PacWave Anchoring and Mooring Study

Stein Housner and Senu Sirnivas

National Renewable Energy Laboratory

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List of Acronyms

CALM	catenary anchor leg mooring
DEA	drag embedment anchor
kN	kilonewton
m	meter
mm	millimeter
MW	megawatt
NREL	National Renewable Energy Laboratory
OWC	oscillating water column
PNNL	Pacific Northwest National Laboratory
s	second
t	ton
SPM	single-point mooring
WEC	wave energy converter

Executive Summary

PacWave, a marine energy test facility off the coast of Oregon in the United States, is set to test various sizes and shapes of wave energy converters (WECs) over the next couple of years. The facility has energetic waters, subsea power cables, and on-land infrastructure ready to use for WEC developers wanting to test their devices. However, WEC developers do not always have mooring system components designed or acquired for device stationkeeping during testing, and PacWave does not own any mooring system components for developers to use. The challenge addressed in this report is to determine the best method of acquiring mooring system components for WECs expected to be tested at PacWave.

Not all WECs tested at PacWave will be of the same design; some may be similar in shape and function but may not be the same between developers. This means that the most cost-effective mooring system design for one WEC may not satisfy design criteria for another WEC. Therefore, other than designing and acquiring specific mooring system components for each WEC that is tested at PacWave, which can be expensive, mooring system components at PacWave can be designed to support a wide range of WEC sizes and functions while still satisfying all mooring design criteria at an affordable price. This report details the design process and potential acquisition costs of general mooring system components to be used at PacWave. A series of assumptions are initially defined that are used in the mooring design process, such as the expected types of WECs to be deployed at PacWave, the most common types of mooring system configurations, and the most common types of mooring line configurations. It is also assumed that the designed mooring systems would be temporary mooring systems, so that they could be repeatedly installed and uninstalled, rather than permanent mooring systems, which would remain installed on-site.

These assumptions, as well as the PacWave environmental conditions and other modeling assumptions, are used to design 43 different mooring systems consisting of various line configurations, layout orientations, and footprint sizes to serve two general styles of WECs. Each mooring line design has its line diameters, line lengths, and intermediate point masses or volumes sized to meet mooring design criteria and minimize cost. The results provide a wide range of mooring system designs that could potentially be used for various types of WECs deployed at PacWave, but a determination of specific mooring designs to be acquired was not made. However, a set of "acquisition scenarios" are detailed to provide a sense of the overall cost to acquire certain quantities of mooring system components.

Using these results, it is initially recommended that the most cost-effective mooring acquisition scenario would be for PacWave to purchase and retain the mooring system components used for the first few devices that are tested at PacWave from the developers, rather than purchase a predetermined set of components, as outlined in this report. This way, PacWave can slowly compile reliable and proven mooring system designs that can be reconfigured for future deployments.

Table of Contents

List of Figures

List of Tables

1 Introduction

PacWave, with its location off the coast of Oregon in some of the most energetic waters in the nation and a buildout to support grid-connected devices, is poised to become a leader in field testing wave energy converters (WECs) at high technology readiness levels. As part of the device deployment and testing protocols at PacWave, the client is responsible for providing all mooring system components because there are currently no mooring system components specified for PacWave (Oregon State University 2021). The National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory (PNNL) have been tasked with conducting a preliminary analysis of permanent or temporary mooring systems at the PacWave South site. Previous work for this task included a global trade study of mooring systems used for WECs (Cavagnaro and Sirnivas 2022) and a site characterization of PacWave South (Sirnivas et al. 2021). The current report will use the results of the previous studies to inform the design of various mooring system configurations that could be used at PacWave, and the costs of acquiring these general mooring system components can be compared to the costs of mooring systems designed specifically for client devices.

For optimal performance and power output, each WEC tested at PacWave would ideally have its own mooring system tailored to its individual design and function. However, this can be difficult and expensive if the device is to be tested for a short period of time because the cost of the mooring system contributes significantly to the total cost of a WEC (Whittaker and Folley 2005; Xu, Wang, and Guedes Soares 2019). Permanent mooring systems, which are mooring systems permanently installed on-site with the ability to easily attach and detach to and from devices, can be used to avoid the costs of acquiring specific mooring components for individual devices. A mooring strength and fatigue analysis on a permanent mooring system at the U.S. Navy Wave Energy Test Site in Hawaii found that all mooring components met line tension and fatigue design criteria when connected to a WEC (DNV GL 2019). However, when no WEC device is attached to the mooring system, these permanently installed components were at a high risk of damage and failure due to potential fatigue of the mooring system components.

One solution to mitigate the risks of permanent mooring systems is to have a stock of general, standardized mooring system components at a PacWave facility that clients can preselect and temporarily install for testing their specific device. When testing is completed, they can recover and return the mooring system components back to PacWave. For the purposes of this report, this temporary mooring system solution is the assumed deployment style for mooring systems at PacWave. The objectives of this report are to (1) determine the types and sizes of mooring system components that could be used to effectively moor the expected devices that will be tested at PacWave and (2) provide cost estimates for acquiring the mooring system components.

2 Background

The trade study (Cavagnaro and Sirnivas 2022) that was performed as part of this task documented the mooring and anchoring systems of WECs that were deployed at various wave energy test sites between 2003 and 2022. Most of the deployments were in water depths between 30 and 70 meters (m) with mostly sandy seabeds. Point absorbers are the most common type of WEC deployed, with a majority of WECs having three-point mooring systems in a variety of configurations (catenary, semi-taut, or taut), and primarily being anchored by either deadweight (gravity) or drag embedment anchors (DEAs). Another key finding and recommendation of the trade study was that standard mooring components should not be permanently installed in standard configurations because mooring system designs are highly dependent on the device function.

Over the years, many archetypes of WECs have been developed to extract wave energy in different ways, and there has not been a distinctive convergence on an optimal design type. Most WECs can be categorized as one of the following: point absorbers, overtopping (or terminator) devices, oscillating water columns (OWCs), attenuators, oscillating wave surge devices, submerged pressure differential devices, or rotating mass devices (Xu, Wang, and Guedes Soares 2019; Qiao et al. 2020; Sound & Sea Technology Engineering Solutions 2009; Tethys Engineering undated; Esteban, Lopez-Gutierrez, and Negro 2017; The Liquid Grid undated). Point absorbers use the vertical motion of a floating body in response to the change in wave elevation to extract energy. Overtopping devices create an upper reservoir of water to use the difference in water level and potential energy to extract energy. OWCs extract energy through the pressure differential in a water column as waves cause the water level to rise and fall in the column. Attenuators are floating bodies parallel to the wave direction that typically use the motion of flexible joints in response to changes in wave elevation to extract energy. Oscillating wave surge devices extract energy from the oscillatory motion of a flap about a pivoted joint in response to surge motion in the waves. Pressure differential devices, which can be submerged or semi-submerged, use the pressure differential fluctuations as waves pass by the device to extract energy. Rotating mass devices have an internal mass that rotates about a rotational alternator in response to wave motions to extract energy. These devices can be deployed onshore, nearshore, or offshore, but this analysis will only consider offshore WECs for PacWave. Figure 1 depicts some of the most common types of WECs studied and their differences in size, shape, and function.

