PNNL-27988

Pacific Northwest NATIONAL LABORATORY

Humpback Whale Encounter with Offshore Wind Mooring Lines and Inter-Array Cables

Final Report

October 2018

A Copping
M Grear

This report is available from the Bureau of Ocean Energy Management by referencing OCS Study BOEM 2018-065. The report may be downloaded from BOEM's Recently Completed Environmental Studies – Pacific web page at http://www.boem.gov/Pacific-Completed-Studies/.

BOEM Bureau of Ocean Energy Management

Prepared for the **Bureau of Ocean Energy Management** under an Interagency Agreement with the U.S. Department of Energy
CONTRACT DE-AC05-76RL01830

U.S. DEPARTMENT OF ENERGY

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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OCS Study BOEM 2018-065

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

Floating offshore wind farms have been proposed in the deep waters off the U.S. west coast and Hawaii to provide renewable energy to coastal populations. Anchoring floating wind platforms to the seabed requires multiple mooring lines that pass through the water column from platforms at the surface to the sea floor. Electrical cables also will be draped in the water column between wind platforms. Concerns have been raised that large cetaceans might encounter lines from an offshore wind array, potentially causing harm, including entanglement, to the whales. There are few floating offshore wind arrays anywhere in the world where this encounter can be tested and no completely appropriate industrial analogues that can be applied. Understanding this potential risk to whales requires other means of visualizing the likelihood and mechanisms of encounter. An animation has been developed as a method for communicating this potential risk. This report provides the information used to create an animation of humpback whales encountering mooring lines and inter-array cables from a hypothetical floating offshore wind farm.

Acronyms and Abbreviations

3D	three dimensional
BOEM	Bureau of Ocean Energy Management
HMPE	High Modulus PolyEthylene (material used for mooring lines)
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
MW	Megawatts
m	meters
rpm	rotations per minute
s	seconds

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1.0 Introduction

Floating offshore wind farms have been proposed in the deep waters off the U.S. west coast and Hawaii to provide renewable energy to coastal populations. Anchoring floating wind platforms to the seabed requires multiple mooring lines that pass through the water column from platforms at the surface to the sea floor. Electrical cables will also be draped in the water column between wind platforms. Concerns have been raised that large cetaceans might encounter lines from an offshore wind array, potentially causing harm, including entanglement, to the whales from the encounter. There are few floating offshore wind arrays anywhere in the world where this encounter can be tested, and no completely appropriate industrial analogues that can be applied. Understanding this potential risk to whales requires other means of visualizing the likelihood and mechanisms of encounter. An animation has been developed as a method for communicating this potential risk. This report provides the information used to create the animation of humpback whales encountering mooring lines and inter-array cables from a hypothetical floating offshore wind farm.

The Bureau of Ocean Energy Management (BOEM) Pacific Region asked the U.S. Department of Energy through Pacific Northwest National Laboratory (PNNL), to provide visualizations and input to scenarios that describe potential encounters of a humpback whale adult-calf pair with mooring lines and inter-array cables from a floating offshore wind farm. To inform the animation of the humpback whales (*Megaptera novaeangliae*) encountering an offshore wind farm, it was necessary to collect data that describe the physical attributes of the animals and their swimming and diving behavior in the vicinity of a floating offshore wind farm. A literature review was undertaken to collect whale morphometrics and behavior data to drive the encounter scenarios between a humpback whale adult-calf pair with an offshore wind farm. BOEM Pacific staff provided a description and parameters associated with a hypothetical offshore wind farm.

2.0 Literature Review of Humpback Whale Parameters

The literature review to collect appropriate whale data was conducted using published literature sources and online databases. While the animation is directed at humpback whale populations off the shores of California and Hawaii, it was assumed that worldwide population behavior would not differ significantly. Hence, the literature review was expanded to include morphometric and behavior data from humpbacks worldwide.

Creating realistic scenarios requires the input of several parameters, loosely described as morphometric and behavioral. These parameters include body length, pectoral fin length, body width, and fluke length for adults and for calves (morphometric); humpback behavior while diving, traveling, or foraging for the adult and for the adult-calf pair (behavioral); and dive depths, lengths, and time between breathing for adult and adult-calf pair (behavioral).

