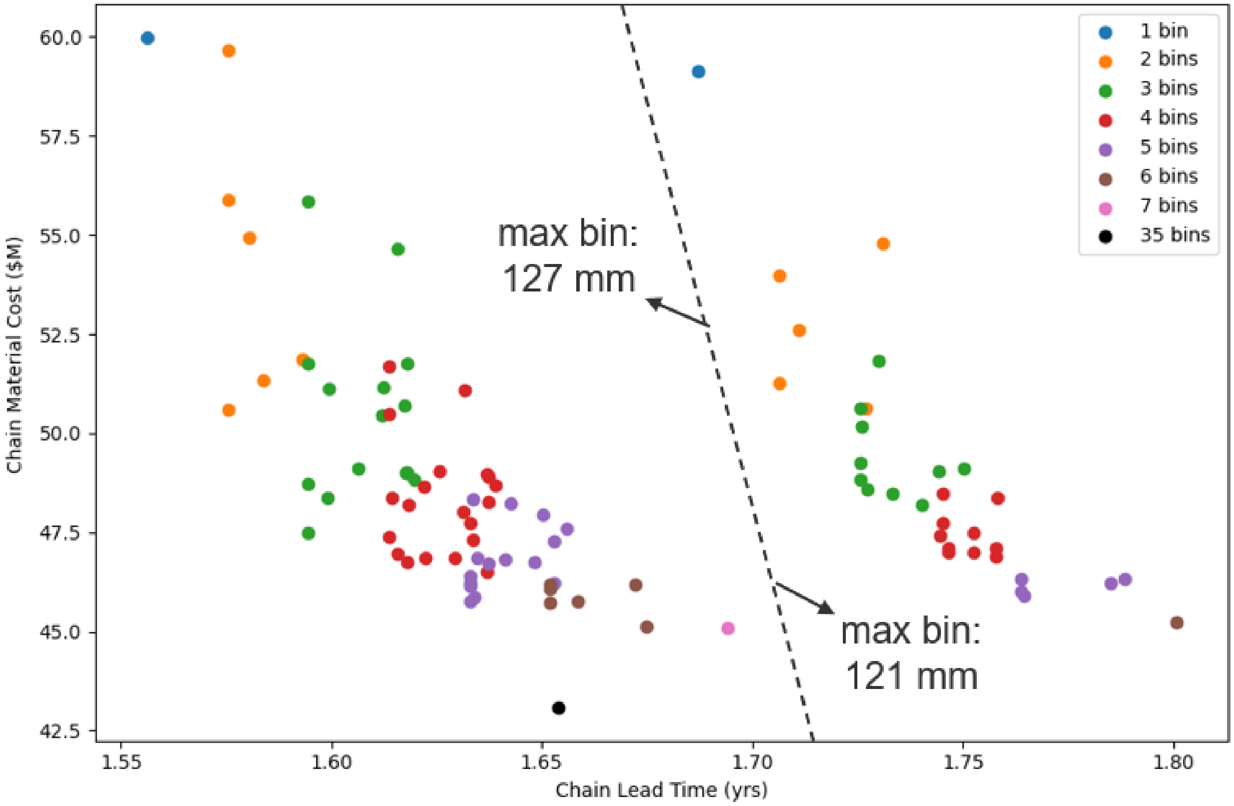


Figure 32. The multi-objective design space of different farm-level mooring system designs with different numbers of bins and bin values for chain diameter for the Humboldt site

In general, the designs with one bin have the highest material costs and the lowest lead times and the designs with the most amount of bins have the lowest material costs but higher lead times. Binning all chain diameters into one bin of 127 mm resulted in the blue dot in the upper-left-hand corner of the plot, which has the lowest lead time since all the chain diameters are the same and no manufacturing retooling is required; however, it has the highest material cost, since some chain diameters were doubled up and all were increased to 127 mm. The next blue dot over represents one bin at a value of 121 mm. This design has a higher lead time because all baseline chain diameters above 121 mm had to be doubled up (as opposed to the limit of 127 mm). Sets of bins with a maximum bin value less than the manufacturing limit of 127 mm require more mooring lines to be doubled up. These designs have an increase in supply chain lead time since there are now more chains to be manufactured, but slightly less material costs than their counterparts since the lower chain diameters use less material per chain.

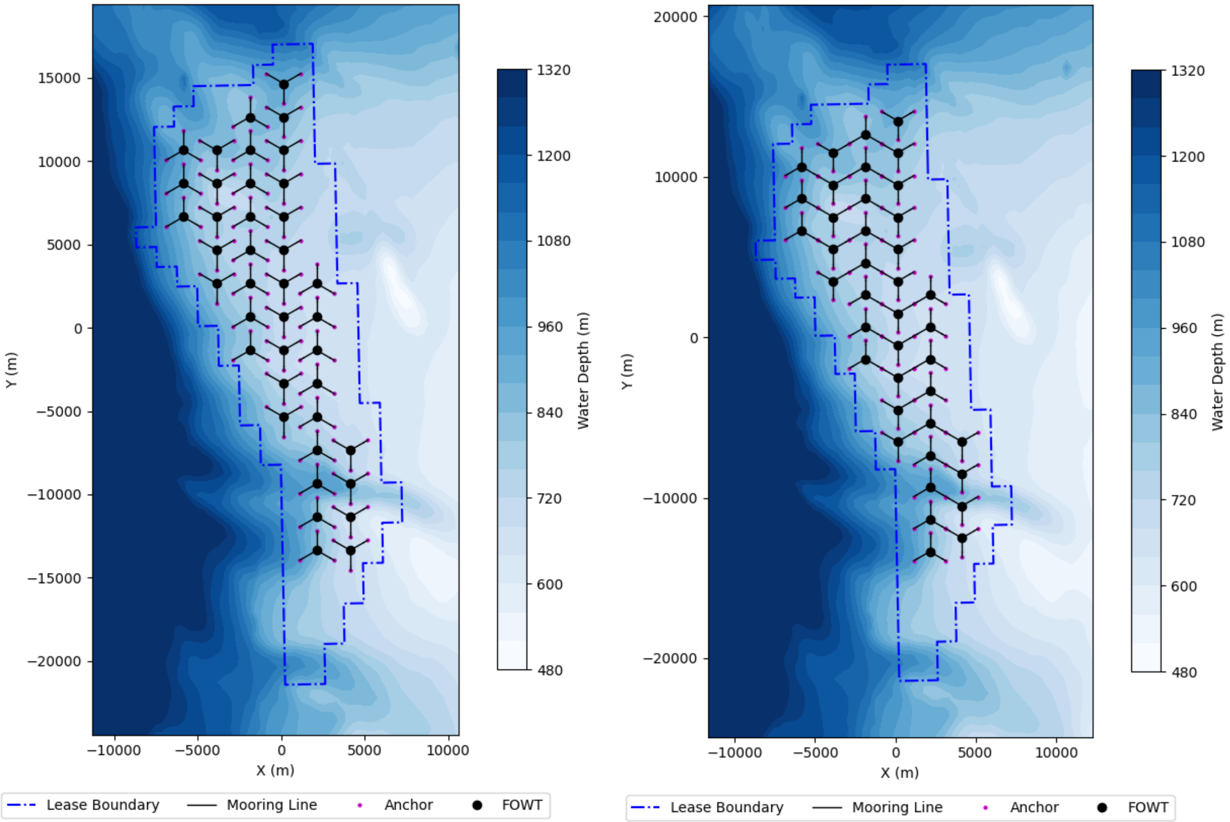
Each increase in the number of bins adds roughly an extra week of lead time since each new bin is at least 6 mm away from the previous one, requiring a week (0.02 years) of downtime to retool machinery. There are small variations and differences in lead times between each design due to the number of chain sections that are loaded onto each railcar (as a function of weight) and the number of trips the railcars need to make. Designs of the same number of bins typically show the highest costs when diameters are farthest apart or closest together. For example, the most expensive orange dot in Figure 32 has two bin values of 127 mm and 91 mm, since there are very few chain diameters less than or equal to 91 mm. The least expensive orange dot has two bin values of 127 mm and 109 mm, since this design minimized the number of chains rounded up to 127 mm while minimizing the value of the second bin.

The baseline design, with 35 unique chain diameters (out of 168 chain sections), has a lead time of 1.65 years and the lowest material cost of $43 million. The design with one bin at 127 mm has a lead time of 1.56 years and a material cost of nearly $60 million. The baseline designs have a bin value at 127 mm, which means no unnecessary chain sections are doubled up. A Pareto front can be drawn between the 127-mm one-bin design (upper-left blue dot) and the baseline design with 35 bins (lower black dot), where each design along that curve represents a minimization of the multi-objective. The pink dot with seven bins has a higher lead time than the baseline design because it requires six different machinery setups, whereas the baseline design only requires five bins and five different machinery setups due to its distribution of diameters.

To select one chain standardization, we chose the design with three chain diameters of 103, 115, and 127 mm. This design is represented by the green dot in Figure 32 with a lead time of 1.59 years and a material cost of $47.5 million. The practicality of manufacturing and handling 35 different chain diameters of the baseline design was going to be more difficult than storing and handling three sizes, and we determined that standardizing all chain sections to one diameter would increase the total cost more than necessary.

5.2.2 Shared Anchor

In parallel to standardizing the chain diameters, we implemented the shared anchor standardization technique to reduce the number of anchors and logistical complexity. We generated a shared anchor layout that requires the least amount of change from the baseline layout (Figure 33a) to preserve the behavior and sizing of the baseline design components while achieving good anchor-sharing efficiency, where each shared anchor supports two mooring lines in opposite directions. Only the layout and anchoring radii are changed, and each platform's mooring system orientation is maintained (Figure 33b).



(a) (b)

Figure 33. (a) Baseline Humboldt design and (b) standardized shared anchor design

In this design (Figure 33b), the columns of the layout that contain a platform with a mooring line oriented downwind are moved either up or down in the *y*-direction so that the anchors can share mooring lines. This also requires a small change in the original anchoring radius from 1,200 m to 1,154.7 m to align with the layout geometry. This creates 25 instances of overlapping anchors, or 25 shared anchors with 70 other individual anchors for a total of 95 anchors, compared to the baseline number of 120 anchors.

Once the layout and the anchoring radii are changed, each anchor now has a new water depth and we can employ our methodology of redesigning the diameters, lengths, and thicknesses of the anchors based on interpolating the load time series at the new water depths and using the new soil properties at those depths. We also use a transfer function to calculate the loads on the padeye of each anchor relative to the maximum load at the mudline. The new anchor dimensions are listed in Appendix H, where the minimum diameter for suction piles was set at 2.0 m. Rows highlighted in orange represent shared anchors, and rows in bold represent D&G anchors.

All suction pile designs minimized their weights at a maximum length-to-diameter ratio of six, which means that the suction piles wanted to be as slender as possible, regardless of whether they were in soft clay or medium clay. The new shared anchor design includes only four D&G anchors in rocky soils as opposed to eight in the baseline design. Two of them are shared anchors, where we assume D&G piles can be designed for multiple mooring connections and support the doubling up of mooring lines attached to the anchor when baseline diameters are larger than 127 mm. Each shared anchor is labeled in Appendix H according to its attached mooring lines. For example, anchor FOWT1a-5a represents a shared anchor with mooring lines 1a and 5a attached.

These anchor sizings are only based on the assumed soil properties and expected maximum combined mooring line loads and not on any other design aspects such as the installation process or anchor failure probabilities. The polyester rope lengths of each mooring line are adjusted to maintain the original horizontal pretension on the platform, but the new loads they exert on the anchor due to the adjustment is not expected to change significantly.

5.2.3 Anchor Diameter

With the 86 new unique anchor diameters defined (rounded to the nearest millimeter) in the shared anchor layout, including the four D&G piles, we applied the same binning approach we used for chain diameters to the new anchor diameters, where each set of bins represents a farm-level mooring system design with a total mooring system cost and supply chain lead time. Each design is represented in Figure 34 by a colored dot.

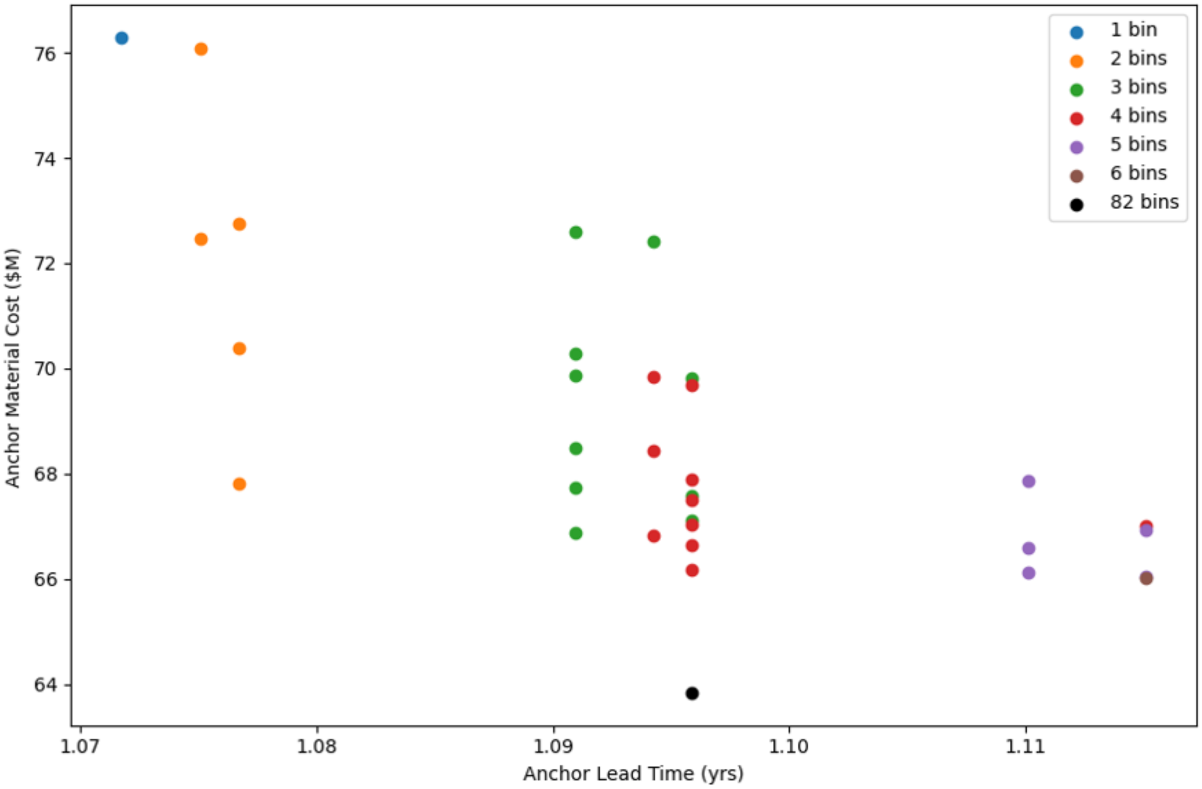


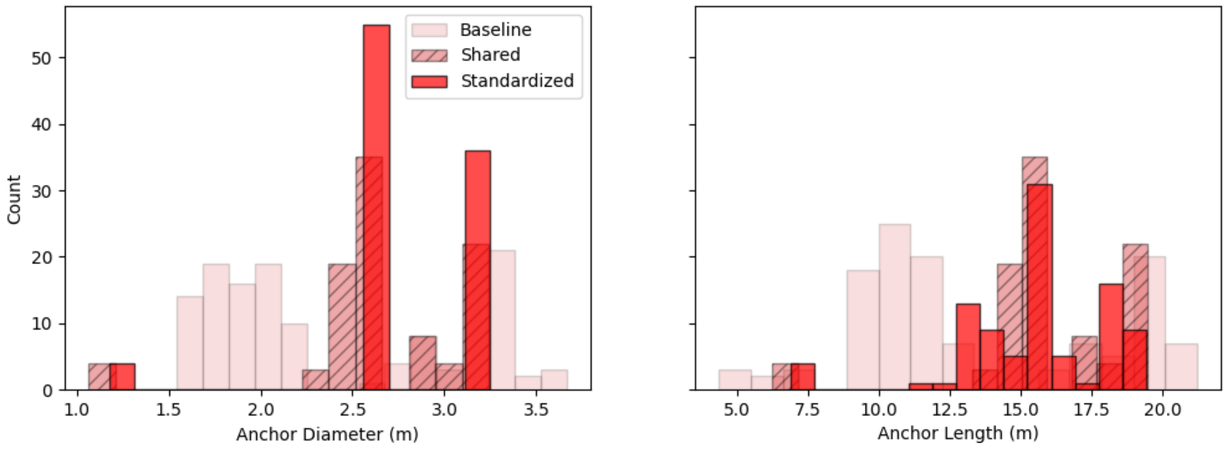
Figure 34. The multi-objective design space of different farm-level mooring system designs with different numbers of bins and bin values for suction pile diameters for the Humboldt design

The four D&G piles are all standardized to the maximum D&G pile diameter of 1.2 m (47 in) and are not shown in Figure 34. Suction pile anchor diameter bin values range from 2.25 to 3.25 m (which are the maximum and minimum anchor diameters for the shared anchor design) by increments of 0.2 m. Each anchor diameter standardization also involves an adjustment to the length and thickness of the anchor to main its original capacity. The top-left blue dot represents the design with one bin of anchor diameters at 3.25 m, which produces the largest total material cost of anchors (as a function of anchor weight after adjustments are made to length and thickness to match existing capacity) but the lowest lead time (no machinery retooling required). From there, increasing numbers of bins increases lead time but decreases component material costs until the baseline shared anchor design is reached (black dot) with 82 unique diameter bins. However, since we assume that anchor manufacturing equipment can manufacture diameters within 0.2 m of each other and that we have two assembly lines running, the baseline shared anchor design only requires an extra 2 weeks of downtime to retool machinery relative to one standardized size.

The number of assembly lines helps reduce lead time. We use an assembly line methodology of ensuring each assembly line receives a similar number of anchors so that they both operate for a similar amount of time, with only one week of downtime required for one line. Otherwise, if we were to divide them up based on number of bins, for example, one assembly line would run for much longer than another. For instance, the orange dot with standardized anchor diameters of 2.45 m and 3.25 m (at 1.075 years and $72.5 million) is able to reduce the total cost relative to the blue dot since 25 of the 91 suction piles can have their diameters standardized to 2.45 m. If all 66 anchors with diameters of 3.25 m were to be manufactured by one assembly line and the other 25 anchors with diameters of 2.45 m were to be manufactured by the second assembly line, the total lead time would be much higher than the distribution of 46 and 45 anchors to each line since one line would have 20 extra anchors (21.7 extra weeks) to manufacture. Therefore, each assembly line may require downtime to reset machinery, but the total lead time can be minimized as opposed to designating specific anchor bins to specific assembly lines.

Any small difference in lead time for designs with the same number of bins are due to how the model distributes different anchors to different assembly lines and how long the transportation vessel waits to reach a capacity of six anchors. In general, the differences in supply chain lead time between different bin sizes are small, requiring trade-offs between weeks of extra manufacturing time and millions of dollars of material.

Regardless, we selected the design with two suction pile anchor diameters of 2.65 m and 3.25 m along the Pareto front to best minimize lead time and anchor material cost (while also qualitatively considering other project considerations like storage and installation), represented by the orange dot in Figure 34 with an anchor supply chain lead time of 1.077 years and a material cost of $67.8 million. This design costs $8.5 million less than the design where all anchors are standardized to 3.25 m but can avoid any additional complexities of working with 82 different anchor sizes. These costs include the adjustments to anchor lengths and thicknesses as functions of changes in diameter to maintain original capacities. The changes in supply chain lead time are not expected to impact the overall project timeline significantly but are still worthwhile to analyze and draw trade-offs. The final standardized anchor sizes are compared to the baseline anchor sizes and the shared anchor sizes in Figure 35.



(a) (b)

Figure 35. Anchor (a) diameters and (b) lengths of the baseline (light red), shared anchor (hatched), and standardized (dark red) designs for Humboldt

5.2.4 Standardized Design Results

The results of these three standardization techniques applied to the baseline designs, while ensuring the polyester ropes are adjusted to maintain the baseline pretension after all changes are applied, are shown in Table 14. The baseline design also has its chain sections doubled up so that its supply chain can be comparatively modeled in ORBIT.

Table 14. Standardized Design Parameters for the Humboldt Site

Parameter	Baseline	Standardized	Percent Difference
Number of Chain Sections	336	336	0%
Total Length of Chain (m)	71,935	71,935	0%
Total Weight of Chain (t)	16,572	18,372	10.9%
Chain Material Cost ($M)	42.8	47.5	11.0%
Number of Rope Sections	120	120	0%
Total Length of Polyester (m)	114,771	110,635	-3.6%
Total Weight of Polyester (t)	3,320	3,200	-3.6%
Polyester Material Cost ($M)	24.8	24.0	-3.2%
Number of Anchors	120	95	-20.8%
Total Weight of Anchors (t)	5,950	6,705	12.7%
Anchor Material Cost ($M)	61.0	68.7	12.6%
Chain Lead Time (years)	1.65	1.59	-3.6%
Rope Lead Time (years)	1.26	1.26	0%
Anchor Lead Time (years)	1.40	1.08	-22.8%

The standardization of chain diameter increased the total weight and cost of chain by 11% ($4.7 million) but contributed to a decrease in supply chain lead time of 3.6% (3 weeks). There is no increase in chain length between the two models since it is assumed that the baseline chain sections are also doubled up when greater than 127 mm to simulate the domestic supply chain model. Additionally, standardizing to only three sizes can be more practical for the storage and installation processes and it better enables the use of spare parts because specific chain diameters are not needed.

The shared anchor technique eliminated the need for 25 anchors, and the anchor diameters were adjusted to standardized sizes with additional adjustments to the anchor lengths and thicknesses to maintain capacity, which increased the total weight and material cost of the anchors by 12.7% but resulted in a reduction in anchor supply chain lead time by 22.8%. The majority of the decrease in lead time is due to the reduced number of anchors from shared anchors, but the anchor diameter standardization also reduces lead time by a small amount. In contrast, the increase in anchor material due to standardized diameters and corresponding changes to length and thickness was more than the decrease in anchor material due to the reduction of 25 anchors from the shared anchor design.

The polyester rope lengths changed slightly to accommodate the new tensions from standardization, which decreased costs slightly but did not affect supply chain lead time, as the takt time of rope is based on the number of splices and not the length. The final supply chain process of the standardized Morro Bay design is shown in Figure 36.

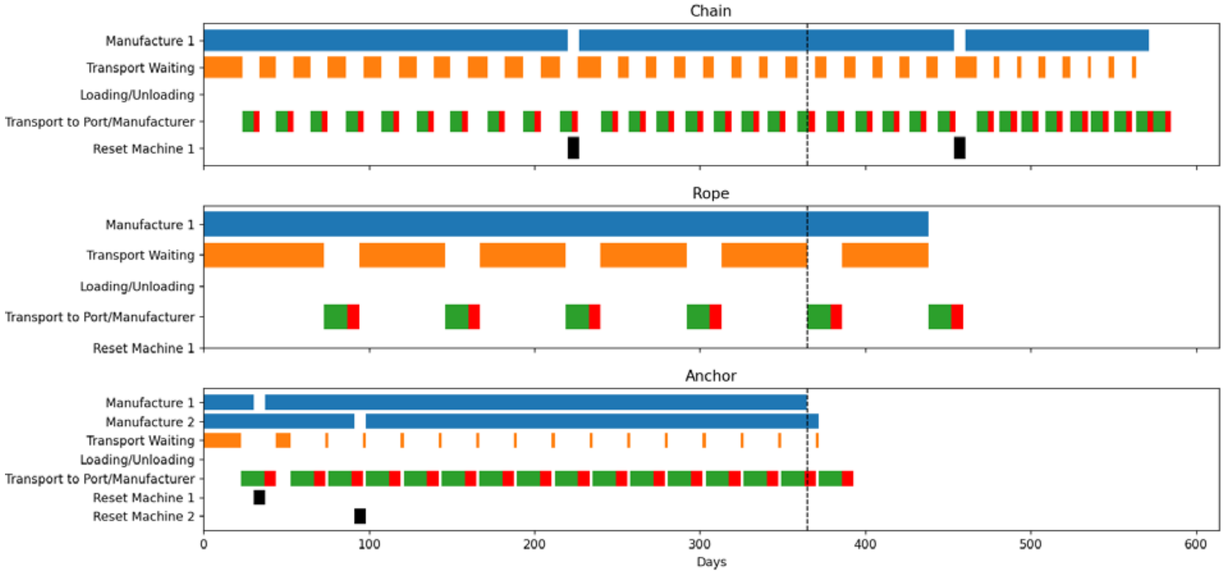


Figure 36. Humboldt standardized design supply chain process

As expected, each change in chain diameter requires a week of downtime to retool machinery for the next diameter bin value. The first anchor assembly line manufactures all D&G pile anchors, then as many 2.65-m suction piles as it can before it hits its limit of half the total number of anchors. The second anchor assembly line manufactures the remaining 2.65-m suction piles and then all the 3.25-m suction piles. The rope supply chain is not influenced by standardization. All transportation railcars or vessels travel to port and back to the manufacturing facility faster than the facility can produce complete sets of components, creating wait time for the railcars or vessels. Generally, the total lead time is a function of the manufacturing time limits, as the transportation railcars and vessels have to wait for components to complete manufacturing. Additional assembly lines, as shown in the anchor supply chain timeline, can speed up this process.