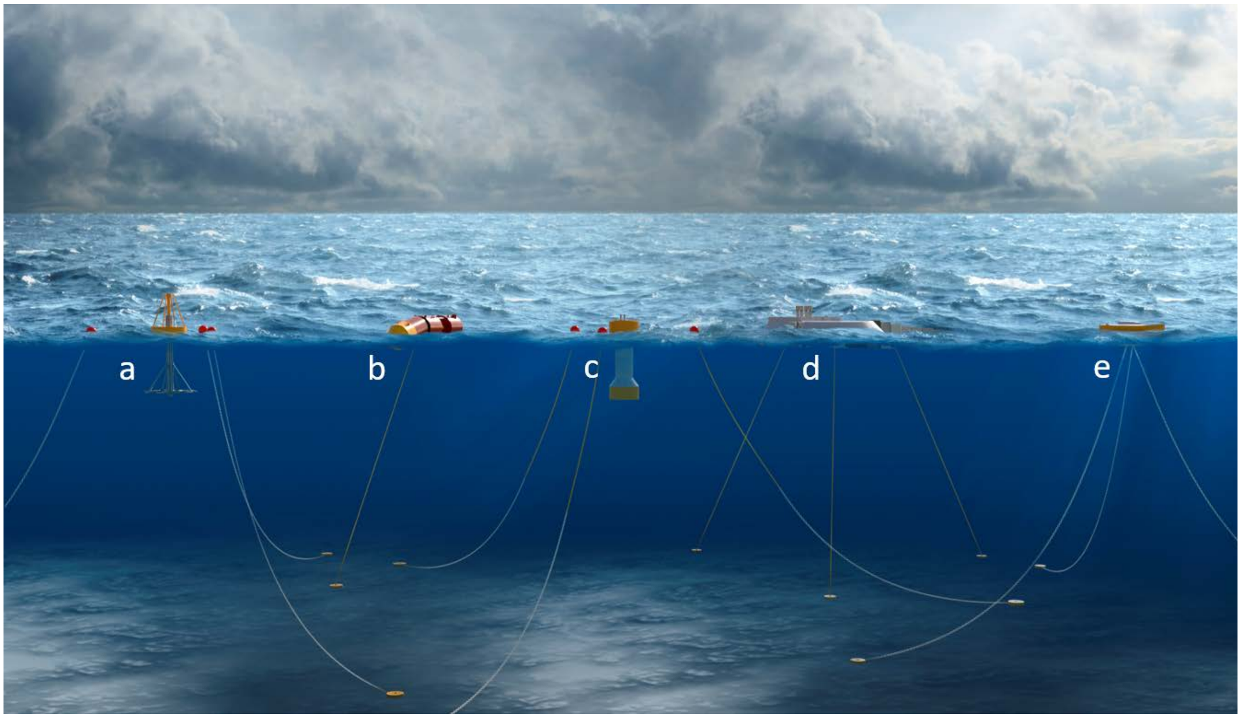


Figure 1. Common WEC topologies and illustrative mooring system designs: (a) point absorber, (b) attenuator, (c) floating OWC, (d) overtopping device, and (e) rotating internal mass WEC.
Graphic by Josh Bauer, NREL

Mooring systems can also be designed in a variety of configurations and styles. In general, there are two styles of mooring systems: spread mooring systems (used by WECs in Figure 1a, c, d) and single-point mooring (SPM) systems (used by WECs in Figure 1b, e). Spread mooring configurations typically consist of three or four mooring lines encircling the floating device with either catenary, semi-taut, or taut moorings. The term "catenary" refers to a relatively slack mooring that achieves compliance through the line's weight, typically made of chain (like in Figure 1a, e), "taut" refers to a tensioned mooring line that achieves compliance through the line's elasticity, typically made of synthetic rope (like in Figure 1b, d), and "semi-taut" refers to a mooring line that achieves compliance through a combination of the line's weight and elasticity, typically made of a portion of chain near the anchor and synthetic rope near the fairlead (like in Figure 1c). SPM systems typically consist of a single attachment point to the device that allows the device to weathervane. Common types of SPM systems include turret mooring systems (like Figure 1e), where the device is allowed to swivel about the attachment point and can be moored by any number of mooring lines; catenary anchor leg mooring (CALM) systems, where a floating buoy is moored to the seabed by catenary mooring lines and attaches to the WEC at a single point by a separate mooring line, called a hawser mooring; and single anchor leg mooring (SALM) systems, where a floating buoy is moored to the seabed by a single mooring line (similar to the individual lines of Figure 1a, c) and also attaches to the WEC at a single point by a hawser mooring. The SPM system of Figure 1b is a simple taut mooring system that connects the device to the seabed using only one line, like a single anchor leg mooring system, but attaches directly to the WEC, like a turret system.

Mooring lines can be designed with a number of line types, such as chain, wire rope, or synthetic rope, and can be anchored by various types of anchors, such as deadweight (gravity) anchors, DEAs, suction piles, or plate anchors. They can also include any number of mooring connectors, clump weights, or buoyancy modules, in any combination of line types, to effectively moor a WEC (Xu, Wang, and Guedes Soares 2019; Harris, Johanning, and Wolfram 2006; Qiao et al. 2020; Sound & Sea Technology Engineering Solutions 2009). In this report, the term "weight-float" refers to a line configuration with a clump weight nearest to the anchor and a buoyancy float nearest the fairlead, and the term "float-weight" refers to a line configuration with a buoyancy float nearest the anchor and a clump weight nearest the fairlead.

Each type of WEC is only compatible with certain mooring configurations. This mooring analysis will generalize the types of WECs expected to be deployed at PacWave and specify assumptions on the likely mooring systems used for each WEC to determine the sizes, types, and costs of the mooring system components required.

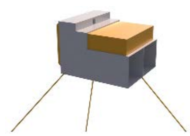
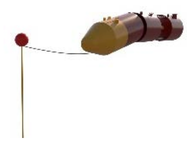
3 Methods

To determine the required sizes and types of mooring system components for WEC deployments at PacWave, a set of assumptions is detailed to narrow the scope of potential mooring system designs. These assumptions are classified as system, modeling, cost, or berthing assumptions.

3.1 System Assumptions

Future WECs and mooring systems at PacWave have the potential to be designed in a number of styles. Using data from the global WEC trade study (Cavagnaro and Sirnivas 2022), as well as other sources (e.g., Xu, Wang, and Guedes Soares 2019; Oregon State University 2019), the most likely WECs to be deployed at PacWave are point absorbers, OWCs, and attenuators. Point absorbers and attenuators can be moored by either a spread mooring system or a single point mooring system, but OWCs are typically only moored by spread mooring systems. Spread mooring systems and SPM systems, like CALMs, can have any number of attached mooring lines in various orientations around the WEC, but most use three or four mooring attachments. Each attachment can be of a different line configuration or length, but this analysis will assume all mooring lines in a system are identical and that each mooring attachment only has one anchor. The mooring lines can be designed in many different line configurations, such as catenary moorings, semi-taut moorings, or taut moorings. The mooring lines can also have various types of anchors and consist of various types of synthetic or wire rope, but for simplicity, this analysis will assume that all anchors will be either DEAs or deadweight (gravity) anchors and all rope in a line configuration will be polyester. The assumed WEC types and mooring system descriptions used in this report are tabulated in Table 1, and they will be designed for the PacWave environment and have their component acquisition costs compared.