2.1 Morphometrics

Appendix A details the morphometric data for adult humpbacks and calves. The greatest collection of morphometric data was gleaned from Woodward et al. (2006) who attempted to create an "average whale." Their report amasses data from several species of baleen whales, and provides the most comprehensive overview of the range of humpback sizes. The average whale is a combination of male and female measurements (Woodward et al. 2006), for which there is no significant difference in fluke or flipper dimensions. Winn and Rechiley (1985) reported that females are a bit longer (12.09 m) compared to males (11.58 m).

The population associated with each set of morphometric data was noted, with a particular focus on the populations that travel between Alaska and Hawaii and those that travel between California and Costa Rica or Mexico. Because of the overall small sample sizes, the number of animals measured in each study was recorded as an approximate measure of data quality.

It is clear from the calf morphometrics that the population of humpbacks off the Hawaiian coast may be different than those migrating past California. Humpbacks give birth in warm breeding grounds in Hawaii or Central America (Mexico/Costa Rica); this results in the California coast calves gaining weight over a longer period of time, which results in slightly larger calves than those born in Hawaii. Because the best available data are generally from the Hawaii population, the calf measurements used are largely from neonates. Growth curves from Chittleborough (1965) indicate that three year old humpbacks typically attain at least 80% of their adult size. Because humpback whales grow quickly and can double in length during the first year, it was assumed that a calf migrating off the coast of California would be approximately half the length of the adult.
For the purposes of the animation, BOEM and PNNL determined that the largest cross-section (and perhaps the most at risk for entangelment) configuration of humpback whales would be an adult female and calf pair. Using values drawn from the scientific literature, a generic adult female and a generic calf whale of approximate weaning size were created as input to the animation. The data are summarized in

Table 1. The full data sets are available in Appendix A: Morphometric Data (Table A.1 through Table A.6)

Table 1. Averaged Morphometric Data Used for Animated Encounter Scenarios

	Measurement		Measurement
Adult Female Length	13.18 m	Calf Length[a]	6.59 m
Adult Female Girth[b]	9.85 m	Calf Girth[b]	4.92 m
Adult Female Fluke Length[c]	4.44 m	Calf Fluke Length[c]	2.22 m
Adult Female Flipper Length[d]	4.06 m	Calf Flipper Length[d]	2.03 m

(a) Calculated as half the adult length
(b) Calculated as girth = 0.747 × length, at the axilla.
(c) Calculated as Fluke Span Length = 0.337 × Length.
(d) Calculated as Flipper Length = 0.308 × Length.

2.2 Behavior

The behavioral parameters required for the animation included general observations of behavior, as well as dive speeds, dive depths, dive times, traveling speeds, and foraging speeds. The behavior of humpback whales can vary based on many factors, including the social context (i.e., traveling or socializing with a group or with a calf) and the environmental context (i.e., wind speed or water depth) (Kavanaugh et al. 2017). It should be noted that all diving speeds were associated with adult whale foraging. During foraging, adult whales have been observed to dive down, rapidly change speed, lunge for prey at a fairly constant depth, and return to the surface (Goldbogen et al. 2008). Assessing accurate dive times is challenging because there is a bimodal distribution of times based on the number of breaths each whale takes at the surface and the type of behavior in which they are engaged (The Marine Mammal Center 2017; Goldbogen et al. 2008). Aggregated dive/foraging times and other parameters are summarized in Table 2. The detailed behavioral data for adult humpbacks and calves can be found in Appendix B: Behavioral Data (Table B.1 through Table B.).

Table 2. Averaged Measurements of Adult Humpback Whale Behaviors

Behavior	Measurement
Dive Speed	2.0 m/s
Maximum Dive Depth	132 m
Dive Duration	6.34 min
Foraging Speed	2.5 m/s
Traveling Speed	3.81 km/hr

3.0 Humpback Whale Model

A three dimensional (3D) conceptual whale model was created based on the morphometrics collected from the literature. The whale model was created in the 3D open source modeling software Blender[1] using the box modeling technique, as a simple animated shape. Every dimension of the whale, including the girth or width of the fin, was based on data gathered during the literature review. Pictures and videos of humpback whales were used to better understand the movement of the whales and to augment the data collected. Color and texture were then applied to the model to develop a more realistic representation of a humpback whale (Figure 1).

Figure 1. Humpback Whale Model Based on Literature Review Dimensions

After the simple whale model was created, it was "rigged." Rigging allows the model to be articulated, allowing the whale model to bend and distort as a real whale might. The rigging tracks the general location of the humpback whale model's spine, allowing caudal oscillation, which constitutes the whale's typical swimming mode. Additional articulated "bones" were added to enable the whale mouth to open and the fins to move (Figure 2). At every node shown in Figure 2, the whale can be moved and rotated, allowing for different movements and changes in aspect in the animation.