This final standardized design represents some of the most influential standardization techniques applied to the Humboldt baseline design using the domestic supply chain model. Shared anchor layouts show promise to reduce cost and lead time but the standardization of anchor sizes results in larger increases in cost and lead time. Manufacturing anchors—shared or not—in multiple assembly lines (using our assembly line assumptions) or fewer bin sizes will result in the lowest lead times and the most realistic supply chain scenarios.

5.3 Morro Bay

The baseline and standardized Morro Bay designs use six mooring lines per turbine. We applied the binning approach to the Morro Bay baseline chain diameters and anchor diameters, after the anchors had been redesigned for shared anchor loads. This section covers the standardization process and decisions for each of the three techniques—chain diameter, shared anchor, and anchor diameter—and then combines them all into one standardized design. When developing the standardized design, we again aimed to balance the trade-offs between minimizing cost and supply chain lead time while considering practical manufacturing and transportation logistics.

5.3.1 Chain Diameter

For the chain diameters of the Morro Bay standardized design, the full range of feasible diameter sets was generated between diameters of 68 and 98 mm using increments of 6 mm. Each set was run through the supply chain model, and the total component material costs were calculated. No chain sections are required to be doubled up in this design since all diameters are less than 127 mm and can be manufactured by the domestic supply chain. Figure 37 shows the multi-objective design space between different standardized chain diameter bins. Each colored dot represents a farm-level mooring system design where each color represents a different number of bins and different dots of the same color represent different bin values. Again, the chain material cost is only calculated as a function of diameter using a single cost coefficient and is assumed to be independent of manufacturing time and number of bins.

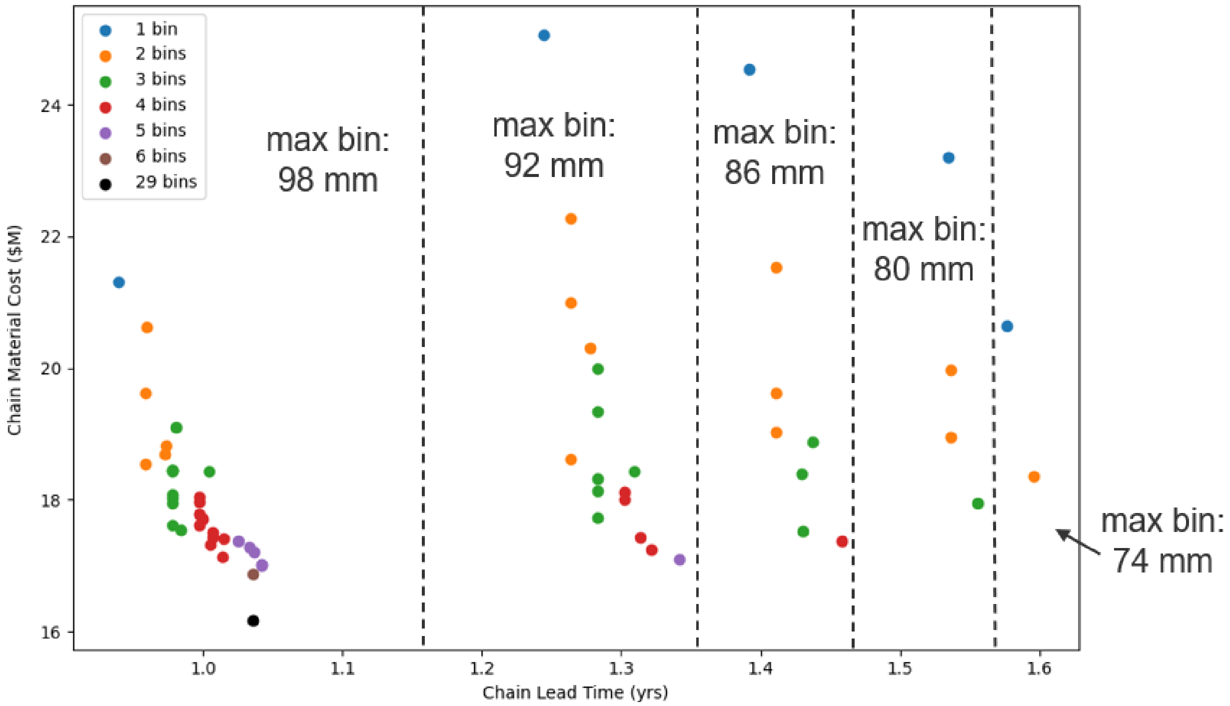


Figure 37. The multi-objective design space of different farm-level mooring system designs with different numbers of bins and bin values for chain diameter for the Morro Bay site

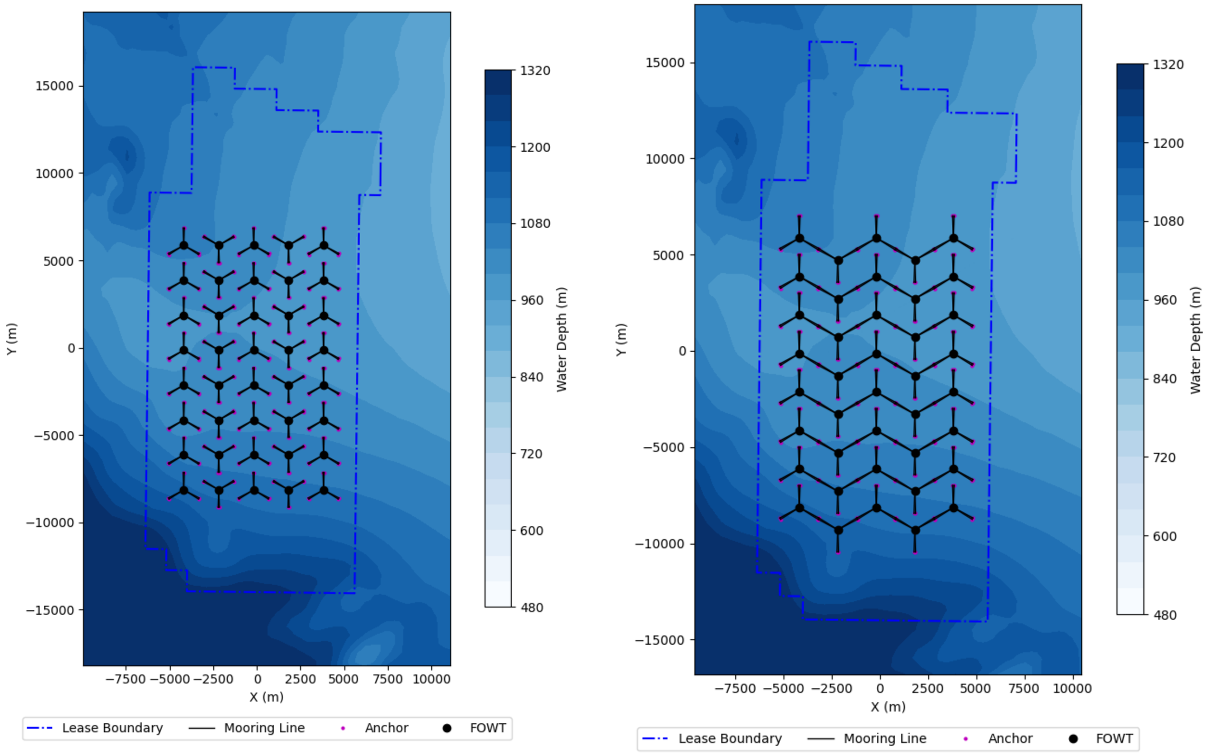
Even though chain sections are not required to be doubled up, when bin sizes are set with a maximum bin value less than the maximum chain diameter of the baseline design, the larger chain sections need to be doubled up since they cannot be rounded up to an existing bin. This is why there are consecutive Pareto fronts in Figure 37 moving from left to right across the plot. The left-most blue dot represents a design with a maximum bin value of 98 mm (the highest chain diameter in the baseline designs), which requires no chain sections to be doubled up. The next blue dot to the right (at 1.24 years and $25 million) represents a design with a maximum bin value of 92 mm, which requires all chain sections originally designed between 92 and 98 mm to be doubled up and rounded up to the bin value of 92 mm. Therefore, the most practical designs will be the ones that require no doubling up, which have the lowest lead times.

Higher amounts of standardization result in higher costs but lower lead times, and lower amounts of standardization result in lower costs but higher lead times. Each increase in the number of bins adds roughly an extra week of lead time since each new bin is at least 6 mm away from the previous one, requiring 1 week (0.02 years) of downtime to retool machinery. There are small variations and differences in lead times between each design due to the number of chain sections that are loaded onto each railcar (as a function of weight) and the number of trips the railcars need to make. Designs of the same number of bins have higher costs when diameters are farthest apart or closest together. For example, the design with bin values of 68 mm and 98 mm has the highest cost for two-bin designs ($20.6 million) but the design with bin values of 74 mm and 98 mm has the lowest cost for two-bin designs ($18.5 million), since this design minimized the number of chains rounded up to 98 mm while minimizing the value of the second bin. A Pareto front can be drawn from the baseline designs (black dot) to the design with one bin value of 98 mm (left-most blue dot), which minimizes both supply chain lead time and component cost.

To select a standardized bin set and values for the Morro Bay design, we chose the design with 3 chain diameters of 74, 86, and 98 mm. This design is represented by a green dot in Figure 37 with a lead time of 0.98 years and a total cost of $17.5M. The practicality of manufacturing and handling 29 different chain diameters of the baseline design was going to be more difficult then handling three sizes, and we determined that standardizing all chain sections to one diameter would increase the total cost more than necessary.

5.3.2 Shared Anchor

In parallel to standardizing the chain diameters, we implemented the shared anchor standardization technique to reduce the number of anchors and logistical complexity. We generated a shared anchor layout that requires the least amount of change from the baseline layout (Figure 38a) to preserve the behavior and sizing of the baseline design components while achieving good anchor-sharing efficiency, where each shared anchor supports two mooring lines in opposite directions. Only the layout and anchoring radii are changed, and each platform's mooring system orientation is maintained.



(a)

(b)

Figure 38. (a) Baseline Morro Bay design and (b) standardized shared anchor design

The second and fourth columns of floating platforms of the shared anchor layout (with one mooring line oriented downwind) are shifted down in the *y*-direction, and the original anchoring radius of all mooring lines of 1,000 m is increased to 1,154.7 m so that the anchors can overlap and become shared anchors. The six mooring lines and anchors per floating platform are simple to create overlapping anchor locations, as shown in Figure 39. The shared anchor design creates 64 shared anchors and 112 individual anchors (176 total), compared to the original 240.

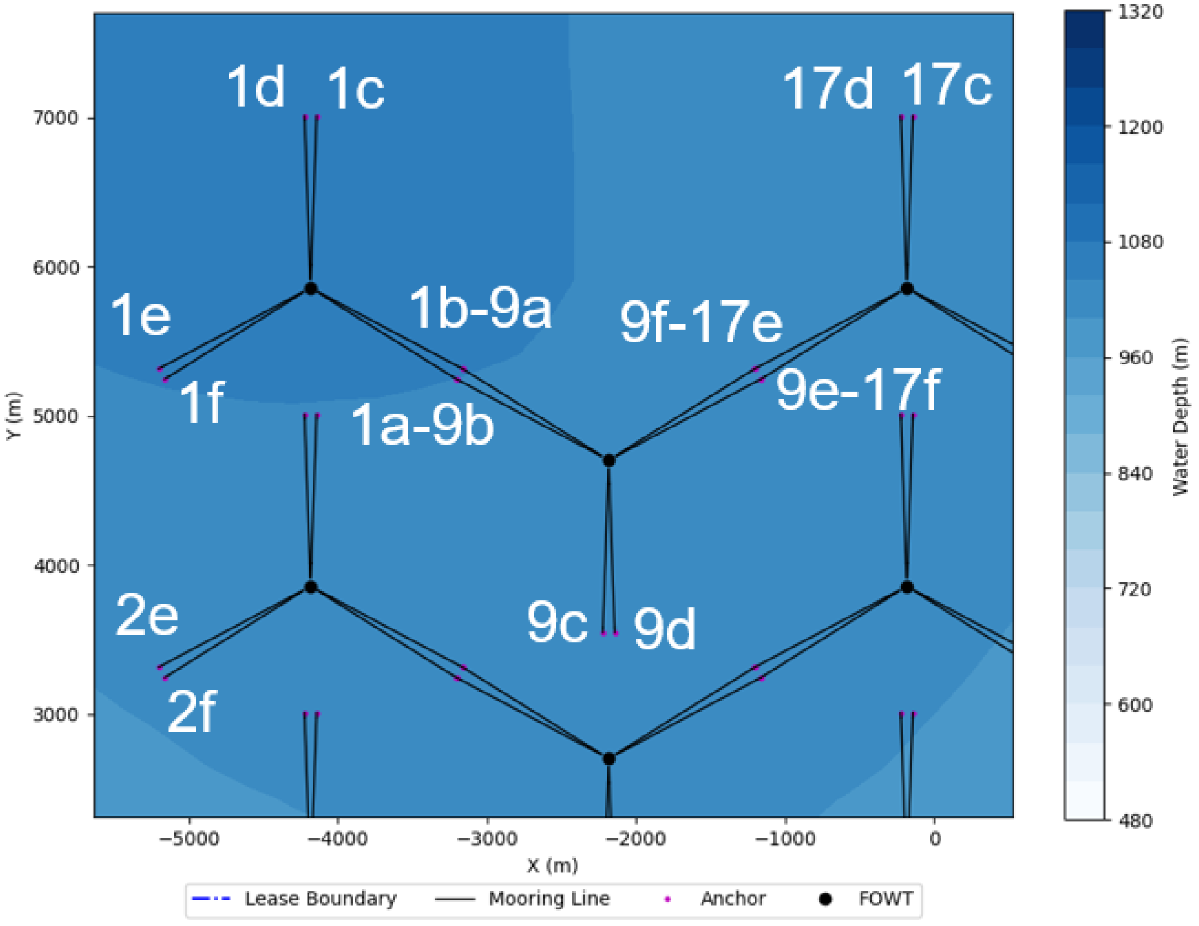


Figure 39. Zoomed in view of the Morro Bay shared anchor design showing overlapping anchors and anchor labels

With the layout positions and anchoring radii updated, each anchor now has a new water depth and we can employ our methodology to redesign the diameters, lengths, and thicknesses of the anchors based on interpolating the load time series at the new water depths. We also use a transfer function to calculate the loads seen by the padeye of each anchor relative to the maximum load seen at the mudline. The new anchor dimensions are listed in Appendix I, where the minimum diameter was set to 2.0 m. Rows highlighted in orange represent shared anchors. There are no D&G anchors in the Morro Bay designs since the soil is assumed to be mud across the entire array, but we assume that anchor depths deeper than 1,000 m use soft clay soil properties and anchor depths shallower than 1,000 m use medium clay soil properties.

All suction pile anchor designs minimized their weights at a maximum length-to-diameter ratio of six, which means that the suction piles wanted to be as slender as possible regardless of whether it was located in soft clay or medium clay. Each shared anchor is labeled in Appendix I according to its attached mooring lines. For example, anchor FOWT1a-9b represents a shared anchor with mooring lines 1a and 9b attached (Figure 39).

These anchor sizings are only based on the assumed soil properties and expected maximum combined mooring line loads and not on any other design aspects like installation processes or failure probabilities. The polyester rope lengths of each mooring line are adjusted to maintain the original horizontal pretension on the platform, but the new loads they exert on the anchor due to the adjustment is not expected to change significantly.

5.3.3 Anchor Diameter

With 117 new unique shared anchor diameters defined (rounded to the nearest millimeter) in the shared anchor layout, we applied the same binning approach we used for the chain diameters to the new anchor diameters, where each set represents a farm-level mooring system design with a total mooring system cost and supply chain lead time. Each design is represented in Figure 40 by a colored dot.

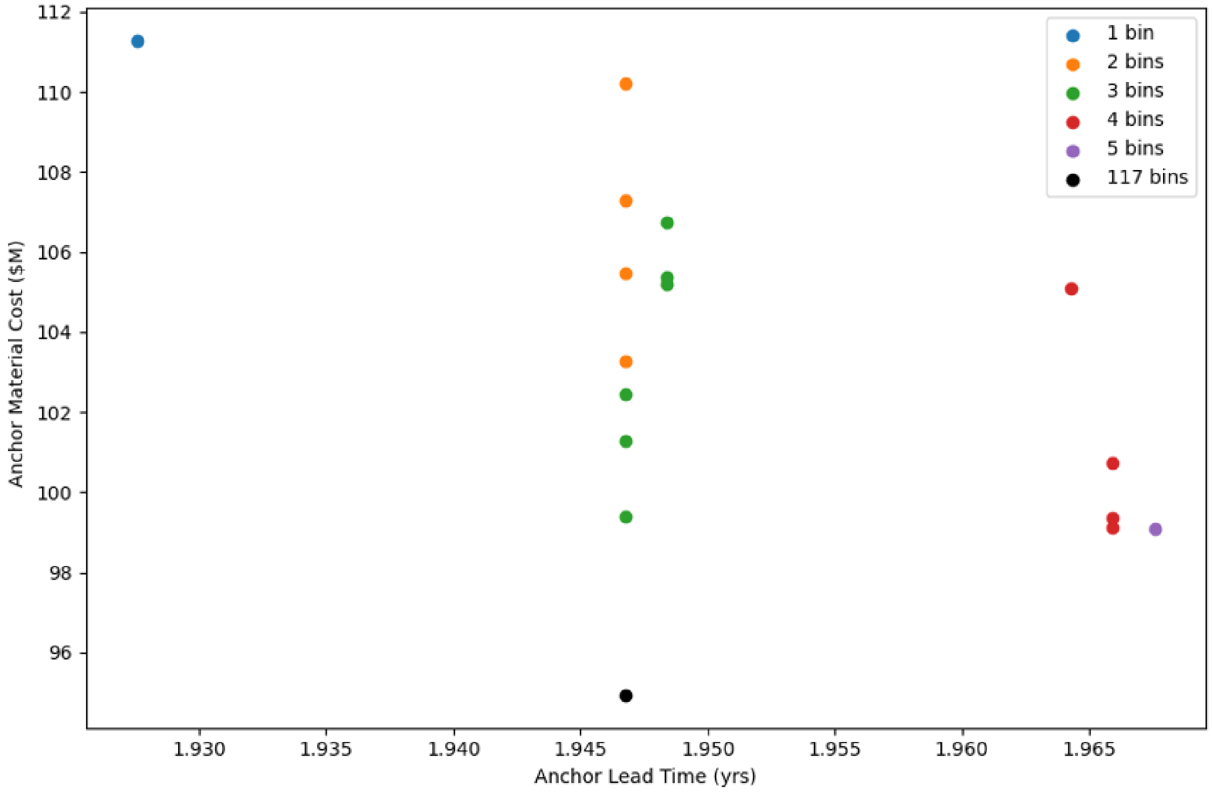


Figure 40. The multi-objective design space of different farm-level mooring system designs with different numbers of bins and bin values for anchor diameter for the Morro Bay site

Anchor diameter bin values range from 2.1 m to 2.9 m by increments of 0.2 m (which are also the maximum and minimum anchor diameters for the shared anchor design). The top-left blue dot represents a design with all anchor diameters of one diameter bin value of 2.9 m, producing the largest total cost of anchors (as a function of anchor weight after adjustments are made to length and thickness to match existing capacity) and the lowest supply chain lead time (no machinery retooling required). Normally, a Pareto front can be drawn between the most standardized design (blue dot) and the baseline shared anchor design (black dot), but the baseline shared anchor design has the same anchor supply chain lead time as designs with two or three anchor diameter bins.

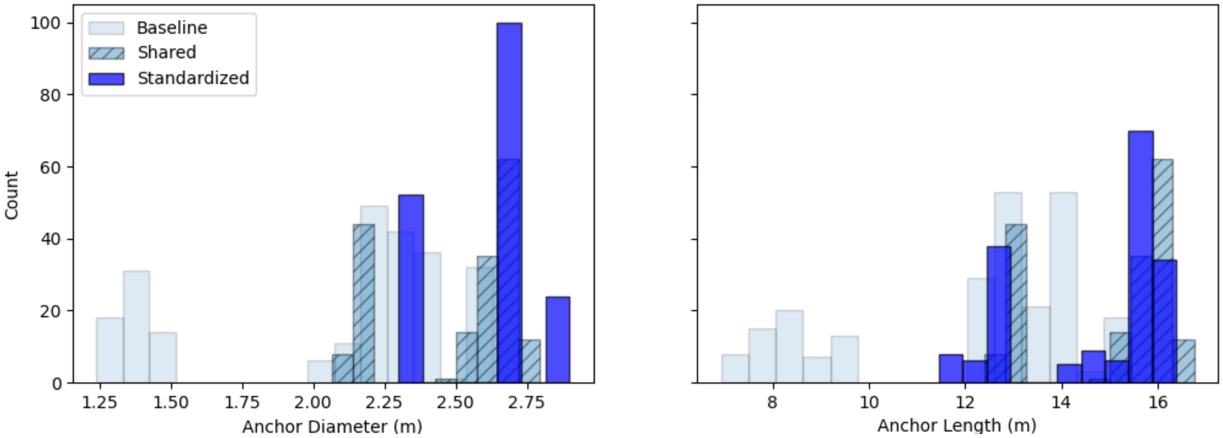
The reason for this is our supply chain modeling assumptions. We currently assume two anchor manufacturing lines that each take the same number of anchors out of the total number of anchors to manufacture, where anchor manufacturing stops to retool machinery for newer sizes in increments of 0.2 m. In the shared anchor design, each anchor diameter is its own bin, but downtime only occurs when a new anchor size is greater than 0.2 m from the initial diameter used for that bin. The shared anchor design splits anchors up between the two assembly lines, and because of the small distribution of anchor diameters in the shared anchor design, the first assembly line manufactures 88 anchors from bins between 2.065 m to 2.206 m without retooling and then jumps to bin sizes of 2.500 m to 2.634 m without retooling, since there are no anchor diameters between 2.206 m and 2.500 m. This distribution only requires one period of downtime to retool. The second assembly line then manufactures the 88 anchor diameters between 2.634 m and 2.793 m, which requires no downtime to retool. This setup only increases supply chain lead time by 1 week relative to all anchors of the same size with no downtime required.

The same logic applies to bin sizes with two or three diameters and is based on how the anchor diameters are split between the assembly lines. The design with bin values of 2.3 m and 2.9 m, for example, still requires a total downtime of 1 week because there are 52 anchors with diameters less than 2.3 m in the shared anchor design, which are all manufactured in the first assembly line, and 36 anchors with diameters binned to 2.9 m that are also manufactured in the first assembly line, totaling 88 anchors. The second assembly line manufactures all remaining 88 anchors at a diameter of 2.9 m. The switch from 2.3 m to 2.9 m in the first assembly line requires 1 week of downtime.

Designs with four bin values require more manufacturing time than the baseline designs. For example, a design with bins of 2.1 m, 2.3 m, 2.5 m, and 2.9 m sends the smallest 88 anchors, which include shared anchor diameters of 2.1 m to diameters greater than 2.5 m, to the first assembly line, which requires three instances of downtime to retool for new 2.3-m diameters, then 2.5-m diameters, then 2.9-m diameters. The second assembly line requires no downtime since all diameters involved are binned to 2.9 m. This means the higher distribution of anchor diameter bins in the shared anchor design results in less lead time because the retooling criteria are functions of the distribution of bin sizes (whether they are ± 0.2 m from another bin), where the baseline design has a smaller distribution of anchor diameters.