Table 1. WEC Types and Mooring Configurations Used for PacWave Sizing Analysis

	Point Absorber		OWC	Attenuator	
Mooring Configuration	Spread 	SPM 	Spread 	Spread 	SPM 
Number of Lines	3–4	1	3–4	3–4	1
Layouts					
Line Configuration 1	Catenary	Taut	Catenary	Catenary	Taut
Line Configuration 2	Semi-taut	Taut float	Semi-taut	Semi-taut	Taut float
Line Configuration 3	Semi-taut weight-float	Semi-taut float-weight	Semi-taut weight-float	Semi-taut weight-float	Semi-taut float-weight
Anchor Type	DEA	Deadweight	DEA	DEA	Deadweight
Reference Model	RM3		RM6	None	

As stated before, point absorbers and attenuators can be moored by either spread mooring systems or single point mooring systems, but OWCs are typically larger WECs that are only moored by spread mooring systems. The images of each WEC in Table 1 are not representative of all WECs of that type and are only used as illustrations. For example, the specific point absorber WEC shown would likely not be well suited for a single taut SPM system, but other types of point absorbers might be well suited for those types of SPM systems. The mooring line for the point absorber SPM system is assumed to attach directly to the WEC, the mooring line for the attenuator SPM system is assumed to attach directly to a buoy, which has another line to attach to the WEC, and the mooring lines for the attenuator spread system is assumed to work for both a spread mooring system and a SPM turret system.

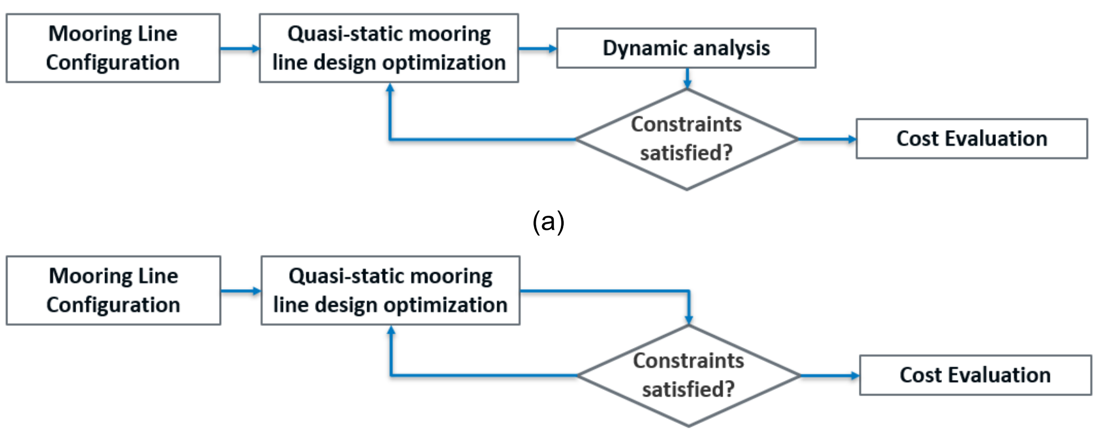
The spread mooring configurations can be designed for two layout configurations: one with three mooring lines, and one with four mooring lines, each with lines attached at evenly spaced intervals around the device. The orientation of the three mooring line configuration is assumed to have mooring lines at 0°, 120°, and 240° (referred to as 60° headings), and the orientation of the four mooring line configuration is assumed to have mooring lines at 45°, 135°, 225°, and 315°

(referred to as 45° headings), where 0° is aligned with the positive surge axis downstream and a positive angle is defined as counterclockwise. These orientations were chosen because they require larger sizes of mooring lines compared to offset orientations (e.g., 60°, 180°, and 300° mooring lines) with the primary load direction traveling left to right, which increases the mooring systems' likelihood of effectiveness for the expected WECs at PacWave.

These mooring configuration assumptions are based on the mooring configurations for the point absorber Reference Model 3 (Neary et al. 2014) and the OWC Reference Model 6 (Bull et al. 2014) and were selected because their designs are likely to support most other types of WECs and mooring configurations expected to be deployed at PacWave.

3.2 Modeling Assumptions

The primary modeling assumption in this analysis involves the level of fidelity used in the design process. The typical mooring system design process (IEC 2021), reframed in Figure 2a, starts by adjusting the mooring line parameters using a quasi-static tool, feeding those parameters into a dynamic simulation tool, and checking the dynamic outputs to determine if all constraints are satisfied. Due to the time constraints and logistics of this project, the mooring system design process used for this analysis bypasses the dynamic simulation check and only checks mooring constraints in the quasi-static design stage (Figure 2b). Even though it has been studied that quasi-static analyses for mooring systems for WECs can underpredict mooring sizes by up to 50% (Thomsen et al. 2017), it was determined that full dynamics simulation checks were out of scope, and that the quasi-static constraint limits can be adjusted to overcompensate.



(a)

(b)

Figure 2. (a) Common mooring system design process and (b) the mooring design process used for this PacWave mooring analysis

The quasi-static design tool used for this sizing analysis uses the MoorPy framework (Hall et al. 2021) and optimizes the mooring line parameters to minimize the cost of the mooring system while satisfying all relevant physical constraints. Minimizing the mooring system cost generally assumes minimizing the mooring system component sizes, but many conservative assumptions were taken to overestimate the sizes of the components to ensure they would be feasible for multiple WEC designs and to account for the lack of dynamics in the design process.

In this analysis, mooring lines are parameterized by their anchor spacing, line lengths, line diameters, and intermediate point weights and volumes, if applicable. Physical constraints for this analysis include a maximum horizontal offset, a minimum seabed lay length (to ensure no vertical uplift forces on DEAs), a ratio of minimum breaking load to maximum tension safety factor, and a maximum rope depth (to avoid rope contact with the seabed). In this analysis, the maximum mean horizontal offset of a device is assumed to be 20 m, the minimum seabed lay length is assumed to be 20 m, and the ratio of minimum breaking load to maximum tension safety factor is increased from 2.0 in the standards (American Petroleum Institute 2005) to 2.5 to account for the lack of a dynamic constraint check.

These constraint values are primarily dictated by the extreme environmental sea state. The quasi-static tool represents the extreme motions of the device in response to the extreme environmental sea state by a mean horizontal offset and a dynamic horizontal offset about the mean offset. The dynamic horizontal offset is difficult to determine without running a dynamic simulation but is conservatively estimated as 10 m for each device. The extreme sea state parameters (based on the site characterization study [Sirnivas et al. 2021] and other PacWave resource assessments [Dunkle et al. 2020]) are listed in Table 2. The primary direction that waves travel at PacWave is from west to east (Dunkle et al. 2020).

Table 2. Extreme Sea State Parameters of the PacWave Site

Environmental Parameter	Value
Water Depth (m)	70
Extreme Wave Height H_s (m)	13.5
Extreme Wave Period T_p (seconds [s])	19.8
Extreme Current Speed v (m/s)	1.0

One of the inputs to the design tool that varies between the different WECs is the expected horizontal force on the floating body, which influences the offset of the device, which affects the mooring design. The quasi-static design tool can ensure that the offset of the WEC stays within its offset limits based on the expected horizontal force on the floating body and the opposing horizontal force of the mooring lines. In this analysis, the expected horizontal force on the floating body, F_H, is assumed to be a combination of the drag force on the body and the mean viscous drift force (which is estimated for irregular waves in Hall and Goupee [2015]), given by the following equation:

$$F_H = \frac{1}{2}\rho C_d A v|v| + \frac{\pi \rho C_d D {H_s}^3}{3{T_p}^2}$$

The first term in the equation is the drag force, and the second term is the assumed mean viscous drift force. C_d is the drag coefficient on the body, A is the cross-sectional area of the body, D is the diameter of the body, and ρ is the density of the water. These values may vary between the different devices, which will cause the optimal mooring line parameters to change between devices. Drag coefficients are a function of several other parameters like the full body geometry and the Reynold's number, but common object drag coefficients similar to the device shapes are assumed for this analysis. The cross-sectional area (A) is calculated as the area perpendicular to the dominant wave direction, and the equivalent diameter (D) of the WEC is estimated as based on its waterplane area. The assumed parameters for the expected horizontal force on each body are given in Table 3.