The calf model was created by scaling the full sized (adult) model to one-half size.

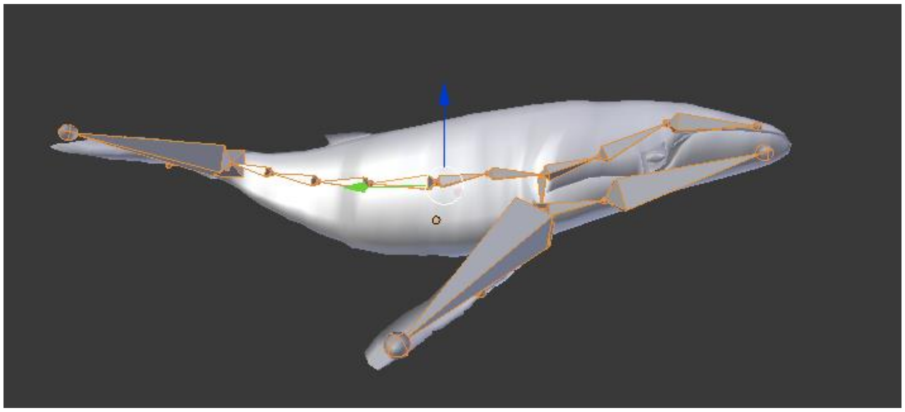

Figure 2. Humpback Whale Model with Rigging Highlighted in Orange

[1] https://www.blender.org

4.0 Floating Wind Farm Parameters and Model

The description and characteristics for the animated hypothetical floating offshore wind farm were provided by BOEM, based on an amalgam of information from unsolicited wind energy lease requests, an existing floating wind installation (i.e., Hywind Scotland Pilot Park), industry input, and design expert knowledge. The wind farm parameters for the animation were chosen based upon reasonable estimates and assumptions. The description and characteristics of the wind farm can be found in Appendix C.

Building on the descriptions and characteristics of the floating wind array, an initial representation was created in AutoCAD. The turbines, floating platform dimensions, depth profile, and cable design were created from the data provided to PNNL by BOEM. The AutoCAD drawings of the scene can be found in Appendix C: Wind Array Data (Figures C.1, C.2, and C.3), with overdrawn line thicknesses to highlight the inter-array cables and mooring lines. Through discussions between BOEM and PNNL, an 8 MW turbine was chosen for mounting on the floating platform; turbine specifications were fashioned after a Vestas 8 MW turbine with a 82 m blade length (MHI Vestas 2014). The turbines were configured in a 3 × 3 array (Figure C.3) that could be repeated and scaled to a represent a larger installation.

The AutoCAD drawings were used to inform a 3D scale model of the wind farm created in Blender. The Blender model was animated to create a series of dynamic scenes; an example is shown in Figure 3. A total of 10 buoys are used to buoy the inter-array cable over the distance of 820 m between platforms; the floating buoys are 1.6 m in length with a 1.9 m outer diameter.