Different sorting strategies could be used in the supply chain model but would result in similar findings with possibly higher lead times. For example, a design with two anchor diameters of 2.3 m and 2.7 m could have one assembly line manufacture all anchors with 2.3 m and the other assembly line manufacture all anchors with 2.7 m. This setup would result in zero downtime to retool machinery since there would be no changes in sizes, but since there would be 52 anchors with a diameter of 2.3 m and 124 anchors with a diameter of 2.7 m, the total manufacturing time of the second assembly line would increase by 39 weeks (36 additional anchors at 182.5 hours per anchor), which is much more than the individual weeks needed to retool for different diameters.

In terms of minimizing supply chain lead time as well as material cost, the shared anchor design with 117 bins and the shared anchor design with only 1 bin are the most optimal. However, the difference in lead time between the two designs is only two weeks, which is likely not as significant compared to a cost difference of $16.5 million. This makes the shared anchor design the most attractive but considering other project logistical considerations such as storage and installation, we select a standardization to three anchor diameters of 2.3 m, 2.7m, and 2.9 m, represented by a green dot in Figure 40 with a supply chain lead time of 1.947 years and a cost of $99.4 million. This design has an increase in material cost by $4.6 million relative to the shared anchor design but reduces the number of unique anchor diameters to manufacture from 117 to 3 while maintaining the same lead time. These anchors then have their thicknesses adjusted based on Equation 4 and their lengths resized to maintain their original capacity. The changes in supply chain lead time are not expected to impact the overall project timeline significantly but are still worthwhile to analyze and draw trade-offs. The final standardization anchor sizes are compared to the baseline anchor sizes and the shared anchor sizes in Figure 41.



(a)

(b)

Figure 41. (a) Anchor diameters and (b) lengths of the baseline (light blue), shared-anchor (hatched), and standardized (dark blue) designs for the Morro Bay site

5.3.4 Standardized Design Results

After all standardization techniques are applied, we ensure the polyester rope lengths are adjusted to maintain the original horizontal pretension of the baseline design due to the changes in anchor depths and chain diameters. No doubling up of mooring chain is needed for the Morro Bay design since all chain sections can be manufactured domestically, and there exists a bin value at the maximum size of 98 mm. The final standardized design results are shown in Table 15 with a comparison to the baseline design.

Table 15. Standardized Design Parameters for the Morro Bay Site

Parameter	Baseline	Standardized	Percent Difference
Number of Chain Sections	480	480	0%
Total Length of Chain (m)	42,903	42,903	0%
Total Weight of Chain (t)	6,240	6,767	8.4%
Chain Material Cost ($M)	16.1	17.5	8.7%
Number of Rope Sections	240	240	0%
Total Length of Polyester (m)	285,391	312,335	9.4%
Total Weight of Polyester (t)	2,914	3,189	9.4%
Polyester Material Cost ($M)	21.8	23.9	9.6%
Number of Anchors	240	176	-26.7%
Total Weight of Anchors (t)	7,712	9,698	25.7%
Anchor Material Cost ($M)	79.1	99.4	25.7%
Chain Lead Time (years)	1.04	0.98	-5.8%
Rope Lead Time (years)	2.46	2.46	0%
Anchor Lead Time (years)	2.60	1.95	-25.0%

Standardizing the chain diameters into three bins for the Morro Bay design resulted in an increase of 8.4% in chain weight and cost but contributed to a decrease in supply chain lead time of 5.8% (3 weeks). Chain length remains the same because no standardization adjustments were made to length. Also, standardizing to only 3 sizes can be more practical to the manufacturing, transportation, storage, and installation processes, and allow for easier spare parts to be used.

The changes to the polyester rope are larger than equivalent changes in the Humboldt design since there is a larger change in anchoring radius to account for shared anchors in the Morro Bay design. This increased rope material costs but did not affect the supply chain lead time, as the takt time of rope is based on the number of splices and not the length.

The shared anchor and anchor diameter standardization eliminated the need for 64 anchors (26.7%) and decreased supply chain lead time by 25.0% but increased the total weight of anchors by 25.7%. The standardization of anchor diameters (and corresponding changes to the lengths and thicknesses) was the primary contributor to the increase in cost, and the shared anchor technique was the primary contributor to the decrease in supply chain lead time. The reduction in anchor quantity due to sharing anchors was factored into the total costs, but the total cost increased due to a combination of anchor dimension standardization and the resizing of the shared anchors to accommodate shared loads. Using the shared anchor design without anchor diameter standardization would provide more desirable results, but the feasibility of manufacturing 117 different anchor diameters was found to be unpractical and the current anchor diameter standardization was the next best option. The final supply chain process of the standardized Morro Bay design is shown in Figure 42.

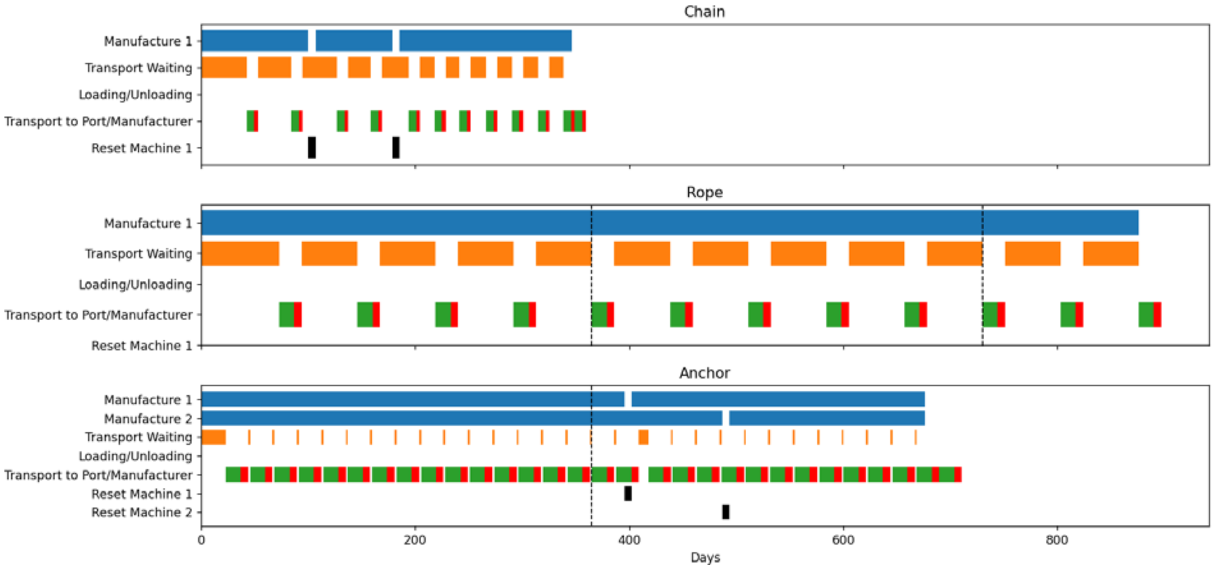


Figure 42. Morro Bay standardized design supply chain process

As expected, each change in chain diameter requires a week of downtime to retool machinery for the next diameter bin value. The first anchor assembly line manufactures all anchors of 2.3 m and then some of the anchors of 2.7 m. The second anchor assembly line manufactures the remaining anchors at 2.7 m and then the last anchors with diameters of 2.9 m. The rope supply chain is not influenced by standardization. All transportation railcars or vessels travel to port and back to the manufacturing facility faster than the facility can produce complete sets of components, creating wait time for the railcars or vessels. The total lead time is a function of the manufacturing time limits. Additional assembly lines, as shown in the anchor supply chain timeline, can speed up this process.

This final standardized design represents some of the most influential standardization techniques applied to the Morro Bay baseline design using the domestic supply chain model. Shared anchor layouts show promise to minimize both cost and lead time and can likely be further improved technically and realistically, but the standardization of anchor sizes results in larger increases in cost. Developing strategies to divide up anchors between different assembly lines while considering the time and cost needed to accommodate different sizes on the same assembly line drives the total supply chain lead time for anchors.

6 Comparative LCOE Analysis

To evaluate our standardized mooring system designs, we performed a comparative levelized cost of energy (LCOE) analysis between the standardized designs and the baseline designs in both lease areas. These LCOE results are estimates based on available data and certain assumptions for the cases considered, subject to the approximations and limitations of the models used. The absolute values have a high degree of uncertainty and are not meant to be findings in their own right. Rather, the emphasis is on the relative differences between the cases and the estimation of how standardization affects LCOE in a relative sense. We present a brief description of the methodology used to perform the LCOE comparison, including model assumptions. Then we report on the results and key findings of the LCOE analysis.

6.1 Methodology

LCOE provides a standardized metric to quantify the lifetime cost of electricity and compare the economic competitiveness between different generating sources. It requires calculations of capital expenditures (CapEx), operational expenditures (OpEx), and annual energy production (AEP), as well as a fixed charge rate (FCR), as shown in Equation 5.

$$LCOE = \frac{FCR * CapEx + OpEx}{AEP} \tag{6}$$

To provide a comparative LCOE analysis between two mooring system designs, we compute the LCOE for each design, with a focus only on the components of LCOE that will be affected by the mooring system standardization. For LCOE components that are not affected by the mooring standardization, we rely on existing values from previous work where possible.

NLR's open-source modeling tools have been developed to calculate each component of LCOE, similarly done in Housner and Mulas Hernando (2024):

- ORBIT models the design, installation logistics, and associated costs of all project components over time using a discrete-event simulation framework that allows for weather delays and vessel interactions (Nunemaker et al., 2020). Simulating these discrete events allows for the total CapEx to be calculated.
- The Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) provides a discrete-event modeling framework for operations and maintenance activities, such as component failures, scheduled maintenance tasks, and equipment mobilization, which can produce OpEx over a project's lifetime.
- The FLOw Redirection and Induction in Steady State (FLORIS) tool calculates AEP and wake losses of the wind turbines across the wind farm with given site conditions.

Fixed charge rate is a financial metric derived from various financial assumptions to annualize a project's initial investment. We assume a fixed charge rate of 6.48%, based on the 2022 Cost of Wind Energy Review (Stehly et al., 2023) but apply it with 2024 U.S. dollars.

These modeling tools are combined into one framework to simulate the combined installation and operations and maintenance activities across a project's lifetime while considering weather delays, vessel availabilities, and the energy production of each wind turbine over time. This provides a realistic CapEx, OpEx, and AEP that are used to calculate LCOE. We run these tools for the standardized mooring system designs and the baseline mooring system designs for each lease area and compare their LCOE. The following describes the inputs and assumptions used for each modeling tool as we simulate each project's lifetime.

Both the baseline designs and standardized designs consist of 40 15-MW wind turbines in uniform gridded layouts in the southwest Humboldt lease area (OCS-P0562) and the central Morro Bay lease area (OCS-P0564). They both use taut mooring lines with smaller sections of chain near the anchors and fairleads and longer sections of polyester rope throughout the water column. The Humboldt mooring systems consist of three mooring lines attached to each platform, providing no redundancy, whereas the Morro Bay baseline mooring systems consist of six mooring lines attached to each platform, providing redundancy. The Humboldt mooring systems also include suction piles and D&G anchors, depending on local soil conditions, whereas the Morro Bay mooring systems only include suction piles. The primary difference between the baseline designs and standardized designs is the quantities and sizes of mooring system components (chain, rope, anchors) that have been redesigned in the standardized designs considering the domestic supply chain. The standardized design wind turbine layout slightly changes to account for shared anchors, which will also affect the array cable layout and AEP results, but otherwise all other LCOE components of the project will remain the same.

The estimates of LCOE in this project depend heavily on the modeling assumptions and features of the ORBIT and WOMBAT models and the particular assumptions used in this project. The modeling approach of the FLORIS model is also important to the absolute LCOE values, but we do not detail it here since AEP affects all results approximately equally and is not influential to the comparative conclusions we focus on.

As explained in Section 3.3, the ORBIT model was updated to include two new modules: one to describe a custom mooring design with individual mooring lines and anchors, and a supply chain process module. The custom mooring system module takes a spreadsheet input file with descriptions of the mooring system. This allows full customization of mooring component types and sizes, rather than the existing approach of assuming all platforms in the project consist of the same mooring system materials and approximating their total mass and cost from regression data. The input file contains data on the diameter, length, thickness, mass, and cost for each chain, rope, and anchor component. The costs are based on cost coefficients used in MoorPy (Hall et al., 2021), representing the manufactured cost of components, and are used to calculate the total mooring system design CapEx. These cost coefficients hold some uncertainties in market prices, manufacturing processes, and amount per order but provide a good estimation for this level of analysis.

The new supply chain module, which was described in Section 3.3, models the processes associated with manufacturing and delivering each component to port. It currently focuses on the duration and sequencing of steps within these processes, providing lead time as the key output that can be affected by standardization techniques applied to mooring system designs. The module does not yet account for the associated manufacturing and transportation costs. Instead, these costs are represented within the cost assumptions for each mooring system component. This modeling approximation means that manufacturing and shipping cost impacts from standardization are not captured. The supply chain module would require additional inputs such as transportation railcar or vessel day rates to calculate shipping costs based on the total amount of transportation time, which is a logical future step for model development.

ORBIT's mooring system installation logic has been updated for this design comparison since the default logic does not accurately represent shared anchor installation sequences. In reality, a mooring system installation vessel would have deck space allotted for anchors, chain lockers allotted for chain, and reels allotted for synthetic rope. The vessel would load as many components as it could for one installation trip to minimize the number of trips to and from site. The vessels used in ORBIT do not have this level of detail and can only load certain mooring "packages" each time at port. It can decide whether or not it can load a package based on its maximum allowable weight or deck space, but it cannot load an irregular number of mooring lines and anchors. To account for shared anchors, we employ the installation logic of loading and installing all anchors in the wind farm first, and then loading and installing all mooring lines in the wind farm (Ma et al., 2019). Any other installation strategy could not be implemented in ORBIT without a higher level of model upgrade. Additionally, the installation process assumes transit to and from the centroid of the wind farm rather than each turbine, so the impact of the order that different components are loaded and installed is not included.

Array cables were not considered in scope for this project, but their costs are necessary when calculating the LCOE. Using our current turbine positions and the ability of our LCOE modeling tools to only consider continuous strings of array cables, we created representative array cable layouts for each design with two substations and five strings of eight turbines per site. These cables use 185 mm^2 and 630 mm^2 (Janocha et al., 2024) conductor sizes in fully suspended dynamic cable configurations that float 200 m below the waterline. The cables are not specifically designed for fully suspended conditions and are only used to estimate the cost of material and installation of the system for the purpose of the LCOE analysis. We assume two floating substations for the Humboldt design for more realistic array cable strings given the irregular shape of the lease area, two floating substations for the Morro Bay site, and an onshore substation for each of them.

The LCOE modeling includes the following site-specific assumptions and inputs:

- The port of Humboldt is 50 km from the Humboldt site, with a large amount of storage space that does not influence the supply chain transportation process. The distance to landfall, which is used to calculate the export cable length, is 40 km.
- The port of Long Beach is 475 km from the Morro Bay site, with a large amount of storage space that does not influence the supply chain transportation process. The distance to landfall, which is used to calculate the export cable length, is 90 km.
- We use example vessels provided in the ORBIT vessel library for mooring system installation, array cable installation, and floating platform tow-out that do not change between the two mooring designs. The mooring system installation vessel we use has a maximum deck space of 1,000 m^2 and a maximum cargo weight of 5,000 t. It travels at a speed of 10 km/h and has a day rate of $122,700.
- We use model weather data of the Humboldt site from 1998 to 2019 to specify inputs to the FLORIS model, as well as the weather windows for installation and maintenance activities.

- The operations and maintenance costs use default WOMBAT inputs, a crew transfer vessel, a dive support vessel, and an anchor handling vessel to perform repairs and replacements. The mooring line and anchor repair and replacement rates are based on data from Housner and Mulas Hernando (2024), but we represent each repair and replacement rate in this work for the entire mooring system, rather than each mooring line or anchor. Other mooring system failure rates exist, such as in Hall et al. (2024), but do not include suction pile rates, which were needed for this analysis. No other differences in failure rates based on mooring system component size were made.
- We refer to soft costs as a combination of indirect, non-physical costs associated with the construction and decommissioning of the project. These costs are based on default ORBIT values found in documentation (NLR, 2020).
- The LCOE values exclude supply chain and port infrastructure investments as well as transmission upgrades beyond the point of interconnection, which may be partially or fully paid by the developer to enable project development.

6.2 LCOE Results

The LCOE analysis tool, combining aspects from ORBIT, WOMBAT, and FLORIS, was used to calculate the LCOE of each mooring design for each site. The simulations were performed 10 times for each design to average the AEP and operations cost because the operations cost is based on failure probabilities over 20 years that are modeled stochastically, which vary between simulations. The following sections show the breakdowns of the average LCOE calculation of each of the baseline and standardized designs for the Humboldt and Morro Bay sites. Then, we show a comparative chart of LCOE highlighting the differences between the designs.

6.2.1 Humboldt

Figure 43 shows a waterfall chart of the modeled average LCOE breakdown of the baseline Humboldt design, divided into CapEx and OpEx components, normalized by the AEP to provide LCOE metrics.

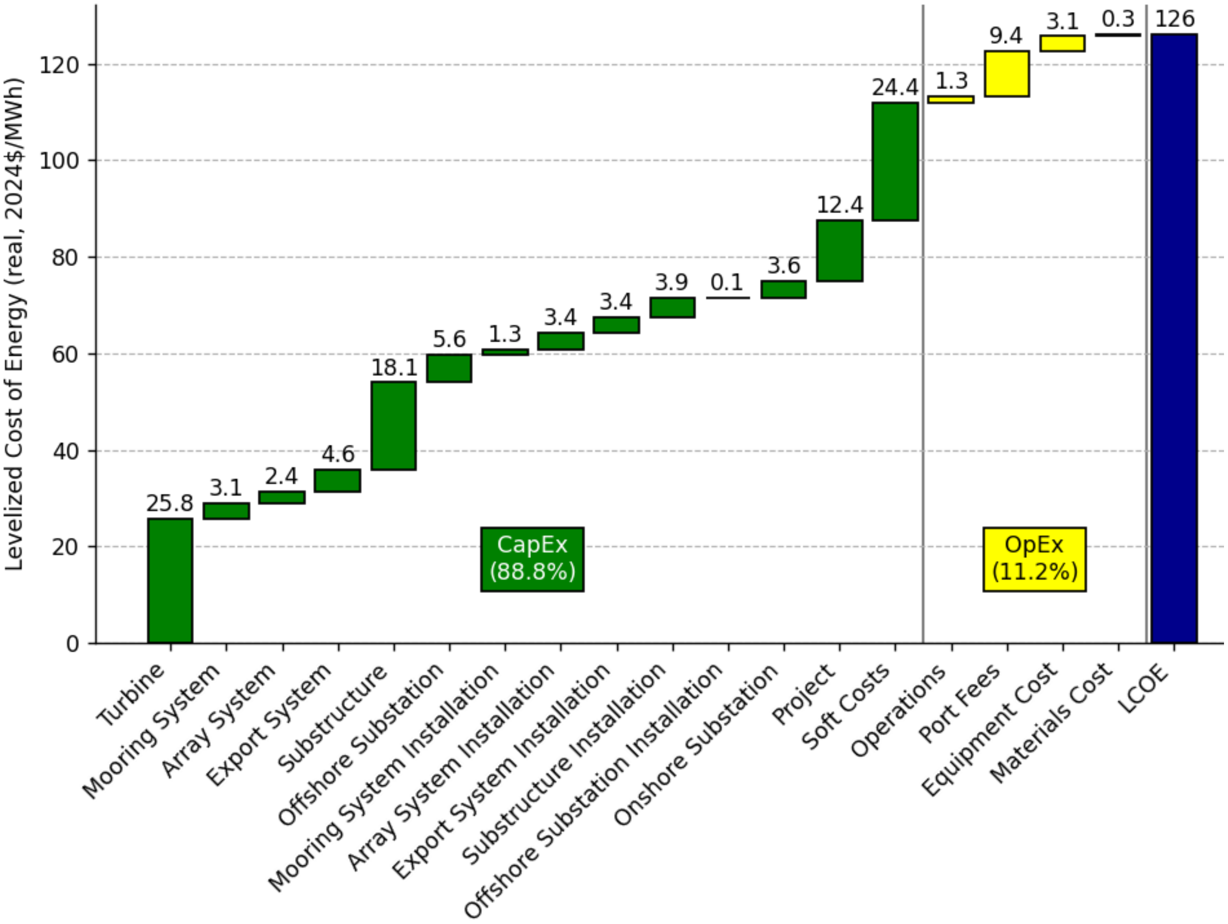


Figure 43. LCOE breakdown of baseline Humboldt design

The predicted total LCOE of the baseline Humboldt design is $126/MWh in 2024 U.S. dollars. The wind turbines, substructures, and project and soft costs make up a majority of the LCOE. CapEx contributes 88.8% of the LCOE, and OpEx contributes 11.2%. The mooring system design only contributes 2.5% of the total LCOE, and the installation only contributes 1.0% to the total LCOE.

These LCOE values are based on ORBIT cost modeling assumptions as if infrastructure is developed and learning curves have been established for deployment looking ahead to 2050. Projects developed today would likely have much higher LCOE values. The order of magnitude of these results agrees with the order of magnitude referenced in another similar cost modeling projection report (ORE Catapult, 2021).

The standardized Humboldt design has a similar distribution of CapEx and OpEx results as the baseline design, and therefore its breakdown looks similar to Figure 43. Only the mooring system design and installation and soft costs differ between the two designs. Table 16 further details the cost components involved in the LCOE calculation between the two designs.

Table 16. Cost Differences Between the Baseline and Standardized Humboldt Designs

Cost Component	Baseline	Standardized	Percent Difference
Mooring System Components ($/kW)	214.5	232.5	8.4%
Mooring System Installation ($/kW)	86.0	75.3	-12.4%
Soft Costs ($/kW)	1,676	1,674	-0.1%
CapEx ($/kW)	7,690	7,697	0.1%
OpEx ($/kW/year)	62.96	63.12	0.2%
AEP (MWh/kW/year)	4.455	4.417	-0.8%
LCOE ($/MWh)	126.0	127.2	1.0%

The standardized mooring system design, with 25 fewer anchors than the baseline design but larger mooring system component sizes, increases mooring component CapEx by 8.4% but decreases installation CapEx by 12.4%. It only has a slightly greater total CapEx than the baseline design (0.1%) since other CapEx contributors such as turbines and substructures remain constant between the two designs. These absolute CapEx results are much larger than the CapEx results found in Housner and Mulas Hernando (2024) since the present results benefit from updates to the ORBIT cost assumptions using more realistic and current cost data and more accurate representations of soft costs.

The average OpEx per year of the standardized design is affected by the reduced number of anchors and assumed probabilities of failure of shared anchors over a 20-year lifetime. Shared anchor failure rate estimations are based on data from Housner and Mulas Hernando (2024) and are higher than individual anchors but affect LCOE differently depending on the project size. The average OpEx is nearly the same between the two designs, suggesting that the reduction in anchor count in the standardized design reduces operational costs by a similar amount as the increase in cost due to increased shared anchor failure rates.

Additionally, the average AEP over the 10 simulations of the standardized design is 0.8% lower than the baseline design. The new layout of the standardized design (and new wake losses) and the result of increased shared anchor failure rates on the amount of time wind turbines are shut down for repairs contribute to this reduction in AEP. The reduced AEP results in a higher LCOE of the standardized design, even though the total CapEx and OpEx values are similar between designs. A comparison of the two designs in terms of LCOE is provided in Figure 44.