Table 3. Horizontal Force Parameters for Each Type of WEC

	Point Absorber	OWC	Attenuator
Drag Coefficient C_d (-)	0.42	1.05	0.295
Cross-Sectional Area A (m^2)	228	472.5	12.6
Equivalent Diameter D (m)	6	34.7	30.3
Horizontal Force F_H (kilonewton [kN])	66	500	62

Larger WECs like OWCs will require larger mooring system component sizes relative to smaller WECs like point absorbers due to the larger applied environmental forces (even though they will have the same maximum horizontal offset assumptions). The estimated horizontal forces applied to point absorbers and attenuators are relatively close in magnitude, meaning that mooring systems designed for point absorbers will likely be similar to ones designed for attenuators. Therefore, separate mooring system designs for attenuators will not be completed and the designs for point absorbers are assumed to also work for attenuators. All of these modeling parameters and constraints are then used as inputs to the quasi-static design tool to design cost-optimized mooring systems for the set of assumed mooring configurations and WEC types detailed in Table 1.

3.3 Cost Assumptions

The cost of each mooring system component is calculated using the following equations, derived from correspondence with offshore oil and gas industry per their recommendations:

$$cost_{chain} = \$51{,}440/\text{m}^3 \times d^2$$

$$cost_{polyester} = \$2{,}810/\text{m}^3 \times d^2$$

$$cost_{DEA} = \left(\$0.188/\text{kg} \times \frac{F_{anchor}}{\text{g}}\right) \times 1.5$$

$$cost_{deadweight/concrete} = \left(\sqrt{\left(1.6 \times \frac{F_h}{g}\right)^2 + \left(2.0 \times \frac{F_v}{g}\right)^2}\right) \times \$0.075/\text{kg}$$

$$cost_{clump/float} = (m + \rho V) \times \$1.0/\text{kg}$$

where d is the mooring line diameter in m, F_{anchor} is the magnitude of the anchor tension in newtons (N), F_h is the horizontal anchor tension (N), F_v is the vertical anchor tension (N), g is gravity (m/s^2), ρ is the density of the water in kilograms per cubic meter (kg/m^3), and m and V are the mass (kg) and volume (m^3) of a clump weight or buoyancy float, respectively. The chain and polyester rope costs are given in dollars per meter of line length after being multiplied by the squared line diameter, the DEA and deadweight anchor costs are given in dollars after being multiplied by the tension of load on the anchor, and the clump/float cost is given in dollars after being multiplied by the mass or displacement of the clump weight or buoyancy module.

The safety factors of 1.5 for DEAs and 1.6 and 2.0 for deadweight anchors are based on design standards (American Petroleum Institute 2005) but use the permanent mooring value rather than the temporary mooring value to overestimate and account for the lack of a dynamic simulation check. Other system costs, such as installation and operations and maintenance costs, are not included in this analysis because this report is only focused on the cost of acquiring mooring system components.

3.4 Berthing Assumptions

There are four testing berths at PacWave South, each with an east-west length of 1,850 m and a north-south length of 925 m (Oregon State University 2021). It is assumed that anchors for a device deployed in one berth cannot be installed across that berth's boundary into another berth, and it is assumed that mooring systems are to be designed completely symmetrical from all angles. These assumptions and berth dimensions limit the maximum anchor spacing of mooring lines for spread mooring systems. For devices deployed on the centerline of a berth, the berth dimensions create an anchor spacing limit of 530 m for mooring systems with 60° headings, and an anchor spacing limit of 650 m for mooring systems with 45° headings (Figure 3), using layout orientations based on the assumptions made in Table 1 and the primary wave propagation direction at PacWave (west to east). These assumptions also prevent the mooring design process from designing systems with very large footprints, which reduces the number of potential mooring system solutions and allows for a higher number of WECs to be deployed simultaneously.

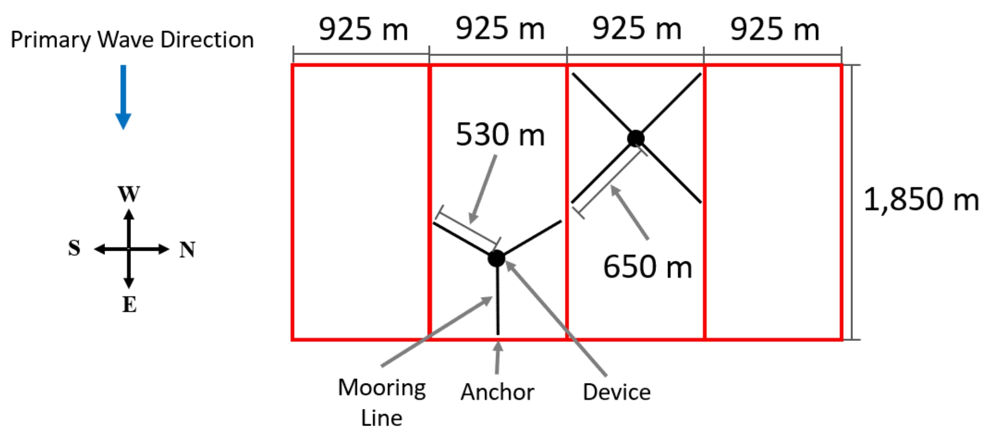


Figure 3. PacWave berth dimensions and their limitations on mooring system anchor spacings

The spacing of WECs and mooring systems within the four berths at PacWave affect how many mooring systems can be installed at one time, which influences how many total mooring systems should be acquired. In their initial documentation (Oregon State University 2019), PacWave preliminarily determines the total number of WECs that can be deployed based on the rated capacities of expected WECs and the maximum capacity of the subsea cables, which is 20 megawatts (MW). They detail an initial development scenario (Figure 4a), which has one WEC and mooring system per berth, and a full build-out scenario (Figure 4b), which has five WECs and mooring systems per berth for a total of 20 systems (Oregon State University 2019). This report will use this information to assume that no more than 20 mooring systems would be deployed at PacWave at a given time. However, the total number and cost of each type of mooring system to be acquired will be difficult to determine under the assumption that clients will have a wide range of mooring system sizes and configurations to choose from.

(a)

(b)