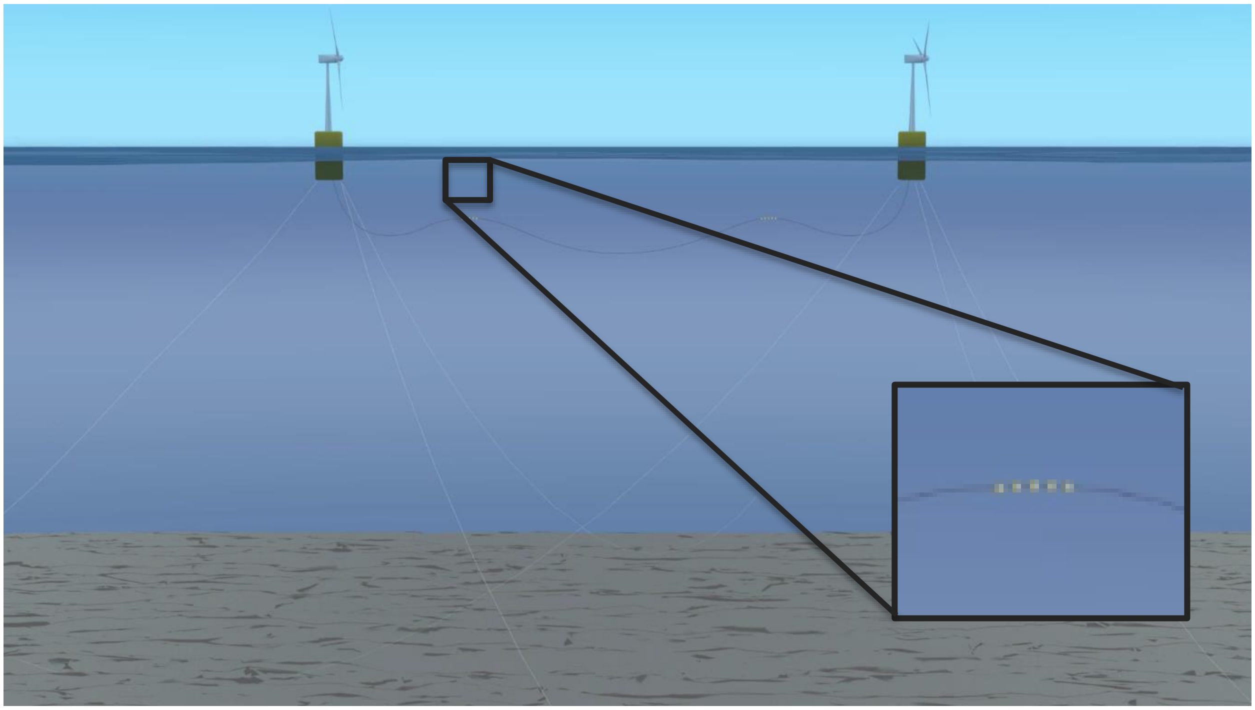

Figure 3. Scaled Drawing of Turbines, Moorings and the Inter-Array Array Cables Around Two Turbines

5.0 Animation Storyline

A storyline was developed to provide a narrative for the animation of the humpback whale and calf encountering the wind farm. The storyline is as follows:

If offshore wind farms are installed off the U.S. west coast or Hawaii, migrating humpback whales may come into contact with these new structures. During this migration, humpback whales are primarily traveling or foraging. The animation follows a mother and calf pair as they traverse the wind farm described in Section 3. The video begins by highlighting the whales' typical migration routes, either through Hawaii or along the west coast. The layout of the nine turbine array is shown, highlighting the mooring line placement and inter-array cable design. The mother and calf pair enter the farm and the mother dives while the calf remains at the surface. During this dive, the mother forages at higher speeds and travels by the mooring lines, buoys, and inter-array cables.

The animation is approximately three minutes in length, made up of a number of views, including zooming in on the whales and lines, and views from several angles to demonstrate the scale and layout of the whales and the wind farm. The swimming speed of the whales and the rotational speeds of the turbines are presented in real time in all frames. This mix of animation techniques illustrates the whales' behavior as the mother-calf pair approach, transit, and forage through the the wind farm.

6.0 Animation and Video Production

The 3D animation was produced in Blender using the literature review input parameters and the animation storyline described in Section 5. Across all scenes, the wind farm parameters provided by BOEM were used, including the water depth of 700 m. For each scene of the animation, the correct speeds associated with the movement of the whales was used, based on data retrieved from the scientific literature; these data are tabulated in Table D.1 in Appendix D, Animation and Video Production Inputs. Adobe Premeire Pro CC 2018 was used to overlay text on a version of the video to tell the story. The text for each scene, as well as any additional animations, are shown in Table D.2 in Appendix D.

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(Includes sources cited in the appendices)

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Appendix A

Morphometric Data

A.1 Length

For the length of each animal, measurements were converted to meters and tabulated (Table A.1). Note that the Woodward et al. (2006) average is taken from many sources. The Marine Mammal Center, located in Sausalito, California, describes an average length of 15–16 m for Northern Hemisphere humpbacks, while reporting an average length of 18 m for Southern Hemisphere humpbacks. However, this information is not cited or reflected in the literature, so was not included in the averages (The Marine Mammal Center 2017).

Table A.1. Length of Adult Humpback Whales

	Length (m)	# of Animals Measured	Information Source	Location of Population
Male	13.6	—	Herman and Antinoja 1977	Eastern North Pacific
	11.58	—	Rice 1964	—
	11.72	19	Nolan et al. 2000	Hawaii
Female	12.09	—	Rice 1964	—
	14.8	—	Herman and Antinoja 1977	Eastern North Pacific
	12.67	26	Nolan et al. 2000	Hawaii
Both sexes	13.5	128	Woodward et al. 2006	
"Typical" whale by equal weighted average	12.83			

For calves, only one measurement was designated as a "calf" as opposed to neonate or newborn (Table A.2). The main source of these data, Holyoake et al. (2012), collected calf data purely about stranded animals (Holyoake et al. 2012). When the one "calf" datum point is included with the neonates, there is a very small difference in the length of male and female calves.