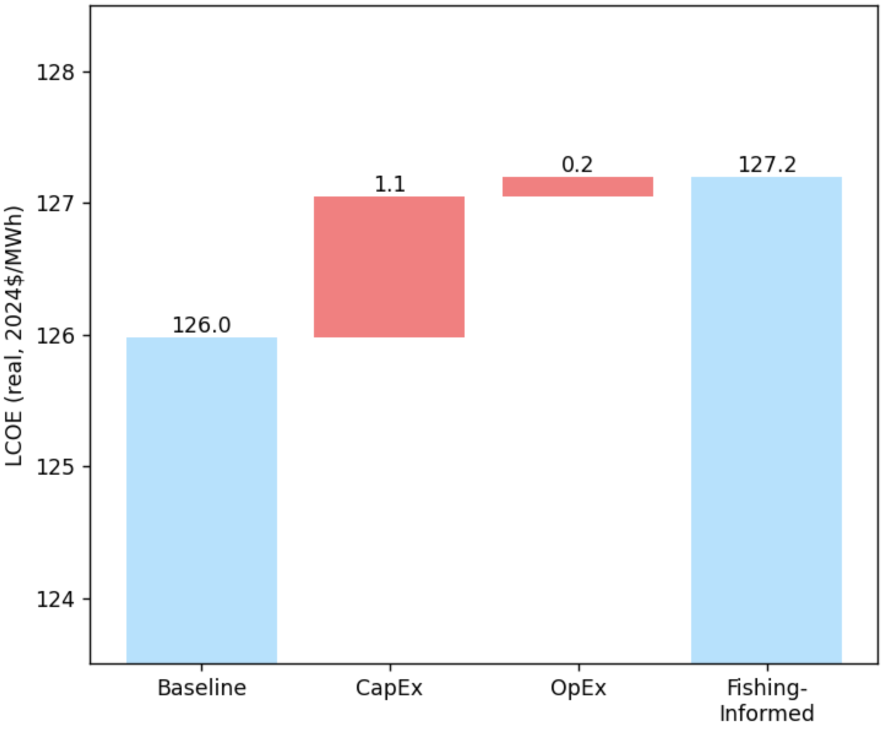


Figure 44. LCOE differences between the baseline and standardized Humboldt designs

Given the reduction in AEP in the standardized design, the average LCOE of the standardized design is 1.0% higher than the baseline design. Shared anchors have been shown to decrease LCOE in both large and small projects but increases in OpEx due to higher shared anchor failure rates have also been shown to be larger than the decreases in OpEx due to reduced numbers of anchors, especially for large projects (Housner and Mulas Hernando, 2024). The average result over 10 simulations of the standardized Humboldt design shows higher wind turbine downtimes due to shared anchor failure rates, as well as increased wake losses, which decreases AEP.

The total CapEx and OpEx between the two designs did not change significantly, but when normalized by AEP, Figure 44 shows an increase between the standardized and baseline designs of $1.1/MWh due to CapEx and $0.2/MWh due to OpEx. This suggests that while standardization can affect mooring system design and installation costs, larger LCOE effects can be found through changes in AEP, which can be affected by the wind farm layout and operational downtime.

6.2.2 Morro Bay

Figure 45 shows a waterfall chart of the modeled average LCOE breakdown of the baseline Morro Bay design, divided into CapEx and OpEx components, normalized by the AEP to provide LCOE metrics.

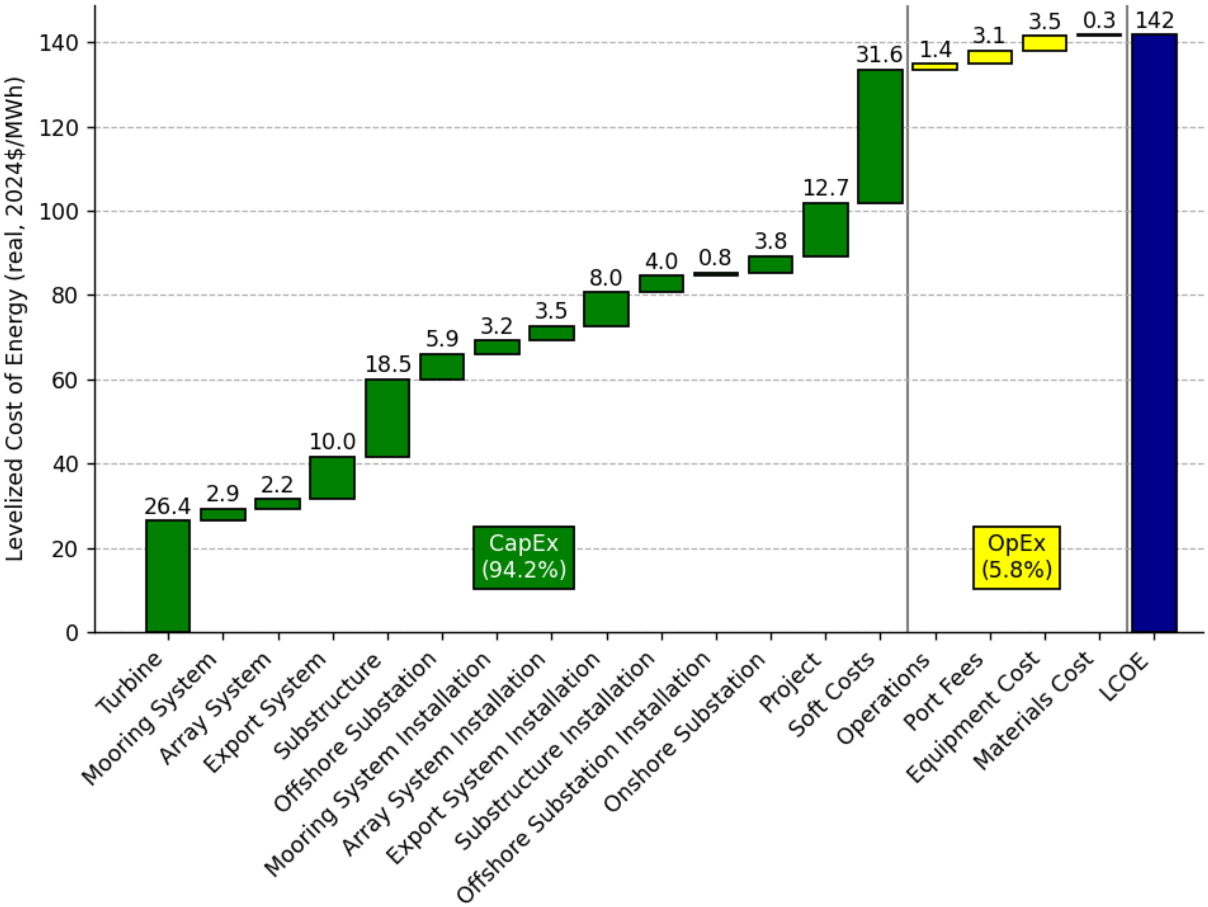


Figure 45. LCOE breakdown of baseline Morro Bay design

The total LCOE of the baseline Morro Bay design is $142/MWh in 2024 U.S. dollars, which is 11% higher than the Humboldt design. The wind turbines, substructures, and project and soft costs make up a majority of the LCOE. The CapEx contributes 94.2% to the LCOE, and the OpEx contributes the other 5.8%. The mooring system design and installation contribute 2.0% and 2.3% of the LCOE, respectively.

Like the Humboldt design, the Morro Bay LCOE values are based on ORBIT cost modeling assumptions as if infrastructure is developed and learning curves have been established for deployment in 2050. The only major differences between the Humboldt and Morro Bay baseline designs are in the export system costs, the mooring system installation costs due to the increased number of components, and the assumed port costs. However, the baseline results from each site are only meant to serve as comparison to the standardized results from each site.

The standardized Morro Bay design produces a similar LCOE breakdown as Figure 45, but only the mooring system design and installation and soft costs differ between the two designs. Table 17 details the cost components involved in the LCOE calculation between the two designs.

Table 17. Cost Differences Between the Baseline and Standardized Morro Bay Designs

Cost Component	Baseline	Standardized	Percent Difference
Mooring System Components ($/kW)	195.0	234.6	20.3%
Mooring System Installation ($/kW)	215.4	192.2	-10.8%
Soft Costs ($/kW)	2,123	2,114	-0.4%
CapEx ($/kW)	8,963	8,971	0.1%
OpEx ($/kW/year)	36.01	35.83	-0.5%
AEP (MWh/kW/year)	4.349	4.397	1.1%
LCOE ($/MWh)	141.8	140.4	-1.0%

The standardized mooring system design, with a reduction of 64 anchors but larger increases in mooring system component sizes, increases component CapEx by 20.3% but decreases installation CapEx by 10.8%. The standardized design only has a slightly greater total CapEx than the baseline design (0.1%) since other CapEx contributors such as turbines and substructures remain constant between the two designs. As with the Humboldt design, these absolute CapEx results are higher than similar work performed previously due to updated modeling assumptions.

The average OpEx per year of the standardized design considers the reduced number of anchors but higher shared anchor failure rates over a 20-year lifetime and is 0.5% less in the standardized design than the baseline design. In contrast to the Humboldt design comparison, this suggests that the reduction in the number of anchors reduces operational costs more than the increase in operational costs due to increased failure rates of shared anchors.

The average AEP over the 10 simulations of the standardized design is 1.1% higher than the baseline design, suggesting that the wake losses of the shared anchor layout are lower than in the baseline design, or that the reduction in anchor count in the shared anchor layout is large enough to reduce wind turbine downtime for maintenance and repairs compared to the baseline design even though the shared anchors increase the probability for shut down following an anchor failure. The increase in AEP is the main contributor to the lower LCOE of the standardized design. A comparison of the two designs in terms of LCOE is provided in Figure 46.

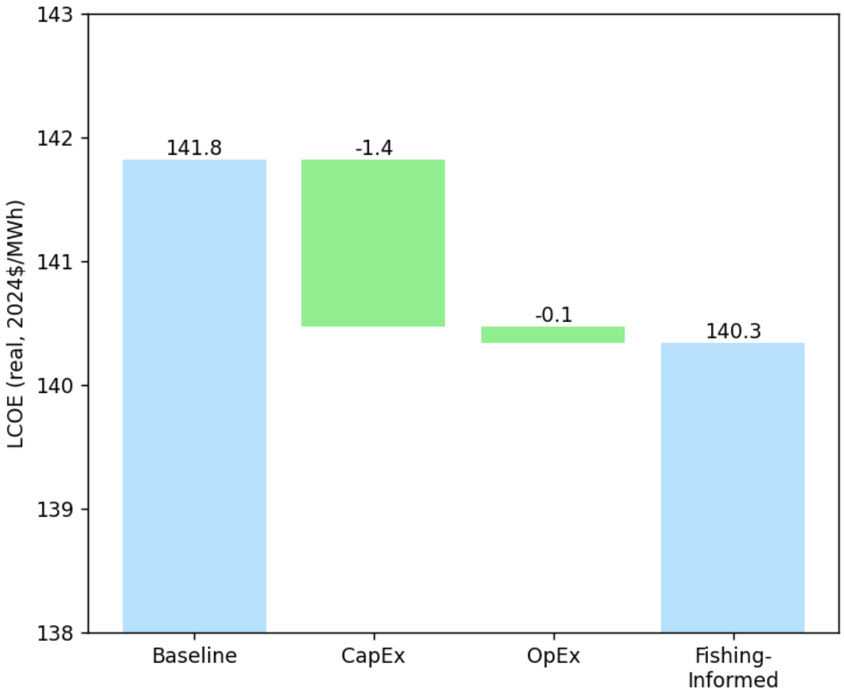


Figure 46. LCOE differences between the baseline and standardized Morro Bay designs

The total LCOE of the standardized design is 1.0% less than the baseline design. As stated in Section 6.2.2, shared anchors generally reduce LCOE but the magnitude of this reduction largely depends on OpEx and AEP. While the standardized design contributes to a 20% increase in mooring system CapEx and a slightly higher total CapEx compared to the baseline design, the difference in AEP between the two designs allows for a reduction in LCOE of the standardized design. In contrast to the Humboldt design, the standardized Morro Bay design appears to have a large enough reduction in anchor count to offset the higher shared anchor failure rates that contribute to wind turbine downtime, as well as lower wake losses, thereby increasing AEP. Additional LCOE reductions may be achievable through further CapEx reductions or strategies to increase AEP.

6.3 Discussion

Looking across the cost results of the two sites, standardization increases the total chain material use and cost in both, by 11% at Humboldt and 9% at Morro Bay. The chain size distribution is large due to fatigue and weight design requirements, so some increase from standardizing sizes is to be expected. The rope material use and cost decreases at Humboldt but increases at Morro Bay, primarily driven by length adjustments for the new layouts and to maintain desired pretensions after chain diameter standardization. The anchor material use and cost increases in both cases, by 13% at Humboldt and 26% at Morro Bay, showing that the efficiencies from sharing anchors is less than the increased material use caused by size standardization. On the other hand, sharing anchors yields reduced installation costs at both sites, by 12% at Humboldt and 11% at Morro Bay. The mooring system contribution to the total LCOE is 2.5% at Humboldt and 2.0% at Morro Bay. Again, these LCOE results are meant for comparison purposes between the baseline and standardized mooring system designs only and are not suitable to compare to the cost of other energy sources.

It is important to note that the cost of the components (including manufacturing and delivery) are modeled as proportional to the amount of material used by mass, so the cost effects of economies of scale or adjusting for different sizes are not accounted for. We do not separately model shipping costs of manufactured components to port, nor storage costs. The manufacturing costs do not include any costs associated with tooling or setup, or the time required to set up machinery, manufacture at the facility, or retool machinery for different component sizes. The costs also do not include any effect of the number of components in the order. Capturing the full impact of standardization on cost would require accounting for all of these factors, but this would require more detailed cost and logistics modeling methods.

7 Discussion on Other Standardization Impacts

Mooring system standardization can impact many aspects of a floating wind project as well as the offshore wind industry more broadly and the supply chains that support it. The previous section presented a comparative LCOE analysis that focuses on how the selected standardization methods affect project economics. That analysis provides a quantitative view of component cost factors in particular, but it does not capture some effects that arise from impacts of standardization on manufacturing costs. We therefore provide an additional, qualitative discussion of supply chain impacts in this section, as well as discussion of the potential effects of mooring system standardization on overall floating wind deployment pathways.

7.1 Component Design and Testing Impacts

The broad range of component sizes associated with the developed baseline designs would result in numerous implications related to sourcing and supply. Many of these effects could have cost impacts that are not accounted for in the modeling described in Section 3.3.

Polyester ropes require unique terminal hardware and connectors. Many of the same suppliers furnishing the mooring system connectors will likely be contracted by the rope manufacturers to provide the requisite termination hardware, in which standardization can further streamline this area of the supply chain. Other connectors, like shackles and thimbles, were not considered in this study but may come from similar vendors as chain and add larger manufacturing and shipping demands to these manufacturers if standardized methods are not used.

Several ongoing efforts are underway to further prove effectiveness of filter barriers and rope constructions against infiltration of marine organisms which may degrade the rope from within. These organisms typically thrive in the ultraviolet zone near the surface of the water. Many designers mitigate this by using chain in this ultraviolet zone as we did in this study. There may be an opportunity to reduce the quantity of chain required if these efforts yield reliable rope solutions for this zone. This could further relieve the overall burden on the mooring chain supply.

Because of varying pile sizes associated with individual designs, room and transport for piles to the staging yard may add complexity as manufacturers optimize processes based on size, length and wall thickness variations. This may require more expansive facilities or spreading orders to additional manufacturers. Individual shared anchors would require further testing and add complexity to calibrate models for each unique loading scenario, particularly because of the multidirectional cyclic loads that shared anchors experience.

Component testing requirements will add cost and time when there are many component sizes. Many standards exist for the design and manufacturing of various mooring components. These standards cover offshore mooring chain, synthetic fiber ropes, chain accessories, and fluke anchors and outline requirements for preapproved designs as well as the process for approving new designs. Given the sheer number and varying size of components, many of the requisite connectors will not fit within a preapproved connector design. As a result, the need for bespoke connectors to go through the full design process will be a challenge. In addition, the material specifications require 1 out of every 25 (or fewer) connectors to be loaded to the break load. Given that the connectors are different sizes, if only five units of a given component size are needed, six units will need to be made with one being the break load specimen, increasing the overall fabrication requirement as well as the amount of testing required. Standard sizes would significantly reduce these testing requirements.

Economies of scale reduce per-unit costs. Reducing the number of unique components will reduce the per-unit costs because the components can be manufactured more efficiently throughout the process, from raw material to final acceptance testing. However, for larger volumes of similar sizes, most manufacturers will want to manufacture the entire project in a single run, which can have knock-on effects on the required lead time and mooring marshalling yard space requirements. A hybrid approach may be advantageous where large volumes of components are made in lots allowing cost savings on a per-unit basis while reducing the storage requirements associated with staggered delivery and installation. This staggered delivery approach also condenses the overall project timeline due to parallel manufacturing and installation efforts.

7.2 Staging and Installation Impacts

Staging and installation requirements were not modeled in this project, but they are an important consideration for which mooring standardization can bring additional benefits.

Some of the port and staging requirements are expected to be affected by standardization. Handling equipment for chain, rope, and pile anchors often varies depending on the component sizes. For example, if piles are individually designed, the different pile diameters, lengths, and wall thicknesses can require different support frames, complicating the transportation and staging requirements. Additionally, the manufacturing schedules for connecting hardware, off-vessel tensioning devices, and different sizes of chain and rope—if not standardized—will have to be thoroughly organized to prevent excessive component build-up in the staging area. If deliveries are not coordinated, installation commencement cannot be realized, and the equipment staging area will be insufficient.

With these considerations in mind, the use of individually sized components means that components are not interchangeable and each component needs to be stored and tracked on an individual basis from the time of its manufacture until it is installed in its unique position in the array. Conversely, using standardized component sizes provides a degree of interchangeability that reduces timing and tracking requirements and allows for the use of common handling equipment. As such, standardized sizes can reduce strain on transportation and storage equipment. For example, the number of reels required for ropes or the number of different slings needed for chains and piles can be significantly reduced.

Test fitting is good practice that is typically undertaken for most permanent mooring projects. Some projects even go to the extent of testing every connection in the yard before deploying offshore to prevent serious delays that would occur if items do not fit together. At a minimum, a sample of each size of connection should be tested after adequate quality assurance and quality control procedures have been completed at the manufacturer to confirm manufacturing within tolerance. With unique component sizes, there is significant time, resources, and risk introduced by all the unique combinations of connection types and sizes. The likelihood of misfit connectors increases with the number of unique component sizes and number of combinations of components.

Yard space allocation should be sized to accommodate more than the footprint of the stored equipment. Allowance must be made for the access and handling of equipment when offloaded and placed in the yard. It is recommended to allow an extra 15%–20% of yard space above the footprint to accommodate this consideration. In addition to moving equipment within the yard, other activities will take also place. The accommodation of various unique component sizes will only increase the required yard space. Standardization approaches can mitigate these increases.

With regard to assembly, suction piles will typically arrive from the manufacturer without many of the final appurtenances. These might include the following:

- Valving
- Remotely operated vehicle interfaces
- Bullseyes
- Transponder interfaces
- Forerunner chains and shackles
- Subsea connectors.

The above items will need to be installed at the yard during the loadout of the suction piles on the transportation vessel. An open area to allow for these activities should be allocated when determining yard sizing and resource allocation (cranes, forklifts, man-lifts, etc.). Handling and assembling these appurtenances will only add complexity for unique anchor sizes.

For many of the mooring systems components there are handling aids to facilitate transport and loading operations. Examples include containers, reels, lifting slings, and spreader bars. If these handling aids can be reused multiple times for standard component sizes throughout the supply chain logistics, it would further reduce the overall burden on the manufacturers to supply components.

The use of shared anchors as a standardization technique, which reduces the total anchor count, could require more logistical and staging support because it inevitably requires some anchors to be shared and some anchors to be individual, which typically results in a large size difference between the two anchor types. Similarly, the use of shared mooring lines as a standardization technique fundamentally adds a different type of mooring configuration, potentially increasing transportation and staging complexity. Understanding the balance between these drawbacks and the potential benefits from reducing component quantities would require more quantitative analysis.

Several installation aids would be needed to interface with deployment equipment with unique geometries of mooring equipment and connectors. An anchor handling vessel, for example, is equipped with the following, which are all designed for specific sizes:

- Shark jaws/Karm Forks (specific sized inserts/maximum size limitations)
- Chain whelp/gypsy wheel (individual wheel for each size)
- Chain locker (chute openings may have size constraints and locker volume capacity is fixed, meaning chains will need to be stacked)
- Winch drums (fixed size; length considerations for polyester).

An anchor handling vessel is shown in Figure 47.

(a) (b)

Figure 47. High-level overview of (a) an anchor handling vessel and (b) a whelp/gypsy wheel specific to one chain size.

Illustration and photo from Delmar Systems

As shown in Figure 47, whelps/gypsy wheels are sized for a specific chain geometry. If each chain is unique per the baseline designs, a corresponding whelp/gypsy wheel will need to be manufactured for each chain size. When loading chains into the chain lockers, chains of different sizes may need to be stacked on each other instead of easily stacking all chain of one size into an individual chain locker. The whelps/gypsy wheels will then need to be changed out on the winch shafts in between chain section deployment. This is a weather-sensitive operation and will likely result in additional installation vessel time to install the preset mooring systems.

Staggering component delivery based on standard sizes and pre-laying the mooring system for installation well ahead of floating turbine tow-out and hookup operations could reduce weather window risk exposure. Wet storage can reduce the required yard allocation by designating space on the seafloor to temporarily store equipment that would otherwise take up quayside space.

7.3 Supply Chain Expansion Impacts

Standardization can help ease supply chain expansion. The long lead times for components identified in Section 4.2 and the current supply chain capacities identified in Section 3.1 point to the need for supply chain expansion if multiple full-scale floating wind projects are to be developed in similar timeframes using primarily domestically produced stationkeeping components. If standard component sizes are identified—particularly across multiple projects—the supply chain as a whole can concentrate its expansion efforts on producing those specific standardized sizes, reducing the amount of new equipment and investment required.

7.4 Operations and Maintenance Impacts

The benefits of standardization for reducing staging requirements are even greater when it comes to maintenance and replacement. Use of standardized sizes simplifies inspection and structural health tracking by reducing the need for different equipment or calculations to accommodate different component sizes. If components need to be replaced, use of standardized sizes makes it more feasible and cost-effective to keep an inventory of common replacement components at port for interchangeability, rather than having to wait for custom-sized replacement components to be manufactured on-demand or keeping an expensively wide variety of replacement components. Similar benefits apply to the equipment used to handle components during replacement operations.

Without standardization, maintenance and intervention will be hindered by the large number of unique component sizes. Spare parts are therefore unlikely to be readily available off the shelf, with manufacturing lead times on the order of 12–18 weeks for new components. As a result, large projects are expected to source spare mooring ropes, chains, and connectors in advance. However, given the number of unique components, maintaining an adequate inventory of spare parts becomes challenging, potentially delaying responses to damaged or failed mooring lines. These factors, while not included in the existing quantitative analysis due to modeling limitations, are expected to be significant.

8 Conclusions

This project investigated the standardization of mooring systems for large arrays of floating wind turbines in deep water. It focused on mooring options for two California lease areas. Baseline taut mooring system designs were developed for each lease area—one with three mooring lines and anchors per platform and one with six mooring lines and anchors per platform—where each mooring line and anchor component was individually designed for its specific water depth and location in the array. The domestic mooring supply chain was also characterized, assessed for its potential to expand, and modeled using the discrete-event simulation capability in the cost and logistics tool ORBIT. After exploring various standardization techniques, standardized mooring system designs were derived from the baseline designs using the domestic supply chain model and innovative standardization techniques. These standardized designs strike a balance between minimizing total component cost, minimizing supply chain lead time, and achieving other benefits of standardization that are not captured in the models. Lastly, an LCOE analysis was performed to compare the standardized designs to the baseline designs.

8.1 Key Findings

The baseline designs demonstrate that designing each mooring system individually will result in significant complexity at the array scale. They produce the most cost-optimal component sizes that satisfy design constraints, but the variety in component sizes increases the manufacturing and shipping burden in terms of increased lead times and costs (only some of which were captured in the models). The Humboldt site has a larger range of water depths than Morro Bay, which resulted in a higher range of component size and length variation. The baseline Humboldt design contains 35 unique chain diameters and 112 unique anchor diameters while the baseline Morro Bay design contains 29 unique chain diameters and 55 unique anchor diameters. The variation in chain and anchor sizes means that manufacturers will have to stop production more often to accommodate different sizes, transportation and storage of components will have to be carefully organized to not create confusion, and installing each component will require more planning and care on the installation vessel. Only two different rope diameters were needed in each design, suggesting that rope diameter standardization can be done with minimal design adjustment. Using our supply chain modeling assumptions, the total manufacturing and delivery time for all stationkeeping components is 1.65 years for the Humboldt baseline design and 2.60 years for the Morro Bay baseline design. The difference is driven mainly by the larger component count in the Morro Bay design, although both estimates depend heavily on the assumed manufacturing capacity.