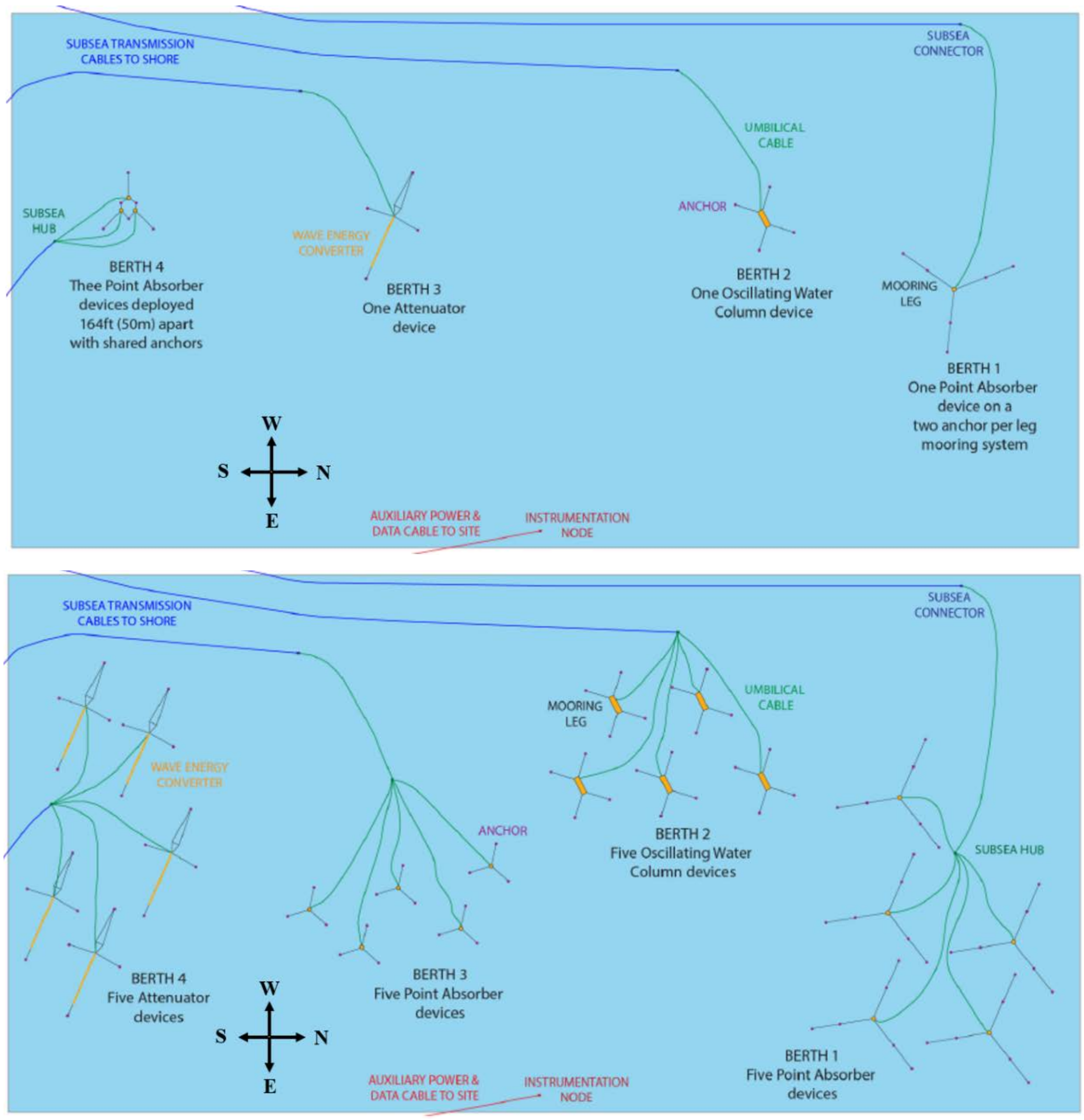


Figure 4. PacWave (a) initial development scenario and (b) full build-out scenario.

Graphics from Oregon State University (2019)

This analysis also assumes that each device will have its own individual moorings and there will be no farm-level array testing, which would have the potential to use shared moorings and/or shared anchors.

4 Results

The following sections detail the results using all the assumptions described above. The spread mooring system designs are presented first, followed by the SPM systems. An image is given for each line configuration, with the WEC in its maximum offset position, its minimum offset position, and its equilibrium position. Each WEC mooring configuration was also designed to accommodate different mooring system footprint sizes, as either “small” (S), “medium” (M), or “large” (L) sizes, if clients wanted to use smaller or larger mooring footprints. Different sizes of the spread mooring systems can also be applied to multi-leg SPM systems like CALMs, if necessary. Each of these mooring system designs were determined to effectively moor the majority of expected WEC designs and mooring systems to be deployed at PacWave.

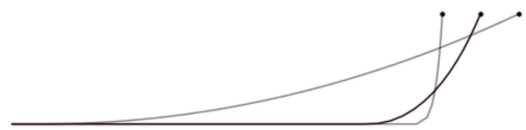
Following the mooring system design and cost results, approximations and suggestions are presented for the total cost of mooring system components at PacWave. The total number of each mooring system type to be acquired cannot be accurately determined at this time if clients are given the option to select different mooring system sizes and configurations. However, to compare design and cost results, a set of acquisition “packages” are presented as potential solutions for total numbers (and costs) of mooring systems to acquire, but it should be noted that these are not definitive solutions and could be subject to change.

4.1 Spread Mooring System Designs

Using the spread mooring system designs listed in Table 1, three line configurations were designed for two mooring layout configurations for three footprint sizes for three WECs, but the mooring systems designed for point absorbers are assumed to also work for attenuators, given the similar applied environmental force on the devices. Tables 4–6 give the anchor spacings, line lengths, line diameters, and clump or float weights for the three different line configurations for spread mooring systems. All anchors for spread mooring systems are assumed to be DEAs.

4.1.1 Catenary

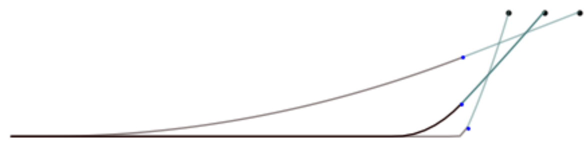
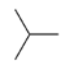
Table 4. Catenary Line Configuration Designs for Two WECs and Two Layout Configurations

WEC	Point Absorber OR Attenuator						OWC					
Line Configuration	Catenary 											
Number of Lines	3			4			3			4		
Layout												
Size	S	M	L	S	M	L	S	M	L	S	M	L
Anchor Spacing (m)	150	300	530	150	400	650	300	400	530	300	500	650
Chain Length (m)	195	331	552	199	429	670	331	426	552	334	525	670
Chain Diameter (millimeters [mm])	99	71	51	76	46	31	195	168	140	148	110	89
Line Cost ($k; k = thousand)	99	85	73	60	47	34	645	615	552	377	329	272
Anchor Cost ($k)	11	19	30	6.5	14	17	145	188	227	86	128	131
Total Material Cost ($k)	329	312	308	265	245	205	2,372	2,410	2,334	1,854	1,830	1,612

In general, larger catenary mooring systems have longer line lengths and smaller chain diameters because these designs are optimized to minimize cost, and the diameter of chain primarily contributes to the total cost of the line. However, the smaller chain diameters and longer line lengths increase tension on the anchors, which increases the size and cost of the required anchors. Referencing the bottom row of Table 4, the total cost of mooring systems with 45° headings varies more between the different footprint sizes than the total cost of mooring systems with 60° headings. Also, the total costs of mooring systems for OWCs are almost an order of magnitude higher than the total costs of mooring systems for point absorbers or attenuators due to the increased environmental load on the WEC (see Section 3.2) that the moorings have to resist.

4.1.2 Semi-Taut

Table 5. Semi-Taut Line Configuration Designs for Two WECs and Two Layout Configurations

WEC	Point Absorber OR Attenuator						OWC					
Line Configuration	Semi-taut 											
Number of Lines		3			4			3			4	
Layout												
Size	S	M	L	S	M	L	S	M	L	S	M	L
Anchor Spacing (m)	300	400	530	300	500	650	-	450	530	-	500	650
Chain Length (m)	248	335	446	259	433	575	-	380	451	-	431	567
Chain Diameter (mm)	73	52	49	58	33	30	-	128	108	-	90	64
Rope Length (m)	75	82	97	69	83	89	-	86	93	-	85	95
Rope Diameter (mm)	119	87	142	126	68	131	-	241	237	-	188	174
Line Cost ($k)	71	48	61	48	25	51	-	335	284	-	187	128
Anchor Cost ($k)	19	17	28	12	11	15	-	131	129	-	81	70
Total Material Cost ($k)	269	197	265	239	141	184	-	1,400	1,239	-	1,070	791

Again, for semi-taut line configurations, the chain diameter (and amount of chain) is the main contributor to the total mooring system cost, relative to the polyester rope length and diameter. The mooring systems with smaller footprints were sized with anchor spacings of 300 m, as opposed to 150 m in the catenary mooring systems, because any smaller mooring system would not be able to meet all constraints of the design process. The mooring systems for OWCs could only have a minimum anchor spacing of 450 m and 500 m for 60° and 45° line headings, respectively, because any smaller mooring lines would also not be able to effectively withstand the large applied environmental force on OWCs. For point absorbers and attenuators, it was found that the medium mooring designs have lower total costs due to both lower required chain diameters and lower anchor tensions. For OWCs, the large mooring designs have lower total costs than the medium mooring designs.