Table A.2. Length of Humpback Whale Calves

	Length (m)	# of Animals Measured	Information Source	Location of Population
Male	4.57	4	Holyoake et al. 2012	Australia
Female	4.58	4	Holyoake et al. 2012	Australia
Both sexes	4-5	—	Herman and Antinoja 1977	—
"Typical" calf by equal weighted average	4.58			

A.1.1 Girth

Girth is described as the maximum body circumference taken at the axilla for the study (Table A.3 and Table A.4). The maximum girth described by Woodward et al. (2006) is a ratio between the girth and body length, resulting in a ratio of 0.747. The average maximum width, assuming a circumferential shape, is then approximately 3.21 m.

Table A.3. Girth of Adult Humpback Whales

	Girth (m)	# of Animals Measured	Information Source	Location of Population
Both sexes	10.08	29	Woodward et al. 2006	—
"Typical" whale by equal weighted average	10.08			

Table A.4. Girth of humpback whale calves.

	Girth (m)	# of Animals Measured	Information Source	Location of Population
Female	2.38	2	Holyoake et al. 2012	Australia

A.2 Fluke and Flipper Length

Compared to other baleen whales, humpback whales have large fluke and flipper lengths in relation to their body lengths (Woodward et al. 2006). The ratios of fluke and flipper lengths to body length is given in Table A.5.

Table A.5. Fluke and Flipper Length of Adult Humpback Whales. Lengths are given as a ratio of the fluke or flipper length to body length (i.e., fluke length/body length).

	Fluke Span Ratio	# of Animals Measured	Information Source	Location of Population
Both sexes	0.341	—	Woodward et al. 2006	—
	0.333	—	Kniest et al. 2010	—
"Typical" whale fluke ratio by equal weighted average	0.337			
	Flipper Length Ratio	**# of animals measured**	**Information Source**	**Location of Population**
Both sexes	0.308	—	Woodward et al. 2006	—
"Typical" whale flipper ratio by equal weighted average	0.308			

Table A.6. Fluke and Flipper Length of Humpback Whale Calves

	Fluke Span	# of Animals Measured	Information Source	Location of Population
Female	1.19	3	Holyoake et al. 2012	Australia
"Typical" calf fluke ratio by equal weighted average	1.19			
	Flipper Length Ratio	# of Animals Measured	Information Source	Location of Population
Female	1.38	3	Holyoake et al. 2012	Australia
"Typical" calf flipper length by equal weighted average	1.38			

Appendix B

Behavioral Data

B.1 Dive Speed

Table B.1. Dive Speed for Adult Humpback Whales. For each entry, a single whale was measured multiple times.

	Dive Speed (m/s)	# of dives measured	Information Source	Location of Population
Foraging (descending)	1.7	43	Goldbogen et al. 2008	California
Foraging (descending)	1.5	15	Goldbogen et al. 2008	California
Foraging (ascending)	1.4	43	Goldbogen et al. 2008	California
Foraging (ascending)	1.4	15	Goldbogen et al. 2008	California
Foraging (descending)	3.0	10	Simon et al. 2012	Greenland
Foraging (descending)	2.2	39	Simon et al. 2012	Greenland
Foraging (descending)	2.2	49	Simon et al. 2012	Greenland
Foraging (descending)	2.0	35	Simon et al. 2012	Greenland
Foraging (descending)	2.2	31	Simon et al. 2012	Greenland
Foraging (ascending)	2.3	10	Simon et al. 2012	Greenland
Foraging (ascending)	2.0	39	Simon et al. 2012	Greenland
Foraging (ascending)	2.0	49	Simon et al. 2012	Greenland
Foraging (ascending)	1.8	35	Simon et al. 2012	Greenland
Foraging (ascending)	2.6	31	Simon et al. 2012	Greenland
"Typical" dive speed by equal weighted average	2.0			

B.2 Dive Depth

Table B.2. Dive Depth for Adult Humpback Whales

	Max Dive Depth (m)	# of Animals Measured	Information Source	Location of Population
Fish Foraging	107	5	Witteveen et al. 2015	Alaska
Zooplankton Foraging	127	3	Witteveen et al. 2015	Alaska
Foraging	139	1	Goldbogen et al. 2008	California
Foraging	156	1	Goldbogen et al. 2008	California
"Typical" max dive depth by equal weighted average	132			