Analysis and discussions with domestic supply chain representatives suggest that the domestic supply chain for stationkeeping components has the potential to supply the needs of single projects at a time. Chain lead time is limited by the maximum diameter in the mooring design, as domestic manufacturing can only currently support diameters up to 127 mm, pending proper offshore chain certifications. Rope lead time is limited by the time needed to splice the ends of each rope, unless other rope termination technologies are adopted. Anchor lead time (for piles) is limited by the transportation logistics between the Gulf Coast and the West Coast but can use many manufacturers and assembly lines if needed. Estimates suggest the domestic supply chain could expand its capacity by 2–3 times in the event of a large and continuous project pipeline consistent with a deployment trajectory of 25 GW by 2045. However, suppliers indicated that certainty about future demand is needed before investing in capacity expansion. Overall, supplying chain, rope, and anchors for West Coast projects can be done, but capacities need to be expanded or designs need to accommodate the limitations. Modeling of the domestic stationkeeping supply chain, including capacities and transportation logic, is now included in the installation cost and logistics tool ORBIT[1].

Among a range of standardization options for floating wind stationkeeping systems, the use of shared anchors provides the largest reduction in lead time, and standardizing mooring chain diameters and pile anchor diameters leads to good supply chain benefits. Shared anchors reduce the total quantity of anchors to be manufactured without significantly increasing anchor sizes. Standardizing chain diameters and anchor diameters to certain sizes allows for less manufacturing downtime to reset machinery and lower lead times, with some increases in material use and cost. The supply chain model assumptions—such as takt time, downtime, the number of assembly lines, and the division of components between assembly lines—heavily affect supply chain modeling results. Other standardization techniques like uniform line lengths or simplified layouts did not influence the supply chain modeling results as much but should still be considered for other logistical benefits. The benefits of standardization can be balanced with material and cost efficiency by using multiple standardized sizes per component type and combining multiple standardization techniques.

The combined application of the most effective standardization techniques into standardized designs for the two lease areas produced reductions in lead time with some increases in cost. Figure 48 summarizes the impacts on total component cost and supply chain lead time for each of the three major stationkeeping component types for each site. We selected standardized designs that balanced cost and lead time while avoiding the individually sized components of the baseline designs.

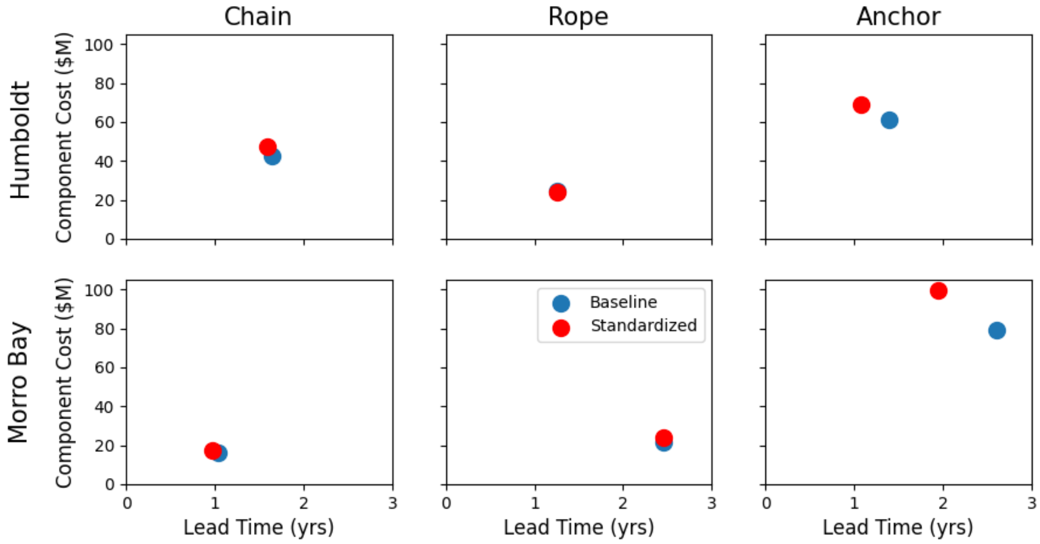


Figure 48. Standardized design impacts on cost and lead time for each component for each site

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[1] The ORBIT mooring supply chain capabilities are at https://github.com/WISDEM/ORBIT/tree/Standard_Mooring.

Effects of the standardization on lead times and LCOE, as predicted by the models and input assumptions, varied between the sites. In the Humboldt standardized design, the chain lead time reduced by 3 weeks, the anchor lead time reduced by 15 weeks, and the rope lead time did not change. The total cost of the standardized mooring system design was 9% higher than the baseline mooring system design due to an increase in chain cost due to standardized sizes and an increase in anchor cost due to the combination of anchor size standardization and reducing anchor counts through shared anchors. In the Morro Bay design, the chain lead time reduced by 3 weeks, the anchor lead time reduced by 8 months, and the rope lead time did not change. The total cost of the standardized mooring system design was 20% higher than the baseline mooring system design primarily due to the larger anchor sizes. The total LCOE of the Humboldt standardized design increased by 1.0% relative to the baseline design while the total LCOE of the Morro Bay standardized design decreased by 1.0% relative to the baseline design. Based on the cost modeling assumptions, these results reflect that changes in AEP, caused by changes in wake losses between array layouts or changes in operational downtime from assumed component failure rates, affect LCOE more than individual component standardization size decisions.

Additional benefits from standardization that were not captured in the cost and supply chain models are also expected. Interchangeability of standardized component sizes reduces risk of error during assembly and installation while allowing for spare parts to be warehoused and replaced more easily. Port operations related to the storage and handling of mooring components will be easier with standardized sizes. The installation operations can be more easily performed with specific sizes that are compatible with vessel handling equipment so as to not require inconvenient vessel modifications. For example, Karm Forks outfitted on vessels are only designed for certain chain sizes, and specific rope reels and winches are designed for specific rope volumes. Additionally, less variability in component sizes reduces the amount of testing and certification required for new offshore-grade components.

This project has increased our knowledge and modeling capabilities with regard to mooring component sizing, approaches to adjusting for bathymetry, shared anchor systems, and supply chain and installation logistics. Many of these learnings and methods are transferrable to other projects, some of which have already benefited in parallel. In the project *Comprehensive Shared-Mooring Solutions to Minimize the Cost, Risk, and Footprint of GW-Scale Floating Wind Farms*, funded by the California Energy Commission, we have implemented the same techniques for adjusting mooring systems for bathymetric variations, and we are sizing the mooring systems considering the supply chain constraints identified in this project. The project *Co-Design Solutions for U.S. Floating Offshore Wind Farms and Fishing Compatibility*, funded by NOWRDC, followed the approach of using standardized chain and anchor diameters, and it used the same method for adjusting mooring systems to accommodate bathymetric variations. Other projects can also benefit from the standardized designs developed in this project, which are described in full detail through input files that are published on GitHub.[2]

Overall, in the course of generating these findings, this project demonstrated the ability to apply standardization techniques and design optimization methods with a mooring component supply

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[2] Input files at: https://github.com/FloatingArrayDesign/ReferenceDesigns/tree/main/Standardized%20Mooring.

chain model in the optimization loop to develop more practical and scalable mooring system designs for large floating wind arrays.

8.2 General Conclusions

The project's findings lead to a number of more general conclusions. The following apply to standardization of taut mooring systems within a floating wind farm in deep water, where there is water depth variation but similar turbines and loading conditions:

- Rope diameters can be easily standardized across the array, as no large changes in rope properties are needed for different water depths.
- When standardizing chain diameters and anchor diameters, the trade-off between minimizing material use (non-standardized) and minimizing manufacturing complexity (standardized) can be balanced considering multiple standardized diameters and their associated production costs and economies of scale.
- Shared anchors can significantly contribute to cost reductions through reduced material costs and installation costs from a reduced anchor count. However, they can create increased variation in anchor sizes.
- The logistics involved in transportation, staging at port, and loading onto installation vessels should be considered in the standardization design process, as these logistical procedures and resource needs (e.g., staging area) may benefit significantly from standardized component sizes.

Some conclusions can also be drawn regarding the domestic mooring supply chain in general, beyond the scope of individual projects:

- Anchor manufacturing has the highest existing capacity within the domestic stationkeeping supply chain, and multiple anchor assembly lines can significantly reduce lead time, especially if each line can be catered towards different anchor sizes to avoid retooling. This efficiency could be further leveraged if anchor sizes were standardized across multiple projects.
- Siting manufacturing facilities closer to port can decrease transportation and logistical demands, reducing component delivery times and costs (especially if the Panama Canal can be avoided). Setting up new facilities near project locations would depend on sufficient project sizes and certainty of demand.
- The current domestic supply chain can adapt for floating wind applications of small scale with modest investment in new certifications and production and transportation upgrades.
- Meeting the demand of a large-scale floating wind deployment pipeline would require substantial investment in new facilities, which suppliers indicate can only be done if there is high confidence in ongoing demand from floating wind projects.

8.3 Limitations and Future Work

Continued development of the mooring system design process considering the domestic supply chain and standardization should be done to develop more practical designs and reduce LCOE. There are several areas where increased detail in the supply chain and logistics modeling could increase the completeness of the quantitative modeling results:

- Higher-fidelity supply chain models that represent more realistic supply chain processes (e.g., suction pile anchor manufacturing models as a function of number of anchor cans or differentiating the thicknesses between each can).
- More refined component cost coefficients that consider other economic factors like economies of scale, manufacturing setup, and shipping logistics can provide better estimates of supply chain contributions to CapEx.
- Additional supply chain studies to analyze the effects of different manufacturing throughput, transportation logistics, or assembly line distribution.
- Including the installation process and vessel requirements in the design process can significantly influence design and LCOE results.

In addition, there are aspects where greater detail could be considered in the mooring system design or new design ideas uncovered in this project could be explored more deeply:

- Including more detailed auxiliary components in the design process would better inform the standardization strategies. For example, accounting for fairlead tensioning components could allow for evaluation of line length standardized options.
- Higher-fidelity anchor modeling, especially for the multidirectional load capacity of shared anchors, could enable more robust anchor sizing approaches and give additional insight on anchor size standardization options.
- The new design concept of doubling up chain sections with bridle-like arrangements at both the platform and the anchor could be modeled with full loads analysis to assess if its chain-sizing benefits are countered by any performance impacts.
- The supply chain and cost impacts of redundant mooring systems (e.g., six-line rather than three-line designs) should be explored further in regard to the trade-off between reduced component sizes and longer lead times as well as potential changes in uptime and operations and maintenance costs.
- More detailed site-specific design—including adjustments to array layouts to increase AEP, avoid undesirable seabed soils, or accommodate other ocean co-users—could also be done to provide greater detail on farm-level design trade-offs and standardization techniques.

Overall, further improvements to how the site and design are represented can allow more detailed analysis and yield more realistic design solutions and insights for supply chain compatibility and LCOE reduction.

References

ABS. (2013). *Offshore Anchor Data for Preliminary Design of Anchor of Floating Offshore Wind Turbines*. American Bureau of Shipping.

ABS. (2022, July). *Requirements for the Certification of Offshore Mooring Chain*. American Bureau of Shipping (ABS).

Allen, C., Viscelli, A., Dagher, H., Goupee, A., Gaertner, E. (ORCID:0000000160332654), Abbas, N., Hall, M., & Barter, G. (ORCID:0000000177578853). (2020). *Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine* (NREL/TP-5000-76773). National Renewable Energy Laboratory, Golden, CO (United States).

API. (2005, October). *API RP 2SK: Design and Analysis of Stationkeeping Systems for Floating Structures*. American Petroleum Institute.

BEXCO. (2004). *Polyester & Dyneema mooring ropes manual 2004*. Bexco. https://ocw.tudelft.nl/wp-content/uploads/deepropemanual.pdf

Biglu, M., Hall, M., Lozon, E., & Housner, S. (2024). *Reference Site Conditions for Floating Wind Arrays in the United States* (NREL/TP-5000-89897). National Renewable Energy Laboratory. https://doi.org/10.2172/2439546

Delmar Systems. (2018). *Vryhof Manual: The Guide to Anchoring*. Vryhof. Available at https://insights.delmarsystems.com/download-the-vryhof-manual

Desmond, C., Hall, M., Shields, M., Averbuch, D., Guillemin, F., Pauline Bozonnet, Aaron Smith, Nailia Dindarova, & Nicolas El Hayek. (2020, July). *Proceedings of Topical Expert Meeting #99: Floating Offshore Wind Array Challenges and Opportunities*. International Energy Agency (IEA) Wind Task 11.

Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., & Viselli, A. (2020). Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine. In *Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine* [Report]. National Renewable Energy Laboratory.

Hall, M., Housner, S., Lozon, E., & Sirnivas, S. (2022). *Shared Mooring Systems for Deep-Water Floating Wind Farms* [New York State Energy Research and Development Authority (NYSERDA) Report]. National Renewable Energy Laboratory.

Hall, M., Housner, S., Sirnivas, S., & Wilson, S. (2021). *MoorPy (Quasi-Static Mooring Analysis in Python)*. National Renewable Energy Laboratory, Golden, CO, USA. https://doi.org/10.11578/DC.20210726.1

Hall, M., Lozon, E., Housner, S., & Sirnivas, S. (2022). Design and analysis of a ten-turbine floating wind farm with shared mooring lines. *Journal of Physics: Conference Series*, *2362*(1), 012016. https://dx.doi.org/10.1088/1742-6596/2362/1/012016. https://doi.org/10.1088/1742-6596/2362/1/012016

Hall, M., Lozon, E., McAuliffe, F. D., Bessone, M. B., Bayati, I., Bowie, M., Bozonnet, P., Castagné, M., Feng, J., Housner, S., Janocha, M. J., Jiang, Z., Kim, Y. Y., Ko, D., Kölle, K., Lee, C. F., Lekkala, M. R., Liang, G., Mahfouz, M. Y., … Wright, C. (2024). *The IEA Wind Task 49 Reference Floating Wind Array Design Basis* (NREL/TP-5000-89709). International Energy Agency Wind TCP. https://doi.org/10.2172/2382797

Housner, S., & Mulas Hernando, D. (2024). *Levelized Cost of Energy Comparison of Floating Wind Farms With and Without Shared Anchors* (NREL/TP-5000-89121). National Renewable Energy Laboratory, Golden, CO (United States).

Humboldt Bay Harbor Recreation & Conservation District. (2023, August 21). *Humboldt Bay Offshore Wind Minimum Viable Port—Project Description*. https://humboldtbay.org/sites/humboldtbay.org/files/FY%202023-24%20MPDG%20Humboldt%20Bay%20Offshore%20Wind%20MVP%20Proposal%20Package_reducedfilesize.pdf

Intermoor. (n.d.). *Intermoor Product Specification Manual*. Acteon. Retrieved June 1, 2023, from https://acteon.com/wp-content/uploads/2023/03/InterMoor-Product-Manual-1.pdf

Janocha, M. J., Ong, M. C., Lee, C. F., Chen, K., & Ye, N. (2024). Reference Power Cable Models for Floating Offshore Wind Applications. *Sustainability*, *16*(7), 2899. https://www.mdpi.com/2071-1050/16/7/2899. https://doi.org/10.3390/su16072899

Lankhorst Offshore. (n.d.). *Cabral 512*. Retrieved https://www.lankhorstoffshore.com/products/cabral-512

Ma, K.-T., Luo, Y., Kwan, C.-T. T., & Wu, Y. (2019). *Mooring System Engineering for Offshore Structures*. Gulf Professional Publishing.

Moffatt & Nichol. (2023). *Pier Wind Concept Phase—Final Conceptual Report*. https://polb.com/port-info/news-and-press/port-of-long-beach-releases-pier-wind-project-concept-05-09-2023/

NLR. (2020). *Documentation for ORBIT* [Read the Docs Documentation]. Soft CapEx Methodology. https://nlrwindsystems.github.io/ORBIT/source/doc_ProjectManager.html#soft-capex-methodology

Nunemaker, J., Shields, M., Hammond, R., & Duffy, P. (2020). *ORBIT: Offshore Renewables Balance-of-System and Installation Tool* (NREL/TP-5000-77081). National Renewable Energy Laboratory, Golden, CO (United States). https://doi.org/10.2172/1660132

ORE Catapult. (2021). *Floating Offshore Wind: Cost Reduction Pathways to Subsidy Free*. ORE Catapult. https://ore.catapult.org.uk/?orecatapultreports=floating-offshore-windcost-reduction-pathways-subsidy-free

Reese, L. C. (1997). Analysis of Laterally Loaded Piles in Weak Rock. *Journal of Geotechnical and Geoenvironmental Engineering*, *123*(11), 1010–1017. https://doi.org/10.1061/(ASCE)1090-0241(1997)123:11(1010)

Shields, M., Cooperman, A., Kreider, M., Oteri, F., Hemez, Z., Gill, L., Sharma, A., Fan, K., Musial, W., Trowbridge, M., Knipe, A., & Lim, J. (2023). *The Impacts of Developing a Port Network for Floating Offshore Wind Energy on the West Coast of the United States* (NREL/TP-5000-86864). National Renewable Energy Laboratory, Golden, CO (United States). https://doi.org/10.2172/2005543

Shields, M., Marsh, R., Stefek, J., Oteri, F., Gould, R., Rouxel, N., Diaz, K., Molinero, J., Moser, A., Malvik, C., & Tirone, S. (2022). *The Demand for a Domestic Offshore Wind Energy Supply Chain* (NREL/TP-5000-81602). National Renewable Energy Laboratory, Golden, CO (United States). https://doi.org/10.2172/1860239

Shields, M., Oteri, F., Stefek, J., & Moser, A. (2021). *30 GW by 2030: A Supply Chain Roadmap for Offshore Wind in the United States Part 1: The Demand for a Domestic Supply Chain* [Deliverable 3.1 for NOWRDC contract #154675]. NREL.

Shields, M., Stefek, J., Oteri, F., Kreider, M., Gill, E., Maniak, S., Gould, R., Malvik, C., Tirone, S., & Hines, E. (2023). *A Supply Chain Road Map for Offshore Wind Energy in the United States* (NREL/TP-5000-84710). https://doi.org/10.2172/1922189

Stehly, T., Duffy, P., & Hernando, D. M. (2023). *2022 Cost of Wind Energy Review*. NREL/PR-5000-88335. https://doi.org/10.2172/2278805

Appendix A. Humboldt Array Information

The floating wind turbines (FOWTs) are numbered sequentially from west to east across the array and from north to south. For example, FOWT1 corresponds to the northwesternmost platform in the array, while FOWT 40 corresponds to the southeasternmost platform. Alphabetical designations are used to identify mooring line orientations around each platform. These designations follow a counterclockwise convention, with letters assigned in increasing alphabetical order starting from the mooring line oriented 120° clockwise from the mooring line pointing directly north or south. For example, FOWT1a refers to the mooring line and anchor connected to FOWT1 that are oriented at 120° in compass coordinates (330° in Cartesian coordinates). FOWT5a refers to the mooring line and anchor connected to FOWT5 that are oriented at 300° in compass coordinates (150° in Cartesian coordinates).

Table A-1 provides a list of the average water depth at each FOWT based on the water depths of the three anchors, a designation for the mooring orientation based on whether a mooring line is oriented directly north or south, and the anchoring radius and anchor type at each anchor.

Table A-1. Humboldt Array Information

FOWT	**Water Depth**	**Anchoring Radius**	**Mooring Orient.**	**Anchor Depth**			**Anchor Type**		
				A	**B**	**C**	**A**	**B**	**C**
No.	(m)	(m)	(-)	(m)	(m)	(m)	(SP or D&G)*	(SP or D&G)	(SP or D&G)
1	916.7	1200	North	832.6	1002.8	914.7	SP	SP	SP
2	894.6	1200	North	805.0	959.7	919.2	SP	SP	SP
3	882.2	1200	North	800.6	978.6	867.4	SP	SP	SP
4	836.1	1200	South	870.9	846.6	790.9	SP	SP	SP
5	776.4	1200	South	818.3	781.6	729.4	SP	SP	SP
6	755.1	1200	South	786.8	711.1	767.4	SP	SP	SP
7	788.2	1200	South	820.2	746.5	797.9	SP	SP	SP
8	824.6	1200	South	866.6	760.3	847.0	SP	SP	SP
9	842.1	1200	North	846.2	842.2	837.7	SP	SP	SP
10	828.2	1200	North	816.2	829.6	838.7	SP	SP	SP
11	757.8	1200	North	768.6	699.9	804.8	D&G	SP	SP
12	746.1	1200	North	756.1	757.5	724.8	SP	D&G	SP
13	742.2	1200	North	720.2	748.8	757.6	SP	SP	D&G
14	745.7	1200	North	715.7	783.9	737.4	SP	SP	SP
15	775.8	1200	North	731.9	843.9	751.7	SP	SP	SP
16	781.7	1200	North	714.3	835.5	795.4	SP	SP	SP
17	922.0	1200	South	946.4	930.4	889.4	SP	SP	SP
18	834.6	1200	South	875.1	817.3	811.5	SP	SP	SP
19	791.6	1200	South	835.6	771.7	767.6	SP	SP	SP

FOWT	Water Depth	Anchoring Radius	Mooring Orient.	Anchor Depth			Anchor Type		
				A	B	C	A	B	C
20	761.7	1200	South	797.7	741.5	746.0	D&G	SP	SP
21	738.4	1200	South	754.9	730.4	729.8	D&G	SP	SP
22	716.6	1200	South	733.5	715.2	701.1	SP	SP	SP
23	705.3	1200	South	723.8	693.8	698.3	SP	SP	SP
24	704.4	1200	South	724.4	681.0	707.7	SP	SP	SP
25	704.7	1200	South	732.5	683.1	698.5	SP	SP	D&G
26	731.8	1200	South	745.1	684.0	766.3	SP	SP	SP
27	790.8	1200	South	815.7	735.9	820.9	SP	SP	SP
28	683.3	1200	North	669.7	680.6	699.7	SP	SP	D&G
29	673.1	1200	North	657.8	686.7	674.8	SP	D&G	SP
30	667.7	1200	North	655.2	675.7	672.1	SP	SP	SP
31	685.2	1200	North	669.7	718.1	667.7	SP	SP	SP
32	722.5	1200	North	700.3	775.5	691.8	SP	SP	SP
33	794.9	1200	North	769.1	879.1	736.4	SP	SP	SP
34	899.5	1200	North	883.0	953.7	861.7	SP	SP	SP
35	853.3	1200	North	734.6	947.3	877.9	SP	SP	SP
36	838.6	1200	North	728.5	950.1	837.1	SP	SP	SP
37	709.0	1200	South	725.6	670.9	730.5	SP	SP	SP
38	769.6	1200	South	888.7	688.4	731.8	SP	SP	SP
39	700.1	1200	South	734.9	690.0	675.4	SP	SP	SP
40	694.3	1200	South	760.7	634.9	687.4	SP	SP	SP

*SP – suction pile; D&G – drilled and grouted pile

Appendix B. Humboldt Mooring Line Design Details

Table B-1 follows the same numerical and alphabetical convention as Table A-1, denoting the Cartesian coordinates of the orientation of each line, and lists the specific mooring line design details for each chain and rope section in the Humboldt baseline design, including the water depth and pretension.