4.1.3 Semi-Taut Weight-Float

Table 6. Semi-Taut Weight-Float Line Configuration Designs for Two WECs and Two Layout Configurations

WEC	Point Absorber OR Attenuator						OWC					
Line Configuration	Semi-taut weight-float 											
Number of Lines	3			4			3			4		
Layout												
Size	S	M	L	S	M	L	S	M	L	S	M	L
Anchor Spacing (m)	100	300	530	100	300	650	100	300	530	100	300	650
Chain Length (m)	65	150	180	70	150	180	65	150	220	65	170	240
Chain Diameter (mm)	100	115	150	100	115	100	200	260	150	200	180	100
Clump Weight (tons [t])	30	10	5	30	10	5	160	125	0	160	80	3
Rope 1 Length (mm)	65	90	265	60	90	380	67	90	200	65	75	264
Rope Diameter (m)	150	200	250	200	200	200	300	350	250	300	235	220
Float Buoyancy (t)	−60	−30	−10	−60	−30	−10	−175	−150	−30	−175	−80	−10
Rope 2 Length (m)	30	80	80	30	80	80	25	75	110	25	70	140
Line Cost ($k)	39	121	269	46	121	144	157	578	309	157	306	178
Clump / Float Cost ($k)	114	52	19	114	52	19	405	335	42	405	202	17
Anchor Cost ($k)	5.7	28	136	4.6	26	80	35	210	130	31	117	97
Total Material Cost ($k)	477	602	1,271	659	798	1,155	1,791	3,372	1,443	2,370	2,458	1,170

Semi-taut weight-float line configurations were able to have all three footprint sizes of mooring systems designed for both point absorbers and WECs to meet all physical constraints, including not allowing the clump weight to contact the seabed. There are fewer clear trends in the chain and rope line properties than the other line configurations, other than the fact that line lengths increase proportionally with the anchor spacings. The most notable design trend is the required weight and buoyancy of the clump weights and floats. The clump weights connecting the bottom chain to the first polyester rope section need to be higher for smaller mooring designs but can be lighter as anchor spacing increases. The buoyancy floats connecting the two polyester rope sections also need to be much larger (more buoyant) in smaller mooring designs but can be smaller as anchor spacing increases. This is likely due to the difference in design-driving constraints in each size of mooring system. The mooring line tension constraint is the primary constraint in the larger mooring designs, whereas the lay length and rope contact constraints are the primary constraints in the smaller mooring designs.

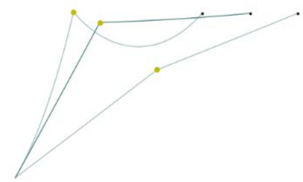
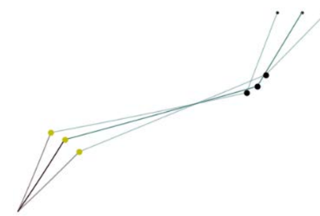
For the smaller mooring systems, the primary cost contributor is the cost of the clump weights and buoyancy floats. For larger mooring systems, the primary cost contributor is the line cost. For point absorbers and attenuators, the line costs increase as anchor spacing increases, which is a direct result of the chain diameter size, and the anchor costs also increase as anchor spacing increases. For OWCs, the most expensive designs are the medium mooring designs due to the larger required chain diameters for these designs, the larger anchor tensions, and the significant size of the clump weights and floats.

Between the three mooring line configuration designs, the semi-taut weight-float designs had much larger costs than the semi-taut or the catenary line configurations, especially for the larger footprint designs. The addition of clump weights or buoyancy modules can sometimes alleviate mooring line diameter or length requirements and manage the mooring line tensions, but the environment and set of design constraints used in this analysis for this line configuration resulted in more expensive components to meet the design criteria. A line configuration with a suction pile instead of a DEA, for example, would eliminate the minimum seabed lay length requirement and likely reduce the chain diameter and length, reducing line costs, but could also potentially increase the maximum tension on the anchor, increasing anchor costs. Investigating other line configurations with adjusted design constraints could result in more comparable designs to the catenary or semi-taut line designs.

4.2 Single-Point Mooring Designs

Using the SPM designs listed in Table 1, three line configurations were designed for two WECs, point absorbers and attenuators, but the mooring systems designed for point absorbers are assumed to also work for attenuators, given the similar applied environmental force on the devices. Table 7 gives the anchor spacings, line lengths, line diameters, and clump or float weights for the three different line configurations for SPM systems. All anchors for SPM systems are assumed to be deadweight (gravity) anchors.

Table 7. SPM System Designs With Three Line Configurations for One WEC

WEC	**Point Absorber OR Attenuator**								
Line Configuration	Taut			Taut float			Semi-taut float-weight		
Number of Lines		1			1			1	
Orientation									
Size	S	M	L	S	M	L	S	M	L
Anchor Spacing (m)	0	0	0	40	100	250	100	200	300
Chain Length (m)	-	-	-	-	-	-	30	40	50
Chain Diameter (mm)	-	-	-	-	-	-	50	60	75
Clump/Float Weight/Buoyancy (t)	-	-	-	-	-	-	−10	−12.5	−15
Rope 1 Length (m)	67	67	67	33	75	122	70	125	200
Rope 1 Diameter (mm)	176	287	409	143	141	147	100	100	100
Clump/Float Weight/Buoyancy (t)	-	-	-	0	−7.5	3.5	10	7.5	5
Rope 2 Length (m)	-	-	-	40	64	127	30	55	70
Rope 2 Diameter (mm)	-	-	-	144	144	141	100	100	100
Line Cost ($k)	5.9	16	31	4.2	7.9	14	6.7	12	22
Clump/Float Cost ($k)	-	-	-	0	10.4	3.7	24	25	26
Anchor Cost ($k)	38	94	188	23	4.1	2.9	3.7	2.3	2.2
Total Material Cost ($k)	44	110	219	27	22	21	34	40	50

The three SPM systems include a single taut-line polyester rope, a single taut rope with a float in the middle, and a semi-taut float-weight line configuration. The taut line configuration was designed in three sizes, where each size had a larger rope diameter, which increased the anchor sizes and total costs. The taut float configuration had varying designs between the different footprint sizes. The small mooring design, with only an anchor spacing of 40 m, does not require any weight or buoyancy at the point between the two polyester ropes, and the line diameters are similar, meaning that a single taut polyester line would also work for this mooring system. The medium mooring design with an anchor spacing of 100 m computed 7.5 tons of buoyancy at the point between the two polyester ropes, whereas the large mooring design computed 3.5 tons of weight at the point between the two polyester ropes. These weights and buoyancies of this intermediate point were found to minimize the overall cost of the system while meeting all constraints. In general, the anchor costs and total costs of the taut float mooring systems decrease as anchor spacing increases.