Table B-1. Humboldt Mooring Line Design Details

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	**Depth (m)**	**Preten. (MN)**	**Diameter (mm)**	**Length (m)**	**Diameter (mm)**	**Length (m)**	**Diameter (mm)**	**Length (m)**
1a (330°)	832.6	1.500	128	240.3	205	1005.5	128	171.6
1b (90°)	914.7	1.487	145	222.9	205	1095.7	145	161.5
1c (210°)	1002.8	1.471	149	204.2	205	1176.9	149	152.8
2a (330°)	805.0	1.504	125	246.2	207	978.9	125	175.6
2b (90°)	919.2	1.486	146	222.0	205	1101.3	146	161.0
2c (210°)	959.7	1.479	145	213.4	205	1134.6	145	156.8
3a (330°)	800.6	1.505	125	247.1	207	975.0	125	176.3
3b (90°)	867.4	1.495	141	232.9	205	1050.1	141	167.1
3c (210°)	978.6	1.475	147	209.3	205	1153.5	147	155.0
4a (150°)	870.9	1.494	157	232.2	205	1083.8	157	166.6
4b (270°)	790.9	1.506	117	249.2	207	960.5	117	177.8
4c (30°)	846.6	1.498	117	237.3	205	1010.4	117	169.7
5a (150°)	818.3	1.502	151	243.3	207	1028.1	151	173.7
5b (270°)	729.4	1.515	111	262.2	207	902.1	111	188.4
5c (30°)	781.6	1.508	113	251.1	207	950.1	113	179.3
6a (150°)	786.8	1.507	148	250.0	207	996.3	148	178.4
6b (270°)	767.4	1.510	115	254.1	207	938.6	115	181.6
6c (30°)	711.1	1.518	110	266.1	207	885.3	110	191.9
7a (150°)	820.2	1.502	152	242.9	207	1032.0	152	173.4
7b (270°)	797.9	1.505	118	247.7	207	967.5	118	176.7
7c (30°)	746.5	1.513	112	258.6	207	918.1	112	185.2
8a (150°)	866.6	1.495	156	233.1	205	1077.8	156	167.2
8b (270°)	847.0	1.498	123	237.3	205	1014.3	123	169.7
8c (30°)	760.3	1.511	112	255.7	207	930.2	112	182.8
9a (330°)	846.2	1.498	129	237.4	205	1018.3	129	169.8
9b (90°)	837.7	1.499	138	239.2	205	1020.7	138	170.9
9c (210°)	842.2	1.499	132	238.3	205	1017.5	132	170.3
10a (330°)	816.2	1.503	126	243.8	207	989.5	126	174.0

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	**Depth (m)**	**Preten. (MN)**	**Diameter (mm)**	**Length (m)**	**Diameter (mm)**	**Length (m)**	**Diameter (mm)**	**Length (m)**
10b (90°)	838.7	1.499	138	239.0	205	1021.7	138	170.8
10c (210°)	829.6	1.501	131	240.9	205	1005.7	131	172.1
11a (330°)	768.6	1.510	121	253.9	207	943.6	121	181.4
11b (90°)	804.8	1.504	135	246.2	207	989.0	135	175.6
11c (210°)	699.9	1.520	115	268.5	207	878.3	115	194.2
12a (330°)	756.1	1.512	120	256.5	207	931.9	120	183.5
12b (90°)	724.8	1.516	127	263.2	207	910.9	127	189.2
12c (210°)	757.5	1.511	122	256.3	207	934.6	122	183.3
13a (330°)	720.2	1.517	116	264.1	207	897.2	116	190.1
13b (90°)	757.6	1.511	131	256.2	207	943.6	131	183.3
13c (210°)	748.8	1.513	121	258.1	207	926.2	121	184.8
14a (330°)	715.7	1.517	116	265.1	207	893.2	116	191.0
14b (90°)	737.4	1.514	129	260.5	207	923.9	129	186.9
14c (210°)	783.9	1.507	126	250.6	207	961.3	126	178.9
15a (330°)	731.9	1.515	118	261.7	207	908.9	118	187.9
15b (90°)	751.7	1.512	130	257.5	207	937.4	130	184.3
15c (210°)	843.9	1.498	132	237.9	205	1019.3	132	170.1
16a (330°)	714.3	1.518	116	265.4	207	891.9	116	191.3
16b (90°)	795.4	1.506	134	248.2	207	979.6	134	177.1
16c (210°)	835.5	1.500	132	239.7	205	1012.0	132	171.2
17a (150°)	946.4	1.481	165	216.2	205	1164.0	165	158.1
17b (270°)	889.4	1.491	127	228.3	205	1054.8	127	164.4
17c (30°)	930.4	1.484	121	219.6	205	1088.2	121	159.8
18a (150°)	875.1	1.493	157	231.3	205	1087.1	157	166.1
18b (270°)	811.5	1.503	120	244.8	207	980.6	120	174.7
18c (30°)	817.3	1.502	115	243.6	207	983.0	115	173.8
19a (150°)	835.6	1.500	153	239.7	205	1046.2	153	171.2
19b (270°)	767.6	1.510	115	254.1	207	938.5	115	181.6
19c (30°)	771.7	1.509	113	253.2	207	941.0	113	180.9
20a (150°)	797.7	1.505	149	247.7	207	1007.3	149	176.7
20b (270°)	746.0	1.513	113	258.7	207	918.2	113	185.3
20c (30°)	741.5	1.514	111	259.6	207	913.1	111	186.1
21a (150°)	754.9	1.512	144	256.8	207	962.2	144	183.7
21b (270°)	729.8	1.515	111	262.1	207	902.5	111	188.3

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	Depth (m)	Preten. (MN)	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)
21c (30°)	730.4	1.515	111	262.0	207	903.0	111	188.2
22a (150°)	733.5	1.515	142	261.3	207	940.8	142	187.6
22b (270°)	701.1	1.520	107	268.2	207	874.6	107	194.0
22c (30°)	715.2	1.517	110	265.2	207	889.0	110	191.1
23a (150°)	723.8	1.516	141	263.4	207	931.1	141	189.4
23b (270°)	698.3	1.520	107	268.8	207	872.1	107	194.6
23c (30°)	693.8	1.521	109	269.8	207	869.1	109	195.5
24a (150°)	724.4	1.516	141	263.3	207	931.5	141	189.3
24b (270°)	707.7	1.519	108	266.8	207	881.1	108	192.6
24c (30°)	681.0	1.523	108	272.5	207	857.0	108	198.3
25a (150°)	732.5	1.515	142	261.5	207	940.1	142	187.8
25b (270°)	698.5	1.520	107	268.8	207	872.2	107	194.5
25c (30°)	683.1	1.522	108	272.0	207	859.0	108	197.8
26a (150°)	745.1	1.513	143	258.9	207	952.2	143	185.5
26b (270°)	766.3	1.510	115	254.4	207	937.5	115	181.8
26c (30°)	684.0	1.522	108	271.8	207	859.8	108	197.6
27a (150°)	815.7	1.503	151	243.9	207	1026.1	151	174.0
27b (270°)	820.9	1.502	121	242.8	207	990.0	121	173.3
27c (30°)	735.9	1.514	111	260.8	207	908.1	111	187.1
28a (330°)	669.7	1.524	111	274.9	207	848.7	111	200.8
28b (90°)	699.7	1.520	125	268.5	207	887.0	125	194.3
28c (210°)	680.6	1.523	113	272.5	207	859.8	113	198.4
29a (330°)	657.8	1.526	110	277.4	207	837.3	110	203.6
29b (90°)	674.8	1.523	122	273.8	207	862.1	122	199.7
29c (210°)	686.7	1.522	113	271.3	207	865.2	113	197.0
30a (330°)	655.2	1.526	109	277.9	207	834.3	109	204.3
30b (90°)	672.1	1.524	122	274.4	207	859.7	122	200.3
30c (210°)	675.7	1.523	112	273.6	207	854.7	112	199.5
31a (330°)	669.7	1.524	111	274.9	207	848.7	111	200.8
31b (90°)	667.7	1.525	122	275.3	207	855.9	122	201.3
31c (210°)	718.1	1.517	117	264.6	207	895.9	117	190.6
32a (330°)	700.3	1.520	114	268.4	207	878.0	114	194.1
32b (90°)	691.8	1.521	124	270.2	207	879.0	124	195.9
32c (210°)	775.5	1.509	125	252.4	207	953.0	125	180.3

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	Depth (m)	Preten. (MN)	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)
33a (330°)	769.1	1.510	121	253.8	207	944.1	121	181.3
33b (90°)	736.4	1.514	129	260.7	207	923.1	129	187.1
33c (210°)	879.1	1.493	136	230.5	205	1054.0	136	165.6
34a (330°)	883.0	1.492	133	229.6	205	1054.2	133	165.1
34b (90°)	861.7	1.496	140	234.1	205	1043.6	140	167.8
34c (210°)	953.7	1.480	144	214.6	205	1127.8	144	157.4
35a (330°)	734.6	1.515	118	261.1	207	911.3	118	187.4
35b (90°)	877.9	1.493	142	230.7	205	1060.4	142	165.8
35c (210°)	947.3	1.481	144	216.0	205	1122.6	144	158.0
36a (330°)	728.5	1.516	117	262.4	207	905.2	117	188.5
36b (90°)	837.1	1.499	138	239.4	205	1020.4	138	171.0
36c (210°)	950.1	1.481	144	215.4	205	1124.9	144	157.7
37a (150°)	725.6	1.516	141	263.0	207	932.5	141	189.1
37b (270°)	730.5	1.515	111	262.0	207	903.1	111	188.2
37c (30°)	670.9	1.524	108	274.6	207	847.9	108	200.6
38a (150°)	888.7	1.491	159	228.4	205	1102.8	159	164.5
38b (270°)	731.8	1.515	111	261.7	207	904.2	111	187.9
38c (30°)	688.4	1.521	108	270.9	207	863.5	108	196.7
39a (150°)	734.9	1.515	142	261.1	207	942.0	142	187.3
39b (270°)	675.4	1.523	104	273.7	207	849.9	104	199.5
39c (30°)	690.0	1.521	109	270.6	207	865.6	109	196.3
40a (150°)	760.7	1.511	145	255.6	207	968.9	145	182.7
40b (270°)	687.4	1.522	106	271.1	207	861.7	106	196.9

Appendix C. Humboldt Anchor Design Details

Table C-1 lists the dimensions (diameter, length, thickness) of each individually sized anchor in the Humboldt baseline design.

Table C-1. Humboldt Anchor Design Details

FOWT		A			B			C	
	D	L	t	D	L	t	D	L	t
No.	(m)	(m)	(mm)	(m)	(m)	(mm)	(m)	(m)	(mm)
1	3.34	20.01	73	3.66	18.32	80	3.61	18.04	79
2	3.35	20.11	73	3.66	18.30	80	3.24	19.45	71
3	3.36	20.13	73	3.29	19.72	72	2.93	20.49	65
4	2.65	18.53	59	1.96	9.80	46	2.77	19.38	62
5	2.94	17.64	65	1.79	10.73	42	1.96	9.82	46
6	1.68	10.11	40	1.78	10.68	42	1.98	9.88	46
7	3.30	16.51	72	1.77	10.64	42	1.97	9.85	46
8	2.92	17.54	65	2.76	19.32	62	2.95	20.68	65
9	3.33	19.96	73	3.30	19.82	72	3.32	19.93	73
10	3.03	21.21	67	3.30	19.82	72	3.33	19.98	73
11	1.60	7.40	38	3.32	19.94	73	1.85	12.94	43
12	2.21	11.04	51	1.60	7.30	38	1.83	12.79	43
13	1.84	12.90	43	1.97	11.81	46	1.60	7.50	38
14	2.01	12.06	47	2.19	10.94	50	1.98	11.88	46
15	2.00	12.02	46	2.18	10.91	50	3.32	19.92	73
16	1.84	12.91	43	2.16	10.82	50	3.33	19.96	73
17	2.89	17.36	64	2.74	19.21	61	3.41	17.04	75
18	3.28	16.40	72	3.06	18.36	68	2.78	19.43	62
19	2.93	17.60	65	1.78	10.68	42	1.97	9.83	46
20	1.60	5.10	38	1.78	10.71	42	1.63	11.43	39
21	1.60	5.10	38	1.64	11.50	39	1.78	10.70	42
22	1.88	9.40	44	1.99	9.93	46	1.78	10.71	42
23	1.88	9.41	44	1.80	10.78	42	1.64	11.48	39
24	1.70	10.20	40	1.79	10.76	42	1.79	10.73	42
25	1.88	9.40	44	1.80	10.78	42	1.60	5.60	38
26	1.69	10.17	40	1.97	9.84	46	1.98	9.90	46
27	2.94	17.65	65	3.43	17.17	75	1.78	10.69	42
28	2.03	12.17	47	1.99	11.94	46	1.60	8.40	38
29	2.03	12.20	47	1.60	7.70	38	2.02	12.12	47

FOWT	A			B			C		
	D	L	t	D	L	t	D	L	t
No.	(m)	(m)	(mm)	(m)	(m)	(mm)	(m)	(m)	(mm)
30	1.86	13.05	44	1.83	12.83	43	2.24	11.22	51
31	2.25	11.24	51	2.00	12.01	46	2.22	11.12	51
32	2.02	12.10	47	1.99	11.96	46	2.20	10.98	50
33	1.99	11.94	46	1.81	12.69	43	3.30	19.78	72
34	3.30	19.82	72	3.29	19.74	72	2.94	20.59	65
35	2.22	11.09	51	3.28	19.69	72	3.25	19.50	71
36	2.22	11.10	51	2.99	20.95	66	2.94	20.61	65
37	1.88	9.41	44	1.79	10.73	42	1.64	11.50	39
38	3.27	16.37	72	1.79	10.73	42	1.98	9.90	46
39	1.55	9.28	37	1.99	9.97	46	1.98	9.89	46
40	1.69	10.15	40	1.99	9.95	46	1.99	9.94	46

Appendix D. Morro Bay Array Information

The Morro Bay design information follows the same numerical and alphabetical convention as the Humboldt design information in Appendix A but includes six lines (D through F). Since pairs of mooring lines and anchors are spread by 4°, FOWT1a now refers to the mooring line and anchor connected to FOWT1 that are oriented at 122° in compass coordinates (328° in Cartesian coordinates).

Table D-1 provides a list of the average water depth at each FOWT based on the water depths of the six anchors, a designation for the mooring orientation based on whether a mooring line is oriented directly north or south, and the anchoring radius of each mooring line. Anchor types are not listed here since we assume suction piles for all anchors.

Table D-1. Morro Bay Array Information

FOWT	Water Depth	Anchoring Radius	Mooring Orient.	Anchor Depth					
				A	B	C	D	E	F
No.	(m)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(m)
1	1046.9	1000	North	1041.4	1041.9	1061.3	1054.9	1045.3	1043.8
2	1017.7	1000	North	1010.3	1011.0	1034.4	1035.3	1007.4	1006.8
3	998.0	1000	North	997.3	997.3	1017.1	1004.6	991.9	992.0
4	997.0	1000	North	1004.1	1004.1	999.9	995.6	991.0	991.5
5	1011.7	1000	North	1019.5	1019.4	1010.9	999.6	1015.8	1015.4
6	1027.7	1000	North	1033.3	1032.4	1035.1	1013.2	1036.4	1037.1
7	1071.7	1000	North	1076.9	1075.2	1067.6	1041.1	1097.4	1098.3
8	1131.5	1000	North	1132.0	1129.4	1114.4	1097.7	1165.7	1167.5
9	1034.9	1000	South	1044.2	1044.6	1044.4	1029.7	1030.2	1030.5
10	1016.8	1000	South	1025.7	1024.7	1041.8	1004.7	1020.0	1020.9
11	1000.9	1000	South	1002.0	1001.5	1030.6	1000.0	1000.8	1001.2
12	1003.5	1000	South	1000.5	1000.7	1012.6	1008.7	1001.3	1001.0
13	1015.6	1000	South	1012.4	1012.9	999.9	1023.4	1011.0	1010.6
14	1032.4	1000	South	1024.6	1024.6	1010.6	1046.7	1026.1	1025.6
15	1063.1	1000	South	1054.1	1055.2	1021.2	1082.2	1052.6	1051.7
16	1108.8	1000	South	1099.7	1101.5	1061.2	1134.5	1091.7	1090.4
17	1018.5	1000	North	1007.4	1007.1	1028.7	1021.5	1027.3	1026.8
18	1006.9	1000	North	996.9	997.0	1023.3	1015.6	1008.9	1008.1
19	997.5	1000	North	993.6	993.3	1011.9	1000.4	999.0	999.1
20	1001.6	1000	North	1002.0	1001.5	1000.5	997.8	1005.1	1005.4
21	1013.5	1000	North	1016.0	1015.5	1005.5	1007.5	1017.2	1017.5
22	1032.0	1000	North	1037.8	1037.1	1018.1	1021.0	1037.0	1037.8
23	1060.1	1000	North	1067.4	1066.3	1039.5	1044.0	1069.0	1070.0

FOWT	**Water Depth**	**Anchoring Radius**	**Mooring Orient.**	**Anchor Depth**					
				A	**B**	**C**	**D**	**E**	**F**
No.	(m)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(m)
24	1096.9	1000	North	1102.6	1101.3	1075.9	1076.7	1111.7	1112.8
25	995.1	1000	South	1005.8	1006.2	1005.4	992.3	986.5	987.0
26	990.2	1000	South	1000.0	1000.1	1002.5	987.1	983.1	983.5
27	988.0	1000	South	991.4	991.6	997.4	989.8	982.6	982.8
28	994.9	1000	South	995.6	995.9	995.9	1000.5	988.4	988.4
29	1009.1	1000	South	1006.7	1007.3	1010.6	1018.7	1001.6	1001.2
30	1030.5	1000	South	1025.5	1026.1	1025.2	1043.0	1023.1	1022.4
31	1057.6	1000	South	1050.8	1051.7	1053.9	1072.3	1049.6	1048.9
32	1090.2	1000	South	1082.0	1083.1	1084.5	1110.2	1078.5	1077.6
33	975.5	1000	North	967.9	967.7	985.6	976.9	982.5	982.1
34	974.2	1000	North	968.6	968.2	984.1	974.1	980.7	980.4
35	977.0	1000	North	973.7	973.2	984.4	974.9	982.9	982.9
36	985.4	1000	North	984.1	983.4	995.9	980.5	992.0	992.3
37	1001.7	1000	North	1003.5	1002.7	1012.7	992.5	1009.5	1010.0
38	1025.1	1000	North	1028.0	1027.1	1034.4	1013.1	1034.6	1035.3
39	1052.2	1000	North	1056.8	1055.7	1064.6	1038.6	1061.5	1062.4
40	1084.6	1000	North	1090.9	1089.7	1096.8	1067.6	1095.6	1096.8

Appendix E. Morro Bay Mooring Line Design Details

Table E-1 follows the same numerical and alphabetical convention as Table D-1, denoting the Cartesian coordinates of the orientation of each line, and lists the specific mooring line design details for each chain and rope section in the Morro Bay baseline design, including the water depth and pretension.

Table E-1. Morro Bay Mooring Line Design Details

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	**Depth (m)**	**Preten. (MN)**	**Diam. (mm)**	**Length (m)**	**Diam. (mm)**	**Length (m)**	**Diam. (mm)**	**Length (m)**
1a (328°)	1041.4	0.983	83	40.0	123	1202.8	83	135.7
1b (332°)	1041.9	0.984	84	39.9	123	1203.4	84	135.6
1c (88°)	1054.2	0.994	96	38.4	123	1215.5	96	134.9
1d (92°)	1054.9	0.995	96	38.3	123	1216.1	96	134.9
1e (208°)	1045.2	0.987	71	39.5	123	1205.2	71	135.4
1f (212°)	1043.8	0.985	71	39.7	123	1203.9	71	135.5
2a (328°)	1010.3	0.956	82	44.1	123	1174.9	82	137.6
2b (332°)	1011.0	0.957	82	44.0	123	1175.5	82	137.6
2c (88°)	1035.3	0.978	96	40.8	123	1198.6	96	136.0
2d (92°)	1035.3	0.978	96	40.8	123	1198.6	96	136.0
2e (208°)	1007.4	0.954	69	44.4	123	1171.3	69	137.8
2f (212°)	1006.8	0.954	69	44.5	123	1170.8	69	137.8
3a (328°)	997.3	0.946	81	45.7	123	1163.3	81	138.5
3b (332°)	997.3	0.945	81	45.7	123	1163.3	81	138.5
3c (88°)	1004.8	0.952	96	44.8	123	1171.2	96	138.0
3d (92°)	1004.6	0.952	97	44.8	123	1171.2	97	138.0
3e (208°)	991.9	0.941	68	46.4	123	1157.5	68	138.8
3f (212°)	992.0	0.941	68	46.4	123	1157.6	68	138.8
4a (328°)	1004.1	0.951	81	44.9	123	1169.3	81	138.0
4b (332°)	1004.0	0.951	82	44.9	123	1169.3	82	138.0
4c (88°)	995.8	0.944	96	45.9	123	1163.3	96	138.6
4d (92°)	995.6	0.944	97	46.0	123	1163.1	97	138.6
4e (208°)	991.0	0.940	68	46.6	123	1156.7	68	138.9
4f (212°)	991.5	0.941	68	46.5	123	1157.0	68	138.9
5a (328°)	1019.5	0.964	82	42.9	123	1183.2	82	137.0
5b (332°)	1019.4	0.964	83	42.9	123	1183.0	83	137.0
5c (88°)	1000.4	0.948	96	45.3	123	1167.3	96	138.3
5d (92°)	999.6	0.947	97	45.4	123	1166.8	97	138.3

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	Depth (m)	Preten. (MN)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)
5e (208°)	1015.8	0.961	70	43.3	123	1178.9	70	137.3
5f (212°)	1015.4	0.961	69	43.4	123	1178.4	69	137.3
6a (328°)	1033.3	0.976	83	41.1	123	1195.5	83	136.2
6b (332°)	1032.4	0.975	83	41.2	123	1194.7	83	136.2
6c (88°)	1013.8	0.959	96	43.6	123	1179.3	96	137.4
6d (92°)	1013.2	0.959	97	43.7	123	1178.9	97	137.4
6e (208°)	1036.4	0.979	71	40.7	123	1197.2	71	136.0
6f (212°)	1037.1	0.979	70	40.6	123	1197.9	70	135.9
7a (328°)	1076.9	1.014	85	35.4	123	1235.1	85	133.6
7b (332°)	1075.2	1.013	86	35.6	123	1233.4	86	133.7
7c (88°)	1041.2	0.983	96	40.0	123	1203.8	96	135.7
7d (92°)	1041.1	0.983	96	40.0	123	1203.8	96	135.7
7e (208°)	1097.4	1.033	74	32.7	123	1252.6	74	132.5
7f (212°)	1098.3	1.034	74	32.6	123	1253.4	74	132.5
8a (328°)	1132.0	1.064	88	28.2	123	1285.1	88	130.8
8b (332°)	1129.4	1.062	89	28.6	123	1282.8	89	130.9
8c (88°)	1096.6	1.032	96	32.8	123	1254.0	96	132.6
8d (92°)	1097.7	1.033	96	32.7	123	1254.8	96	132.5
8e (208°)	1165.7	1.096	78	23.9	123	1315.2	78	129.2
8f (212°)	1167.5	1.097	77	23.6	123	1316.8	77	129.1
9a (148°)	1044.2	0.986	97	39.6	123	1206.7	97	135.5
9b (152°)	1044.6	0.986	95	39.6	123	1206.7	95	135.5
9c (268°)	1030.2	0.974	72	41.5	123	1191.8	72	136.4
9d (272°)	1029.7	0.973	73	41.5	123	1191.5	73	136.4
9e (28°)	1030.2	0.974	91	41.5	123	1193.3	91	136.4
9f (32°)	1030.5	0.974	92	41.4	123	1193.8	92	136.3
10a (148°)	1025.7	0.970	98	42.0	123	1190.2	98	136.6
10b (152°)	1024.7	0.969	96	42.2	123	1189.0	96	136.7
10c (268°)	1004.9	0.952	71	44.8	123	1169.1	71	138.0
10d (272°)	1004.7	0.952	72	44.8	123	1169.0	72	138.0
10e (28°)	1020.0	0.965	91	42.8	123	1184.2	91	137.0
10f (32°)	1020.9	0.966	92	42.7	123	1185.2	92	136.9
11a (148°)	1002.0	0.949	98	45.1	123	1169.0	98	138.2
11b (152°)	1001.5	0.949	96	45.2	123	1168.3	96	138.2

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	**Depth (m)**	**Preten. (MN)**	**Diam. (mm)**	**Length (m)**	**Diam. (mm)**	**Length (m)**	**Diam. (mm)**	**Length (m)**
11c (268°)	1000.0	0.948	71	45.4	123	1164.8	71	138.3
11d (272°)	1000.0	0.948	72	45.4	123	1164.8	72	138.3
11e (28°)	1000.8	0.948	91	45.3	123	1167.0	91	138.3
11f (32°)	1001.2	0.949	92	45.2	123	1167.7	92	138.2
12a (148°)	1000.5	0.948	98	45.3	123	1167.7	98	138.3
12b (152°)	1000.7	0.948	96	45.3	123	1167.6	96	138.3
12c (268°)	1008.7	0.955	71	44.3	123	1172.6	71	137.7
12d (272°)	1008.7	0.955	72	44.3	123	1172.6	72	137.7
12e (28°)	1001.2	0.949	91	45.2	123	1167.5	91	138.2
12f (32°)	1001.0	0.949	92	45.3	123	1167.5	92	138.2
13a (148°)	1012.4	0.958	98	43.8	123	1178.2	98	137.5
13b (152°)	1012.9	0.959	96	43.7	123	1178.4	96	137.5
13c (268°)	1023.5	0.968	72	42.3	123	1185.7	72	136.8
13d (272°)	1023.4	0.968	72	42.3	123	1185.7	72	136.8
13e (28°)	1011.0	0.957	91	44.0	123	1176.2	91	137.6
13f (32°)	1010.6	0.957	92	44.0	123	1176.0	92	137.6
14a (148°)	1024.6	0.969	98	42.2	123	1189.2	98	136.7
14b (152°)	1024.6	0.969	96	42.2	123	1189.0	96	136.7
14c (268°)	1046.6	0.988	73	39.3	123	1206.8	73	135.4
14d (272°)	1046.6	0.988	73	39.3	123	1206.7	73	135.4
14e (28°)	1026.1	0.970	91	42.0	123	1189.7	91	136.6
14f (32°)	1025.6	0.970	92	42.1	123	1189.4	92	136.6
15a (148°)	1054.1	0.994	97	38.4	123	1215.5	97	134.9
15b (152°)	1055.2	0.995	95	38.2	123	1216.3	95	134.9
15c (268°)	1082.6	1.020	74	34.7	123	1239.2	74	133.3
15d (272°)	1082.2	1.019	74	34.7	123	1238.9	74	133.3
15e (28°)	1052.6	0.993	91	38.6	123	1213.5	91	135.0
15f (32°)	1051.7	0.992	92	38.7	123	1212.7	92	135.1
16a (148°)	1099.7	1.035	97	32.4	123	1256.6	97	132.4
16b (152°)	1101.5	1.036	95	32.2	123	1258.2	95	132.3
16c (268°)	1135.1	1.067	75	27.8	123	1287.0	75	130.6
16d (272°)	1134.5	1.067	76	27.9	123	1286.6	76	130.6
16e (28°)	1091.7	1.028	91	33.5	123	1248.8	91	132.8
16f (32°)	1090.4	1.026	92	33.6	123	1247.8	92	132.9

Mooring ID	Depth (m)	Preten. (MN)	Bottom Chain		Polyester Rope		Top Chain	
			Diam. (mm)	Length (m)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)
17a (328°)	1007.4	0.954	81	44.4	123	1172.3	81	137.8
17b (332°)	1007.1	0.954	82	44.5	123	1172.1	82	137.8
17c (88°)	1020.8	0.965	96	42.7	123	1185.6	96	136.9
17d (92°)	1021.5	0.966	96	42.6	123	1186.2	96	136.9
17e (208°)	1027.3	0.971	70	41.9	123	1189.1	70	136.5
17f (212°)	1026.8	0.971	70	41.9	123	1188.7	70	136.6
18a (328°)	996.9	0.945	81	45.8	123	1162.9	81	138.5
18b (332°)	997.0	0.945	81	45.8	123	1163.0	81	138.5
18c (88°)	1014.8	0.960	96	43.5	123	1180.2	96	137.3
18d (92°)	1015.6	0.961	97	43.4	123	1181.0	97	137.3
18e (208°)	1008.8	0.955	69	44.2	123	1172.7	69	137.7
18f (212°)	1008.1	0.955	69	44.3	123	1172.0	69	137.8
19a (328°)	993.6	0.942	81	46.2	123	1159.9	81	138.7
19b (332°)	993.3	0.942	81	46.3	123	1159.6	81	138.8
19c (88°)	999.9	0.948	96	45.4	123	1167.0	96	138.3
19d (92°)	1000.3	0.948	97	45.4	123	1167.2	97	138.3
19e (208°)	999.0	0.947	69	45.5	123	1163.8	69	138.4
19f (212°)	999.1	0.947	68	45.5	123	1163.8	68	138.4
20a (328°)	1002.0	0.949	81	45.1	123	1167.4	81	138.2
20b (332°)	1001.5	0.949	81	45.2	123	1167.0	81	138.2
20c (88°)	997.6	0.946	96	45.7	123	1164.8	96	138.5
20d (92°)	997.8	0.946	97	45.7	123	1165.0	97	138.5
20e (208°)	1005.1	0.952	69	44.7	123	1169.3	69	138.0
20f (212°)	1005.4	0.952	68	44.7	123	1169.5	68	137.9
21a (328°)	1016.0	0.961	82	43.3	123	1179.9	82	137.3
21b (332°)	1015.5	0.961	82	43.4	123	1179.4	82	137.3
21c (88°)	1007.3	0.954	96	44.4	123	1173.6	96	137.8
21d (92°)	1007.5	0.954	97	44.4	123	1173.7	97	137.8
21e (208°)	1017.2	0.962	70	43.2	123	1180.0	70	137.2
21f (212°)	1017.5	0.963	69	43.1	123	1180.3	69	137.2
22a (328°)	1037.8	0.980	83	40.5	123	1199.6	83	135.9
22b (332°)	1037.0	0.979	84	40.6	123	1199.0	84	135.9
22c (88°)	1021.0	0.966	96	42.7	123	1185.8	96	136.9
22d (92°)	1021.0	0.966	96	42.7	123	1185.8	96	136.9

Mooring ID	Depth (m)	Preten. (MN)	Bottom Chain		Polyester Rope		Top Chain	
			Diam. (mm)	Length (m)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)
22e (208°)	1037.0	0.979	71	40.6	123	1197.8	71	135.9
22f (212°)	1037.8	0.980	70	40.5	123	1198.5	70	135.9
23a (328°)	1067.4	1.006	85	36.6	123	1226.3	85	134.2
23b (332°)	1066.3	1.005	85	36.8	123	1225.6	85	134.2
23c (88°)	1044.2	0.986	96	39.7	123	1206.5	96	135.5
23d (92°)	1044.0	0.985	96	39.7	123	1206.4	96	135.5
23e (208°)	1068.9	1.007	73	36.4	123	1226.9	73	134.1
23f (212°)	1070.0	1.008	72	36.3	123	1227.8	72	134.0
24a (328°)	1102.6	1.037	86	32.1	123	1258.2	86	132.2
24b (332°)	1101.3	1.036	87	32.2	123	1257.1	87	132.3
24c (88°)	1076.6	1.014	96	35.4	123	1235.7	96	133.6
24d (92°)	1076.7	1.014	96	35.4	123	1235.8	96	133.6
24e (208°)	1111.7	1.046	75	30.9	123	1265.5	75	131.8
24f (212°)	1112.8	1.047	75	30.7	123	1266.7	75	131.7
25a (148°)	1005.8	0.953	98	44.6	123	1172.5	98	137.9
25b (152°)	1006.2	0.953	96	44.6	123	1172.5	96	137.9
25c (268°)	992.9	0.942	71	46.3	123	1158.5	71	138.8
25d (272°)	992.3	0.941	71	46.4	123	1158.0	71	138.8
25e (28°)	986.5	0.936	91	47.2	123	1154.3	91	139.2
25f (32°)	987.0	0.937	92	47.1	123	1155.0	92	139.2
26a (148°)	1000.0	0.948	98	45.4	123	1167.3	98	138.3
26b (152°)	1000.0	0.948	96	45.4	123	1167.2	96	138.3
26c (268°)	987.5	0.937	70	47.0	123	1153.6	70	139.2
26d (272°)	987.1	0.937	71	47.1	123	1153.3	71	139.2
26e (28°)	983.1	0.934	91	47.6	123	1151.4	91	139.5
26f (32°)	983.5	0.934	92	47.5	123	1152.0	92	139.4
27a (148°)	991.4	0.941	98	46.5	123	1159.6	98	138.9
27b (152°)	991.6	0.941	96	46.5	123	1159.4	96	138.9
27c (268°)	990.1	0.939	71	46.7	123	1156.0	71	139.0
27d (272°)	989.8	0.939	71	46.7	123	1155.7	71	139.0
27e (28°)	982.6	0.933	91	47.7	123	1150.9	91	139.5
27f (32°)	982.8	0.933	92	47.6	123	1151.3	92	139.5
28a (148°)	995.6	0.944	98	46.0	123	1163.3	98	138.6
28b (152°)	995.9	0.944	96	45.9	123	1163.4	96	138.6

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	Depth (m)	Preten. (MN)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)
28c (268°)	1000.9	0.948	71	45.3	123	1165.6	71	138.2
28d (272°)	1000.5	0.948	72	45.3	123	1165.3	72	138.3
28e (28°)	988.4	0.938	91	46.9	123	1156.2	91	139.1
28f (32°)	988.4	0.938	92	46.9	123	1156.2	92	139.1
29a (148°)	1006.7	0.953	98	44.5	123	1173.1	98	137.9
29b (152°)	1007.2	0.954	96	44.5	123	1173.4	96	137.8
29c (268°)	1019.0	0.964	72	42.9	123	1181.7	72	137.1
29d (272°)	1018.7	0.964	72	43.0	123	1181.4	72	137.1
29e (28°)	1001.6	0.949	91	45.2	123	1167.7	91	138.2
29f (32°)	1001.2	0.949	92	45.2	123	1167.7	92	138.2
30a (148°)	1025.5	0.969	98	42.1	123	1189.8	98	136.7
30b (152°)	1026.1	0.970	96	42.0	123	1190.4	96	136.6
30c (268°)	1043.0	0.985	72	39.8	123	1203.3	72	135.6
30d (272°)	1043.0	0.985	73	39.8	123	1203.5	73	135.6
30e (28°)	1023.1	0.967	91	42.4	123	1187.0	91	136.8
30f (32°)	1022.4	0.967	92	42.5	123	1186.5	92	136.8
31a (148°)	1050.8	0.991	97	38.8	123	1212.6	97	135.1
31b (152°)	1051.7	0.992	95	38.7	123	1213.1	95	135.1
31c (268°)	1072.5	1.011	73	36.0	123	1230.1	73	133.9
31d (272°)	1072.3	1.010	74	36.0	123	1230.0	74	133.9
31e (28°)	1049.6	0.990	91	39.0	123	1210.7	91	135.2
31f (32°)	1048.9	0.990	92	39.0	123	1210.4	92	135.2
32a (148°)	1082.0	1.019	97	34.7	123	1240.6	97	133.3
32b (152°)	1083.1	1.020	95	34.6	123	1241.4	95	133.3
32c (268°)	1110.4	1.045	75	31.0	123	1264.6	75	131.8
32d (272°)	1110.2	1.044	75	31.1	123	1264.4	75	131.8
32e (28°)	1078.5	1.016	91	35.2	123	1236.8	91	133.5
32f (32°)	1077.5	1.015	92	35.3	123	1236.1	92	133.6
33a (328°)	967.9	0.921	79	49.6	117	1135.4	79	140.5
33b (332°)	967.7	0.921	79	49.6	117	1135.2	79	140.6
33c (88°)	976.3	0.928	96	48.5	117	1144.6	96	139.9
33d (92°)	976.9	0.928	97	48.4	117	1145.1	97	139.9
33e (208°)	982.5	0.933	68	47.7	123	1147.5	68	139.5
33f (212°)	982.1	0.933	67	47.7	123	1147.1	67	139.5

			Bottom Chain		Polyester Rope		Top Chain	
Mooring ID	Depth (m)	Preten. (MN)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)	Diam. (mm)	Length (m)
34a (328°)	968.6	0.922	79	49.5	117	1136.0	79	140.5
34b (332°)	968.2	0.921	80	49.5	117	1135.8	80	140.5
34c (88°)	973.5	0.926	96	48.8	117	1142.1	96	140.1
34d (92°)	974.1	0.926	97	48.8	117	1142.7	97	140.1
34e (208°)	980.7	0.932	67	47.9	117	1145.8	67	139.6
34f (212°)	980.4	0.931	67	47.9	117	1145.7	67	139.6
35a (328°)	973.7	0.926	80	48.8	117	1140.7	80	140.1
35b (332°)	973.2	0.925	80	48.9	117	1140.1	80	140.2
35c (88°)	974.4	0.926	96	48.7	117	1142.9	96	140.1
35d (92°)	974.9	0.927	97	48.7	117	1143.4	97	140.0
35e (208°)	982.9	0.933	68	47.6	123	1147.8	68	139.5
35f (212°)	982.9	0.933	67	47.6	123	1147.8	67	139.5
36a (328°)	984.1	0.934	80	47.5	123	1151.3	80	139.4
36b (332°)	983.4	0.934	80	47.6	123	1150.7	80	139.4
36c (88°)	980.1	0.931	96	48.0	117	1149.2	96	139.7
36d (92°)	980.5	0.931	97	47.9	117	1149.7	97	139.6
36e (208°)	992.0	0.941	68	46.4	123	1157.6	68	138.8
36f (212°)	992.3	0.941	68	46.4	123	1157.8	68	138.8
37a (328°)	1003.5	0.951	81	44.9	123	1168.8	81	138.1
37b (332°)	1002.7	0.950	82	45.0	123	1168.2	82	138.1
37c (88°)	992.1	0.941	96	46.4	123	1160.0	96	138.8
37d (92°)	992.5	0.941	97	46.4	123	1160.4	97	138.8
37e (208°)	1009.5	0.956	69	44.2	123	1173.1	69	137.7
37f (212°)	1010.0	0.956	69	44.1	123	1173.7	69	137.6
38a (328°)	1028.0	0.972	82	41.8	123	1190.7	82	136.5
38b (332°)	1027.1	0.971	83	41.9	123	1189.9	83	136.6
38c (88°)	1012.8	0.959	96	43.7	123	1178.2	96	137.5
38d (92°)	1013.1	0.959	97	43.7	123	1178.7	97	137.4
38e (208°)	1034.6	0.977	71	40.9	123	1195.6	71	136.1
38f (212°)	1035.3	0.978	70	40.8	123	1196.3	70	136.0
39a (328°)	1056.8	0.997	84	38.0	123	1216.7	84	134.8
39b (332°)	1055.7	0.996	85	38.1	123	1215.8	85	134.8
39c (88°)	1038.2	0.980	96	40.4	123	1201.2	96	135.9
39d (92°)	1038.6	0.981	96	40.4	123	1201.5	96	135.8

Mooring ID	Depth (m)	Preten. (MN)	Bottom Chain Diam. (mm)	Bottom Chain Length (m)	Polyester Rope Diam. (mm)	Polyester Rope Length (m)	Top Chain Diam. (mm)	Top Chain Length (m)
39e (208°)	1061.5	1.001	72	37.4	123	1220.0	72	134.5
39f (212°)	1062.4	1.002	72	37.3	123	1220.8	72	134.4
40a (328°)	1090.9	1.027	86	33.6	123	1247.7	86	132.9
40b (332°)	1089.7	1.026	87	33.7	123	1246.6	87	132.9
40c (88°)	1067.3	1.006	96	36.6	123	1227.2	96	134.2
40d (92°)	1067.6	1.006	96	36.6	123	1227.5	96	134.1
40e (208°)	1095.6	1.031	74	33.0	123	1250.9	74	132.6
40f (212°)	1096.8	1.032	74	32.8	123	1252.0	74	132.5

Appendix F. Morro Bay Anchor Design Details

Table F-1 lists the dimensions (diameter, length, thickness) of each individually sized anchor in the Morro Bay baseline design.

Table F-1. Morro Bay Anchor Design Details

	A			B			C		
FOWT	D			E			F		
	D	L	t	D	L	t	D	L	t
No.	(m)	(m)	(mm)	(m)	(m)	(mm)	(m)	(m)	(mm)
1	2.34	14.04	53	2.59	12.95	58	2.59	12.94	58
1	2.34	14.03	53	2.60	12.98	58	2.35	14.08	53
2	2.33	13.98	53	2.33	13.98	53	2.15	15.07	49
2	2.58	12.90	58	2.59	12.93	58	2.33	14.00	53
3	1.35	9.48	33	1.42	8.52	35	2.57	12.87	58
3	2.32	13.91	53	1.43	8.55	35	1.36	9.50	33
4	2.58	12.91	58	2.33	13.97	53	1.41	8.45	35
4	1.41	8.44	34	1.36	9.50	34	1.45	7.24	35
5	2.33	14.00	53	2.33	14.00	53	2.32	13.91	53
5	1.34	9.40	33	2.34	14.02	53	2.34	14.02	53
6	2.16	15.12	50	2.34	14.03	53	2.14	14.99	49
6	2.57	12.87	58	2.34	14.07	53	2.59	12.96	58
7	2.18	15.27	50	2.35	14.13	53	2.33	14.01	53
7	2.33	13.99	53	2.61	13.05	59	2.37	14.21	54
8	2.38	14.27	54	2.62	13.08	59	2.36	14.16	54
8	2.60	13.00	58	2.63	13.17	59	2.40	14.40	54
9	2.19	13.14	50	2.43	12.15	55	2.44	12.19	55
9	2.43	12.16	55	2.20	13.20	50	2.42	12.09	55
10	2.19	13.11	50	2.19	13.15	50	2.44	12.18	55
10	2.19	13.16	50	2.20	13.19	50	2.01	14.10	47
11	2.18	13.08	50	2.01	14.09	47	2.20	13.19	50
11	2.43	12.14	55	2.43	12.17	55	2.01	14.05	46
12	2.42	12.10	55	2.18	13.11	50	2.44	12.18	55
12	2.19	13.16	50	2.19	13.17	50	2.18	13.06	50
13	2.42	12.10	55	2.19	13.13	50	2.20	13.22	50
13	2.20	13.18	50	2.43	12.17	55	2.42	12.08	55
14	2.18	13.11	50	2.43	12.14	55	2.21	13.25	51
14	2.20	13.22	50	2.20	13.20	50	2.18	13.10	50

		A			B			C	
FOWT		D			E			F	
	D	L	t	D	L	t	D	L	t
No.	(m)	(m)	(mm)	(m)	(m)	(mm)	(m)	(m)	(mm)
15	2.19	13.15	50	2.43	12.16	55	2.22	13.30	51
15	2.06	14.39	47	2.44	12.19	55	2.42	12.11	55
16	2.43	12.15	55	2.22	13.29	51	2.45	12.26	55
16	2.23	13.39	51	2.22	13.30	51	2.43	12.15	55
17	2.33	13.97	53	2.15	15.04	49	2.33	13.96	53
17	2.32	13.95	53	2.34	14.05	53	2.16	15.14	50
18	1.51	7.54	37	1.51	9.09	37	2.32	13.94	53
18	2.58	12.88	58	2.16	15.09	49	2.15	15.08	49
19	1.51	7.54	36	1.35	9.46	33	1.41	8.47	35
19	2.57	12.86	58	1.43	8.57	35	1.36	9.53	34
20	2.33	13.96	53	2.58	12.90	58	1.50	7.49	36
20	1.41	8.45	35	2.59	12.93	58	2.58	12.92	58
21	2.33	13.99	53	2.15	15.06	49	2.32	13.92	53
21	2.14	14.96	49	2.16	15.12	50	2.59	12.94	58
22	2.59	12.94	58	2.34	14.04	53	2.58	12.89	58
22	2.32	13.94	53	2.34	14.07	53	2.59	12.96	58
23	2.35	14.10	53	2.18	15.24	50	2.34	14.01	53
23	2.33	14.00	53	2.36	14.15	54	2.18	15.29	50
24	2.61	13.03	58	2.37	14.20	54	2.35	14.10	53
24	2.59	12.97	58	2.62	13.08	59	2.21	15.45	50
25	2.42	12.10	55	2.19	13.12	50	1.33	7.98	33
25	1.41	7.03	34	1.26	8.79	31	1.24	8.71	31
26	1.25	8.75	31	2.18	13.11	50	1.27	8.87	32
26	1.32	7.94	33	1.40	6.99	34	1.30	7.82	32
27	1.25	8.72	31	1.31	7.87	33	1.33	7.98	33
27	1.32	7.95	33	1.40	6.99	34	1.38	6.92	34
28	1.31	7.86	33	1.31	7.88	33	2.44	12.18	55
28	2.19	13.15	50	1.26	8.80	31	1.31	7.84	32
29	2.18	13.09	50	2.43	12.13	55	2.20	13.21	50
29	2.03	14.21	47	2.19	13.17	50	2.18	13.06	50
30	2.19	13.11	50	2.43	12.14	55	2.44	12.19	55
30	2.20	13.21	50	2.20	13.19	50	2.42	12.09	55

	A			B			C		
FOWT	**D**			**E**			**F**		
	D	**L**	**t**	**D**	**L**	**t**	**D**	**L**	**t**
No.	**(m)**	**(m)**	**(mm)**	**(m)**	**(m)**	**(mm)**	**(m)**	**(m)**	**(mm)**
31	2.19	13.15	50	2.43	12.16	55	2.44	12.21	55
31	2.21	13.26	51	2.20	13.23	50	2.42	12.11	55
32	2.20	13.20	50	2.05	14.34	47	2.23	13.35	51
32	2.22	13.34	51	2.44	12.21	55	2.20	13.20	50
33	1.34	9.36	33	1.49	7.47	36	1.40	8.38	34
33	1.39	8.37	34	1.51	7.54	37	1.51	7.54	36
34	1.40	8.43	34	1.40	8.42	34	1.33	9.29	33
34	1.39	8.36	34	1.42	8.51	35	1.51	7.53	36
35	1.34	9.38	33	1.41	8.44	34	1.48	7.42	36
35	1.33	9.47	33	1.35	9.47	33	1.41	8.48	35
36	1.41	8.48	35	1.41	8.48	35	1.40	8.39	34
36	1.33	9.31	33	1.43	8.55	35	1.42	8.55	35
37	2.33	13.96	53	2.58	12.90	58	1.50	7.48	36
37	1.34	9.37	33	2.33	14.01	53	2.59	12.93	58
38	2.16	15.10	50	2.34	14.02	53	2.58	12.88	58
38	2.32	13.93	53	2.17	15.17	50	2.34	14.06	53
39	2.35	14.08	53	2.35	14.08	53	2.58	12.92	58
39	2.58	12.91	58	2.35	14.13	53	2.35	14.12	53
40	2.60	13.01	58	2.36	14.17	54	2.17	15.20	50
40	2.59	12.95	58	2.37	14.21	54	2.20	15.39	50

Appendix G. Stationkeeping Suppliers

Table G-1 provides an aggregated list of stationkeeping component domestic suppliers and estimated total domestic throughput values and transportation times. Transit times from international sources may vary. Ocean transit from Asia could be 4–7 weeks, whereas transit from Europe to East Coast ports could be 3–4 weeks.