For the semi-taut float-weight configurations, the three footprint sizes had similar shapes, with the main differences being the small increase in float buoyancy and the small decrease in clump weight as anchor spacing increases. The anchor costs are relatively similar among the three footprint sizes, but there is still a trend that the total mooring system cost increases as the anchor spacing increases.

4.3 Mooring Layouts and Total Costs

The exact total cost of mooring system components to be acquired for PacWave testing cannot be accurately determined in this report. The total cost is a function of the number and types of WECs and mooring systems expected to be deployed at PacWave, which should be determined by the decision makers who arrange device testing and who would be acquiring the mooring system components. However, this section will suggest some potential solutions for acquiring sets of mooring system components.

The 43 different mooring system designs detailed in this section offer a wide range of mooring options for PacWave clients to test their device. However, it is unknown if one developer would want the same mooring system design as another developer, so there is still a question of how many of each mooring system would need to be acquired. The berthing assumption that only a maximum of 20 WECs and mooring systems can be deployed at PacWave simultaneously can potentially allow for 20 of the same mooring system to be deployed at the same time or can allow 20 different mooring systems to be deployed at one time. This makes the exact number of each mooring system to acquire difficult to determine since it would depend on the individual WECs and the specific mooring plans of the PacWave clients. The following subsections list potential solutions for narrowing down the mooring system possibilities into example acquisition scenarios.

4.3.1 Baseline Acquisition

The baseline acquisition would acquire four basic mooring systems, one for each berth at PacWave, with the assumption that only one WEC would be tested per berth at a time. The four mooring configurations that would likely encompass the widest range of WEC possibilities, while remaining cost-effective, are:

- One medium, three-line, catenary configuration for point absorbers
- One medium, four-line, semi-taut configuration for OWCs
- One small, three-line, semi-taut weight-float configuration for point absorbers
- One medium, SPM, taut float configuration for attenuators.

These four mooring configurations can serve as a baseline package of mooring system components and are similar to the initial development scenario detailed in Figure 4a. The combined acquisition costs of the four mooring systems total $1.9 million. A depiction of these mooring systems to scale in the PacWave berths is shown in Figure 5.

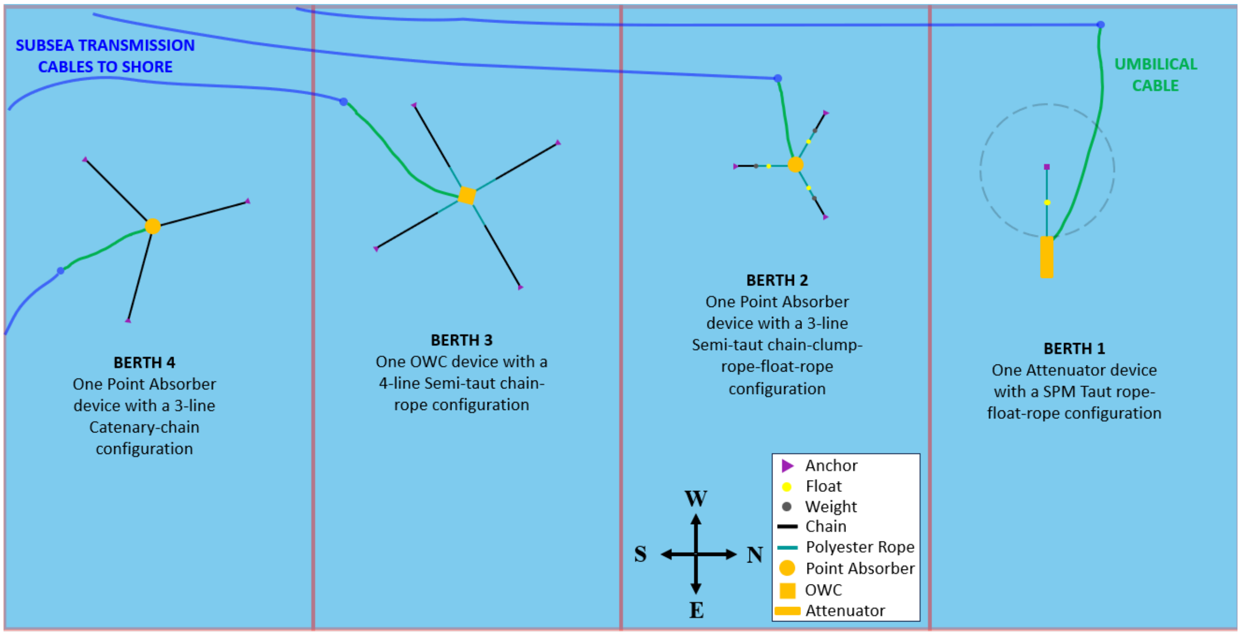


Figure 5. Example PacWave berth configuration using four different mooring configurations with one mooring system per berth

4.3.2 Standard Acquisition

The standard acquisition would acquire the maximum 20 mooring systems, five for each berth at PacWave, so that there are no mooring components left in stock when all 20 WECs are deployed. This acquisition would be similar to the full build-out scenario in Figure 4b. The same four mooring configurations that were used in the baseline acquisition package will also be assumed in the standard acquisition package due to their overall adaptability to the WECs expected to be deployed at PacWave:

- Five medium, three-line, catenary configurations for point absorbers
- Five medium, four-line, semi-taut configurations for OWCs
- Five small, three-line, semi-taut weight-float configurations for point absorbers
- Five medium, SPM, taut float configurations for attenuator.

These 20 mooring configurations can serve as a standard package of mooring system components. The combined acquisition costs of the four sets of five mooring systems total $9.4 million. A depiction of these mooring systems to scale in the PacWave berths is shown in Figure 6.

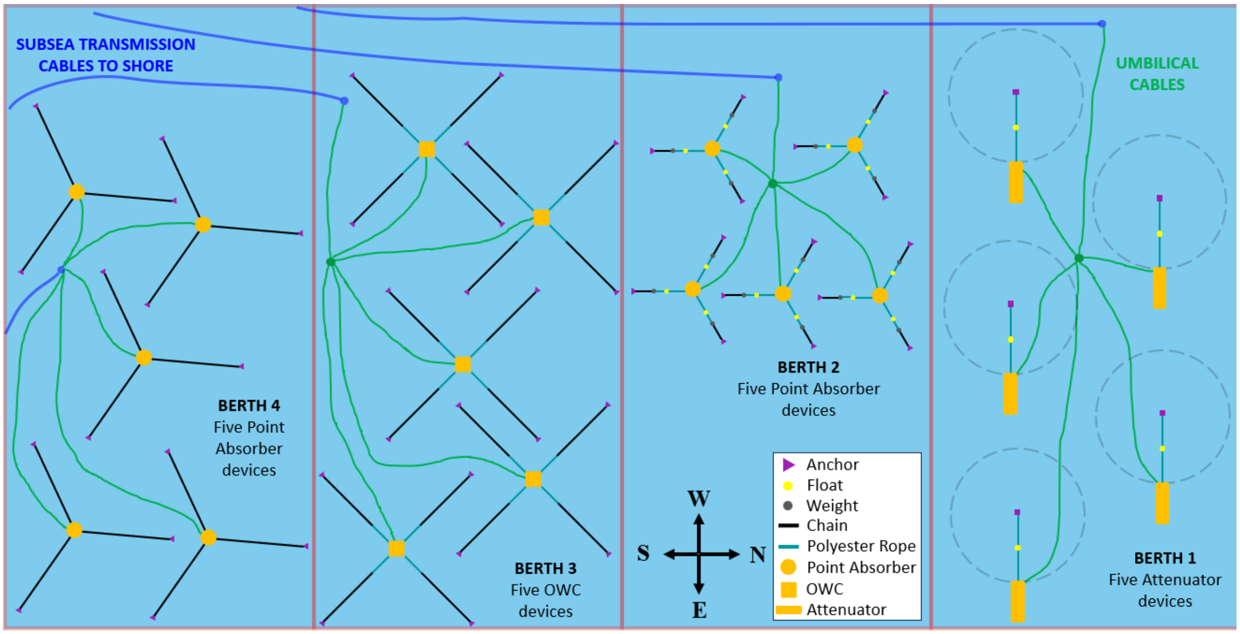


Figure 6. Example PacWave berth configuration using four different mooring configurations with five mooring systems per berth