Table G-1. Domestic Stationkeeping Suppliers and Aggregated Metrics

Component	Number of Suppliers	Annual Total Throughput	Known Certifications	Transit to West Coast Port
Mooring Chain	1	16 kton or 47,000 m	ABS, MIL-C-24633, FM3, ORQ, and Lloyds	Rail + Vessel: 11 days
Polyester Rope	4	104 ropes	DNV, ABS	Vessel: 4–5 weeks Truck: 6–7 days Rail: 6–7 days
Spiral Strand Wire Rope	2	10,000 m		Vessel: 4–5 weeks Truck: 6–7 days Rail: 6–7 days
Suction Pile Anchors	9	200-400	ABS	Vessel: 3–4 weeks Truck: 5–6 days Rail: 5–6 days
Chain Accessories (shackles, thimbles, H-links, etc.)	3	300		Vessel: 3–4 weeks Truck: 5–6 days Rail: 5–6 days
Fairleads/ Tensioners	2	(low)		
Subsea Connectors	1	50	ABS	Vessel: 3–4 weeks Truck: 5–6 days Rail: 5–6 days

Appendix H. Humboldt Shared Anchor Design Details

Table H-1. Shared Anchor Designs for the Humboldt Standardized Design

Orange shading represents shared anchors; bold text represents D&G anchors

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT1a-5a	836.3	Soft Clay	Suction Pile	3.146	18.874	69
FOWT1b	912.9	Soft Clay	Suction Pile	3.146	18.875	69
FOWT1c	999.9	Soft Clay	Suction Pile	3.242	19.451	71
FOWT2a-6a	808.2	Soft Clay	Suction Pile	3.125	18.748	69
FOWT2b	918.3	Soft Clay	Suction Pile	3.150	18.899	69
FOWT2c	956.1	Soft Clay	Suction Pile	3.214	19.281	71
FOWT3a-7a	801.9	Soft Clay	Suction Pile	3.120	18.718	69
FOWT3b	866.8	Soft Clay	Suction Pile	3.110	18.659	69
FOWT3c	974.3	Soft Clay	Suction Pile	3.225	19.350	71
FOWT4a	930.1	Soft Clay	Suction Pile	2.634	15.804	59
FOWT4b	837.2	Soft Clay	Suction Pile	2.877	17.264	64
FOWT4c-9c	840.6	Soft Clay	Suction Pile	3.124	18.743	69
FOWT5b	714.0	Medium Clay	Suction Pile	2.404	14.425	54
FOWT5c-10c	829.7	Soft Clay	Suction Pile	3.115	18.691	69
FOWT6b	766.6	Medium Clay	Suction Pile	2.430	14.579	55
FOWT6c-11c	702.4	Medium Clay	Suction Pile	2.604	15.623	58
FOWT7b	776.4	Medium Clay	Suction Pile	2.436	14.618	55
FOWT7c-12c	758.0	Medium Clay	Suction Pile	2.619	15.716	59
FOWT8a	847.8	Soft Clay	Suction Pile	2.588	15.527	58
FOWT8b	823.0	Soft Clay	Suction Pile	2.871	17.224	64
FOWT8c-13c	748.2	Medium Clay	Suction Pile	2.618	15.706	59
FOWT9a-18a	847.2	Soft Clay	Suction Pile	3.155	18.928	69
FOWT9b	836.4	Soft Clay	Suction Pile	3.086	18.518	68
FOWT10a-19a	817.2	Soft Clay	Suction Pile	3.131	18.786	69
FOWT10b	838.7	Soft Clay	Suction Pile	3.088	18.530	68
FOWT11a-20a	**768.7**	**Rock**	**D&G Pile**	**1.154**	**6.661**	**29**
FOWT11b	802.8	Soft Clay	Suction Pile	3.061	18.364	68
FOWT12a-21a	757.2	Medium Clay	Suction Pile	2.644	15.861	59
FOWT12b	**723.3**	**Rock**	**D&G Pile**	**1.169**	**6.788**	**30**
FOWT13a-22a	722.3	Medium Clay	Suction Pile	2.618	15.711	59
FOWT13b	756.4	Medium Clay	Suction Pile	2.608	15.647	59

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT14a-23a	717.0	Medium Clay	Suction Pile	2.616	15.696	59
FOWT14b	737.4	Medium Clay	Suction Pile	2.600	15.597	58
FOWT14c	782.2	Medium Clay	Suction Pile	2.653	15.919	59
FOWT15a-24a	733.4	Medium Clay	Suction Pile	2.624	15.743	59
FOWT15b	752.3	Medium Clay	Suction Pile	2.607	15.639	58
FOWT15c	840.9	Soft Clay	Suction Pile	3.140	18.838	69
FOWT16a-25a	715.0	Medium Clay	Suction Pile	2.615	15.690	59
FOWT16b	796.2	Medium Clay	Suction Pile	2.629	15.776	59
FOWT16c	832.0	Soft Clay	Suction Pile	3.135	18.810	69
FOWT17a	881.4	Soft Clay	Suction Pile	2.610	15.660	59
FOWT17b	838.4	Soft Clay	Suction Pile	2.882	17.294	64
FOWT17c	851.3	Soft Clay	Suction Pile	2.935	17.612	65
FOWT18b	787.1	Medium Clay	Suction Pile	2.442	14.651	55
FOWT18c	791.5	Medium Clay	Suction Pile	2.454	14.724	55
FOWT19b	752.4	Medium Clay	Suction Pile	2.423	14.539	55
FOWT19c	753.3	Medium Clay	Suction Pile	2.423	14.539	55
FOWT20b	740.2	Medium Clay	Suction Pile	2.417	14.505	55
FOWT20c	734.3	Medium Clay	Suction Pile	2.406	14.438	54
FOWT21b	718.7	Medium Clay	Suction Pile	2.406	14.436	54
FOWT21c	719.5	Medium Clay	Suction Pile	2.396	14.378	54
FOWT22b	691.5	Medium Clay	Suction Pile	2.390	14.341	54
FOWT22c	704.9	Medium Clay	Suction Pile	2.384	14.304	54
FOWT23b	705.8	Medium Clay	Suction Pile	2.397	14.381	54
FOWT23c-28c	680.6	Medium Clay	Suction Pile	2.601	15.607	58
FOWT24b	696.4	Medium Clay	Suction Pile	2.394	14.365	54
FOWT24c-29c	686.0	Medium Clay	Suction Pile	2.599	15.591	58
FOWT25b	740.6	Medium Clay	Suction Pile	2.410	14.461	55
FOWT25c-30c	**675.2**	**Rock**	**D&G Pile**	**1.177**	**6.855**	**30**
FOWT26a	791.0	Medium Clay	Suction Pile	2.233	13.397	51
FOWT26b	806.2	Soft Clay	Suction Pile	2.856	17.137	63
FOWT26c-31c	716.1	Medium Clay	Suction Pile	2.605	15.632	58
FOWT27a	853.9	Soft Clay	Suction Pile	2.588	15.525	58
FOWT27b	887.4	Soft Clay	Suction Pile	2.911	17.467	65
FOWT27c-32c	773.3	Medium Clay	Suction Pile	2.634	15.807	59
FOWT28a	670.2	Medium Clay	Suction Pile	2.614	15.682	59

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT28b	699.1	Medium Clay	Suction Pile	2.566	15.396	58
FOWT29a	658.2	Medium Clay	Suction Pile	2.610	15.659	59
FOWT29b	674.4	Medium Clay	Suction Pile	2.555	15.328	57
FOWT30a	655.8	Medium Clay	Suction Pile	2.607	15.643	58
FOWT30b	672.1	Medium Clay	Suction Pile	2.553	15.321	57
FOWT31a	669.9	Medium Clay	Suction Pile	2.613	15.681	59
FOWT31b	667.8	Medium Clay	Suction Pile	2.551	15.307	57
FOWT32a-37a	700.5	Medium Clay	Suction Pile	2.609	15.651	59
FOWT32b	693.2	Medium Clay	Suction Pile	2.561	15.367	58
FOWT33a-38a	770.3	Medium Clay	Suction Pile	2.651	15.908	59
FOWT33b	737.4	Medium Clay	Suction Pile	2.600	15.597	58
FOWT33c	876.7	Soft Clay	Suction Pile	3.162	18.970	70
FOWT34a-39a	888.4	Soft Clay	Suction Pile	3.186	19.115	70
FOWT34b	866.6	Soft Clay	Suction Pile	3.109	18.655	69
FOWT34c	953.4	Soft Clay	Suction Pile	3.211	19.266	71
FOWT35a-40a	736.5	Medium Clay	Suction Pile	2.625	15.751	59
FOWT35b	872.5	Soft Clay	Suction Pile	3.114	18.684	69
FOWT35c	944.6	Soft Clay	Suction Pile	3.205	19.230	70
FOWT36a	731.8	Medium Clay	Suction Pile	2.640	15.838	59
FOWT36b	837.6	Soft Clay	Suction Pile	3.087	18.524	68
FOWT36c	947.3	Soft Clay	Suction Pile	3.206	19.236	70
FOWT37b	708.0	Medium Clay	Suction Pile	2.401	14.407	54
FOWT37c	**655.1**	**Rock**	**D&G Pile**	**1.065**	**6.237**	**28**
FOWT38b	879.3	Soft Clay	Suction Pile	2.901	17.407	64
FOWT38c	679.8	Medium Clay	Suction Pile	2.361	14.165	54
FOWT39b	653.8	Medium Clay	Suction Pile	2.372	14.232	54
FOWT39c	827.8	Soft Clay	Suction Pile	2.903	17.417	64
FOWT40b	687.8	Medium Clay	Suction Pile	2.389	14.335	54
FOWT40c	614.8	Medium Clay	Suction Pile	2.314	13.884	53

Appendix I. Morro Bay Shared Anchor Design Details

Table I-1. Shared Anchor Designs for the Morro Bay Standardized Design

Orange shading represents shared anchors; bold text represents D&G anchors

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT1a-9b	1039.9	Soft Clay	Suction Pile	2.675	16.049	53
FOWT1b-9a	1040.6	Soft Clay	Suction Pile	2.675	16.053	58
FOWT1c	1054.1	Soft Clay	Suction Pile	2.675	16.050	58
FOWT1d	1054.9	Soft Clay	Suction Pile	2.673	16.037	53
FOWT1e	1043.0	Soft Clay	Suction Pile	2.683	16.095	58
FOWT1f	1041.5	Soft Clay	Suction Pile	2.680	16.078	53
FOWT2a-10b	1009.4	Soft Clay	Suction Pile	2.635	15.811	53
FOWT2b-10a	1010.1	Soft Clay	Suction Pile	2.643	15.860	53
FOWT2c	1038.4	Soft Clay	Suction Pile	2.659	15.955	49
FOWT2d	1038.4	Soft Clay	Suction Pile	2.656	15.938	58
FOWT2e	1005.3	Soft Clay	Suction Pile	2.648	15.888	58
FOWT2f	1004.7	Soft Clay	Suction Pile	2.647	15.880	53
FOWT3a-11b	997.7	Medium Clay	Suction Pile	2.182	13.094	33
FOWT3b-11a	997.7	Medium Clay	Suction Pile	2.184	13.105	35
FOWT3c	1006.6	Soft Clay	Suction Pile	2.627	15.759	58
FOWT3d	1006.4	Soft Clay	Suction Pile	2.624	15.743	53
FOWT3e	991.3	Medium Clay	Suction Pile	2.191	13.144	35
FOWT3f	991.1	Medium Clay	Suction Pile	2.190	13.139	33
FOWT4a-12b	1005.0	Soft Clay	Suction Pile	2.631	15.784	58
FOWT4b-12a	1004.9	Soft Clay	Suction Pile	2.638	15.827	53
FOWT4c	995.8	Medium Clay	Suction Pile	2.181	13.087	35
FOWT4d	995.6	Medium Clay	Suction Pile	2.179	13.074	34
FOWT4e	991.3	Medium Clay	Suction Pile	2.191	13.144	34
FOWT4f	991.9	Medium Clay	Suction Pile	2.190	13.143	35
FOWT5a-13b	1020.4	Soft Clay	Suction Pile	2.655	15.928	53
FOWT5b-13a	1020.3	Soft Clay	Suction Pile	2.654	15.926	53
FOWT5c	998.6	Medium Clay	Suction Pile	2.183	13.100	53
FOWT5d	997.6	Medium Clay	Suction Pile	2.181	13.084	33
FOWT5e	1018.2	Soft Clay	Suction Pile	2.660	15.961	53
FOWT5f	1017.5	Soft Clay	Suction Pile	2.658	15.948	53
FOWT6a-14b	1036.4	Soft Clay	Suction Pile	2.671	16.027	50

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT6b-14a	1035.4	Soft Clay	Suction Pile	2.670	16.019	53
FOWT6c	1014.1	Soft Clay	Suction Pile	2.634	15.806	49
FOWT6d	1013.5	Soft Clay	Suction Pile	2.631	15.787	58
FOWT6e	1042.2	Soft Clay	Suction Pile	2.682	16.091	53
FOWT6f	1042.9	Soft Clay	Suction Pile	2.681	16.084	58
FOWT7a-15b	1078.9	Soft Clay	Suction Pile	2.715	16.289	50
FOWT7b-15a	1077.0	Soft Clay	Suction Pile	2.713	16.278	53
FOWT7c	1036.4	Soft Clay	Suction Pile	2.657	15.943	53
FOWT7d	1036.2	Soft Clay	Suction Pile	2.654	15.924	53
FOWT7e	1102.9	Soft Clay	Suction Pile	2.735	16.411	59
FOWT7f	1103.8	Soft Clay	Suction Pile	2.734	16.404	54
FOWT8a-16b	1132.3	Soft Clay	Suction Pile	2.768	16.609	54
FOWT8b-16a	1129.4	Soft Clay	Suction Pile	2.762	16.569	59
FOWT8c	1091.3	Soft Clay	Suction Pile	2.712	16.271	54
FOWT8d	1092.4	Soft Clay	Suction Pile	2.710	16.259	58
FOWT8e	1170.4	Soft Clay	Suction Pile	2.793	16.756	59
FOWT8f	1172.7	Soft Clay	Suction Pile	2.792	16.750	54
FOWT9c	1012.1	Soft Clay	Suction Pile	2.504	15.026	55
FOWT9d	1012.0	Soft Clay	Suction Pile	2.516	15.096	55
FOWT9e-17f	1027.6	Soft Clay	Suction Pile	2.675	16.049	50
FOWT9f-17e	1028.3	Soft Clay	Suction Pile	2.675	16.050	55
FOWT10c	999.5	Medium Clay	Suction Pile	2.072	12.433	55
FOWT10d	999.5	Medium Clay	Suction Pile	2.088	12.531	50
FOWT10e-18f	1007.6	Soft Clay	Suction Pile	2.655	15.929	50
FOWT10f-18e	1008.4	Soft Clay	Suction Pile	2.657	15.940	47
FOWT11c	1005.4	Soft Clay	Suction Pile	2.499	14.996	50
FOWT11d	1005.4	Soft Clay	Suction Pile	2.508	15.045	55
FOWT11e-19f	999.3	Medium Clay	Suction Pile	2.202	13.211	55
FOWT11f-19e	999.2	Medium Clay	Suction Pile	2.203	13.216	46
FOWT12c	1018.2	Soft Clay	Suction Pile	2.509	15.051	55
FOWT12d	1018.0	Soft Clay	Suction Pile	2.523	15.135	50
FOWT12e-20f	1005.7	Soft Clay	Suction Pile	2.653	15.917	50
FOWT12f-20e	1005.4	Soft Clay	Suction Pile	2.654	15.922	50
FOWT13c	1036.7	Soft Clay	Suction Pile	2.522	15.134	50
FOWT13d	1036.7	Soft Clay	Suction Pile	2.545	15.271	50

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT13e-21f	1018.3	Soft Clay	Suction Pile	2.666	15.993	55
FOWT13f-21e	1017.8	Soft Clay	Suction Pile	2.666	15.998	55
FOWT14c	1068.4	Soft Clay	Suction Pile	2.545	15.270	51
FOWT14d	1068.1	Soft Clay	Suction Pile	2.585	15.507	50
FOWT14e-22f	1039.0	Soft Clay	Suction Pile	2.686	16.117	50
FOWT14f-22e	1038.1	Soft Clay	Suction Pile	2.685	16.108	50
FOWT15c	1113.4	Soft Clay	Suction Pile	2.576	15.457	51
FOWT15d	1113.0	Soft Clay	Suction Pile	2.633	15.800	47
FOWT15e-23f	1072.0	Soft Clay	Suction Pile	2.719	16.314	55
FOWT15f-23e	1070.7	Soft Clay	Suction Pile	2.715	16.292	55
FOWT16c	1151.9	Soft Clay	Suction Pile	2.602	15.615	55
FOWT16d	1151.7	Soft Clay	Suction Pile	2.688	16.129	51
FOWT16e-24f	1116.0	Soft Clay	Suction Pile	2.762	16.572	51
FOWT16f-24e	1114.6	Soft Clay	Suction Pile	2.763	16.577	55
FOWT17a-25b	1005.5	Soft Clay	Suction Pile	2.631	15.787	53
FOWT17b-25a	1005.2	Soft Clay	Suction Pile	2.638	15.829	49
FOWT17c	1020.7	Soft Clay	Suction Pile	2.641	15.847	53
FOWT17d	1021.5	Soft Clay	Suction Pile	2.639	15.835	53
FOWT18a-26b	995.5	Medium Clay	Suction Pile	2.181	13.084	37
FOWT18b-26a	995.6	Medium Clay	Suction Pile	2.183	13.095	37
FOWT18c	1015.6	Soft Clay	Suction Pile	2.636	15.816	53
FOWT18d	1016.7	Soft Clay	Suction Pile	2.634	15.806	58
FOWT19a-27b	993.3	Medium Clay	Suction Pile	2.179	13.074	36
FOWT19b-27a	993.0	Medium Clay	Suction Pile	2.180	13.082	33
FOWT19c	1001.0	Soft Clay	Suction Pile	2.621	15.725	35
FOWT19d	1001.5	Soft Clay	Suction Pile	2.619	15.713	58
FOWT20a-28b	1002.0	Soft Clay	Suction Pile	2.628	15.766	53
FOWT20b-28a	1001.5	Soft Clay	Suction Pile	2.634	15.805	58
FOWT20c	997.3	Medium Clay	Suction Pile	2.182	13.094	36
FOWT20d	997.5	Medium Clay	Suction Pile	2.181	13.083	35
FOWT21a-29b	1016.8	Soft Clay	Suction Pile	2.642	15.855	53
FOWT21b-29a	1016.1	Soft Clay	Suction Pile	2.650	15.898	49
FOWT21c	1006.2	Soft Clay	Suction Pile	2.626	15.757	53
FOWT21d	1006.4	Soft Clay	Suction Pile	2.624	15.743	49
FOWT22a-30b	1038.9	Soft Clay	Suction Pile	2.674	16.043	58

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT22b-30a	1038.0	Soft Clay	Suction Pile	2.673	16.036	53
FOWT22c	1019.7	Soft Clay	Suction Pile	2.640	15.841	58
FOWT22d	1019.7	Soft Clay	Suction Pile	2.637	15.824	53
FOWT23a-31b	1068.5	Soft Clay	Suction Pile	2.704	16.226	53
FOWT23b-31a	1067.3	Soft Clay	Suction Pile	2.703	16.218	50
FOWT23c	1042.1	Soft Clay	Suction Pile	2.663	15.977	53
FOWT23d	1042.0	Soft Clay	Suction Pile	2.660	15.959	53
FOWT24a-32b	1103.8	Soft Clay	Suction Pile	2.740	16.439	58
FOWT24b-32a	1102.3	Soft Clay	Suction Pile	2.739	16.432	54
FOWT24c	1073.9	Soft Clay	Suction Pile	2.695	16.168	53
FOWT24d	1074.1	Soft Clay	Suction Pile	2.692	16.151	58
FOWT25c	988.9	Medium Clay	Suction Pile	2.066	12.397	33
FOWT25d	988.2	Medium Clay	Suction Pile	2.071	12.426	34
FOWT25e-33f	983.1	Medium Clay	Suction Pile	2.189	13.131	31
FOWT25f-33e	983.5	Medium Clay	Suction Pile	2.190	13.140	31
FOWT26c	988.0	Medium Clay	Suction Pile	2.065	12.391	32
FOWT26d	987.8	Medium Clay	Suction Pile	2.071	12.423	33
FOWT26e-34f	981.5	Medium Clay	Suction Pile	2.187	13.124	34
FOWT26f-34e	981.8	Medium Clay	Suction Pile	2.189	13.132	32
FOWT27c	996.9	Medium Clay	Suction Pile	2.071	12.424	33
FOWT27d	996.6	Medium Clay	Suction Pile	2.083	12.500	33
FOWT27e-35f	984.0	Medium Clay	Suction Pile	2.189	13.136	34
FOWT27f-35e	984.0	Medium Clay	Suction Pile	2.190	13.142	34
FOWT28c	1011.4	Soft Clay	Suction Pile	2.504	15.022	55
FOWT28d	1011.0	Soft Clay	Suction Pile	2.514	15.084	50
FOWT28e-36f	993.3	Medium Clay	Suction Pile	2.197	13.180	31
FOWT28f-36e	992.9	Medium Clay	Suction Pile	2.198	13.185	32
FOWT29c	1034.3	Soft Clay	Suction Pile	2.521	15.124	50
FOWT29d	1034.2	Soft Clay	Suction Pile	2.542	15.251	47
FOWT29e-37f	1011.3	Soft Clay	Suction Pile	2.659	15.951	50
FOWT29f-37e	1010.6	Soft Clay	Suction Pile	2.659	15.954	50
FOWT30c	1061.5	Soft Clay	Suction Pile	2.540	15.239	55
FOWT30d	1061.5	Soft Clay	Suction Pile	2.576	15.457	50
FOWT30e-38f	1036.7	Soft Clay	Suction Pile	2.684	16.104	50
FOWT30f-38e	1035.9	Soft Clay	Suction Pile	2.682	16.095	55

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT31c	1095.2	Soft Clay	Suction Pile	2.564	15.381	55
FOWT31d	1095.0	Soft Clay	Suction Pile	2.620	15.718	51
FOWT31e-39f	1063.9	Soft Clay	Suction Pile	2.711	16.266	50
FOWT31f-39e	1062.9	Soft Clay	Suction Pile	2.712	16.271	55
FOWT32c	1147.1	Soft Clay	Suction Pile	2.599	15.595	51
FOWT32d	1147.1	Soft Clay	Suction Pile	2.681	16.087	51
FOWT32e-40f	1099.0	Soft Clay	Suction Pile	2.745	16.473	55
FOWT32f-40e	1097.5	Soft Clay	Suction Pile	2.746	16.477	50
FOWT33a	967.0	Medium Clay	Suction Pile	2.168	13.009	33
FOWT33b	966.6	Medium Clay	Suction Pile	2.167	13.004	36
FOWT33c	976.7	Medium Clay	Suction Pile	2.166	12.993	34
FOWT33d	977.4	Medium Clay	Suction Pile	2.164	12.985	34
FOWT34a	967.6	Medium Clay	Suction Pile	2.169	13.012	34
FOWT34b	967.2	Medium Clay	Suction Pile	2.168	13.009	34
FOWT34c	973.4	Medium Clay	Suction Pile	2.163	12.977	33
FOWT34d	974.1	Medium Clay	Suction Pile	2.162	12.969	34
FOWT35a	973.2	Medium Clay	Suction Pile	2.173	13.039	33
FOWT35b	972.6	Medium Clay	Suction Pile	2.172	13.033	34
FOWT35c	974.3	Medium Clay	Suction Pile	2.164	12.981	36
FOWT35d	974.8	Medium Clay	Suction Pile	2.162	12.973	33
FOWT36a	983.9	Medium Clay	Suction Pile	2.181	13.086	35
FOWT36b	983.1	Medium Clay	Suction Pile	2.180	13.080	35
FOWT36c	979.4	Medium Clay	Suction Pile	2.168	13.007	34
FOWT36d	979.9	Medium Clay	Suction Pile	2.166	12.998	33
FOWT37a	1003.7	Soft Clay	Suction Pile	2.638	15.826	53
FOWT37b	1002.7	Soft Clay	Suction Pile	2.637	15.822	58
FOWT37c	990.8	Medium Clay	Suction Pile	2.177	13.062	36
FOWT37d	991.2	Medium Clay	Suction Pile	2.175	13.053	33
FOWT38a	1028.7	Soft Clay	Suction Pile	2.661	15.963	50
FOWT38b	1027.6	Soft Clay	Suction Pile	2.660	15.961	53
FOWT38c	1011.0	Soft Clay	Suction Pile	2.631	15.787	58
FOWT38d	1011.3	Soft Clay	Suction Pile	2.629	15.773	53
FOWT39a	1057.4	Soft Clay	Suction Pile	2.686	16.119	53
FOWT39b	1056.1	Soft Clay	Suction Pile	2.686	16.118	53
FOWT39c	1036.1	Soft Clay	Suction Pile	2.657	15.941	58

Anchor ID	Depth (m)	Soil Type (-)	Type (-)	Diameter (m)	Length (m)	Thickness (mm)
FOWT39d	1036.5	Soft Clay	Suction Pile	2.654	15.926	58
FOWT40a	1092.0	Soft Clay	Suction Pile	2.717	16.302	58
FOWT40b	1090.5	Soft Clay	Suction Pile	2.717	16.304	54
FOWT40c	1065.0	Soft Clay	Suction Pile	2.686	16.116	50
FOWT40d	1065.4	Soft Clay	Suction Pile	2.683	16.100	60