4.3.3 Lavish Acquisition

The lavish acquisition would ensure that at least one of all 43 mooring designs are available at PacWave to offer clients a wide range of mooring system options. This solution would not necessarily be economically practical, especially in the earlier stages of device testing, but can offer a sense of scale of the cost to include a wide range of mooring system options.

All mooring systems that were designed (except for the large spread mooring systems) have small enough footprints to allow for the maximum of 20 of each mooring system to be deployed at PacWave at a given time. Based on the anchor spacings of the large spread mooring systems, only a maximum of eight large spread mooring systems (two per berth) can be deployed at one time. However, it would be impractical and extremely costly to acquire 20 of each small and medium mooring system with the justification that all 20 of one mooring configuration could be used at one time.

Using the preliminary size estimates of Figure 4b as a guide, the anchor spacings of all the mooring designs, and the consideration to keep WECs close to the subsea cable connection points, the lavish acquisition will assume that there would only need to be a maximum of five mooring systems for each small and medium spread mooring system and a maximum of two mooring systems for each large spread mooring system. For SPMs, there will also be a maximum of five mooring systems for all footprint sizes, since their anchor spacings are not that large relatively. Also, the taut SPM designs have no anchor spacing, which means that there could theoretically be many more taut SPM configurations, but the lavish acquisition will assume there will only be five of these configurations acquired, like the rest of the designs.

With these assumptions, the total number of mooring configurations to be acquired for the lavish acquisition is 179 (134 spread moorings, 45 SPMs). Based on the full build-out assumption of only having 20 mooring systems deployed at one time, this leaves a minimum of 159 mooring systems that would have to be stored at a PacWave facility. However, this would give clients a wide range of mooring system options to choose from, which could provide useful mooring comparisons for their devices. The combined acquisition costs of all 179 configurations sum to $154 million. A detailed table of the summation of each mooring system cost is provided in Appendix A. A depiction of these mooring systems is not provided given the high number of possibilities of mooring system designs in the PacWave berths.

5 Conclusions and Recommendations

After performing a global trade study of mooring systems for WECs and a site characterization study for PacWave South, an analysis of the design and cost of mooring systems for PacWave South was completed. Many assumptions were made to quantify mooring system costs. Three WECs (point absorbers, OWCs, and attenuators) were assumed to represent the majority of devices expected to be deployed at PacWave, each with multiple styles of potential mooring systems, including spread mooring systems and SPM systems of different footprint sizes, layout configurations, and line configurations. A quasi-static design process was used without any dynamic simulations due to project timeline constraints to design various mooring systems while minimizing the overall cost of the system and satisfying all physical constraints. The applied environmental force on each WEC was roughly estimated, and it was found that the assumed point absorbers and assumed attenuators had similar applied forces, meaning that mooring designs for point absorbers would also work for attenuators. Cost estimates for mooring line materials, anchor sizes, and other mooring components were used to calculate the total cost of each mooring system, and the total number and cost of each mooring system could be estimated based on PacWave berth dimension limitations and an assumed maximum number of WECs deployed.

This design process resulted in 43 separate mooring designs (34 spread moorings and 9 SPMs) that could effectively moor either point absorbers, OWCs, or attenuators. In general, the semi-taut spread mooring designs offered the lowest cost options relative to the catenary or semi-taut weight-float designs, and the taut-float SPM designs offered the lowest cost options among the SPM designs. Varying amounts of the mooring systems were organized into acquisition "packages" to provide options for the total number of mooring system types to acquire for future PacWave deployments. These options, however, should not be taken literally and should only be used to guide and inform decision makers on the relative costs of acquiring various mooring system components.

Given the current uncertainty of the number and types of WECs that will be tested at PacWave, it is initially recommended that PacWave purchase and retain the mooring system components used for testing of the first few devices at PacWave from the developers, rather than purchase an example acquisition package as detailed in this report. This way, they can slowly compile a set of reliable and proven mooring system components that can be configured for future deployments. However, conservative component sizes should be used to also work for other WEC types.

This analysis assumed that temporary moorings would be more reliable and cost-effective than permanent moorings. A separate study could be done to determine which style of moorings would be more cost-effective based on fatigue and installation considerations. Also, this analysis used the approach of specifically designing each individual mooring component for a given WEC and mooring configuration. Another approach would have been to preselect more general mooring system components (e.g., 75-mm, 100-mm, or 125-mm chain) and size the other mooring system properties to meet all the design constraints. Costs would likely be of the same order of magnitude, but there could be cost savings in bulk acquisitions or installation procedures. Lastly, shared moorings and shared anchors for WEC arrays were not considered in this study but have potential to introduce even more cost savings and could be used to avoid the constraints on anchors and mooring lines crossing PacWave berth boundaries.

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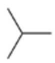
Appendix A. Lavish Acquisition Example Cost Table

Table A- 1. Spread Mooring Design Costs

WEC	**Point Absorber OR Attenuator**						**OWC**					
Number of Lines		3			4			3			4	
Orientation												
Size	S	M	L	S	M	L	S	M	L	S	M	L
Line Configuration: **Spread – Catenary**												
System Cost ($k)	329	312	308	265	245	205	2,372	2,410	2,334	1,854	1,830	1,612
# Systems	5	5	2	5	5	2	5	5	2	5	5	2
Total Cost ($M; M = million)	1.6	1.6	0.6	1.3	1.2	0.4	11.9	12.1	4.7	9.3	9.2	3.2
												57.0
Line Configuration: **Spread – Semi-taut**												
System Cost ($k)	269	197	265	239	141	184	-	1,400	1,239	-	1,070	791
# Systems	5	5	2	5	5	2	-	5	2	-	5	2
Total Cost ($M)	1.3	1.0	0.5	1.2	0.7	0.4	-	7.0	2.5	-	5.4	1.6
												21.5
Line Configuration: **Spread – Semi-taut weight-float**												
System Cost ($k)	477	602	1,271	659	798	1,155	1,791	3,372	1,443	2,370	2,458	1,170
# Systems	5	5	2	5	5	2	5	5	2	5	5	2
Total Cost ($M)	2.4	3.0	2.5	3.3	4.0	2.3	9.0	16.9	2.9	11.9	12.3	2.3
												72.7

SPM System Design Costs

Line Config.		**Taut**			**Taut float**			**Semi-taut float-weight**	
Size	S	M	L	S	M	L	S	M	L
System Cost ($k)	44	110	219	27	22	21	34	40	50
# Systems	5	5	5	5	5	5	5	5	5
Total Cost ($M)	0.22	0.05	1.1	0.14	0.11	0.11	0.17	0.20	0.25
									2.8
						Total Acquisition Cost ($M):			**154.0**