B.3 Dive Duration

Table B.3. Dive Duration for Adult Humpback Whales

	Average Dive Duration (minutes)	# of Animals Measured	Information Source	Location of Population
Foraging	7.7	1 (43 dives)	Goldbogen et al. 2008	California
Foraging	7.9	1 (15 dives)	Goldbogen et al. 2008	California
Fish Foraging	6	5	Witteveen et al. 2015	Alaska
Zooplankton Foraging	6	3	Witteveen et al. 2015	Alaska
Long Dive	4.11	14 (1009 dives)	Kavanaugh et al. 2017	Australia
"Typical" dive duration by equal weighted average	6.34			

B.4 Traveling Speed

Table B.4. Traveling Speed for Adult Humpback Whales

Behavior	Traveling Speed (km/hr)	Time and distance measured	# of Animals measured	With or without calf	Source	Location of Population
Migrating	5	4800 km over 40 days	1	—	Cerchio et al. 2001	—
Migrating	6.25	670 km over 4.5 days	1	With	Mate et al. 1998	Hawaii
Migrating	4.58	1610 km over 14.7 days	1	Without	Mate et al. 1998	Hawaii
Local Movements	2.5	250 km over 3.9 days	1	Without	Mate et al. 1998	Hawaii
Local Movements	2.5	30 km over 0.5 days	1	Without	Mate et al. 1998	Hawaii
Local Movements	3.33	820 km over 9.9 days	1	Without	Mate et al. 1998	Hawaii
Migrating	4.58	1860 km over 17 days	1	Without	Mate et al. 1998	Hawaii
Migrating	2.63	3640 km over 58 days	1	—	Zerbini et al. 2006	Brazil
Migrating	3.83	3720 km over 40 days	1	With	Zerbini et al. 2006	Brazil
Singing	2.34	—	57	Without	Noad and Cato 2007	Australia
Not Singing	3.58	—	28	With	Noad and Cato 2007	Australia
Not Singing	4.17	—	87	Without	Noad and Cato 2007	Australia
Migrating	4.3	—	14	—	Kavanaugh et al. 2017	Australia
"Typical" traveling speed by equal weighted average	3.81					

B.5 Foraging Speed

The foraging speed, as opposed to the speed while diving, is described as the maximum velocity when the whale is lunge-feeding.

Table B.5. Foraging Speed for Adult Humpback Whales

	Lunge Speed (m/s)	# of Lunges Measured	Source	Location of Population
	2.7	362	Goldbogen et al. 2008	California
	2.3	89	Goldbogen et al. 2008	California
"Typical" foraging speed by equal weighted average	2.5			

Appendix C

Wind Array Data

Parameter	Data For Visual Simulation	Justification
Units: ft = feet, kg = kilogram, m = meters, mi = mile, mm = millimeter, nm = nautical miles Other abbreviations: NREL = National Renewable Energy Laboratory		
Ocean Conditions		
Water depth	700 m/2300 ft	Consistent with Pacific Region unsolicited wind energy lease requests received and Hawaii Call for Information and Nomination areas.
Floating Platforms		
# platforms in scalable array unit	9	Sufficient to demonstrate scale of array and whales.
Foundation type	Generic rectangular block	Platform is not the focus of the study, so specific actual platform type was not chosen.
Foundation dimensions	35 m × 35 m	Rough mean of the two platform types that have been proposed in the Pacific Region.
Foundation draft	48 m / 157 ft	Mean of the two platform types that have been proposed in the Pacific Region.
Scalable array unit configuration	Three rows of three platforms each	Realistic configuration based on unsolicited lease requests and NREL expertise.
Spacing between platforms along row	820 m/2690 ft/0.5 mi	Equivalent to 5 rotor diameters for an 8 MW turbine (a realistic turbine size to model), feasible spacing for wake effects along the row. This is a conservative estimate in that it is likely the minimum distance between platforms, therefore on the denser side of array spacing for a whale. This spacing may result in issues of overlap of mooring lines along the seafloor; however, since the lines in the water column and not along seafloor are the focus for this visualization, the overlap issue will not affect the identified spacing.
Spacing between rows	1640 m/5380 ft/1 mi	Equivalent to 10 rotor diameters for an 8 MW turbine (a realistic turbine size to model). This spacing may result in issues of overlap of mooring lines along the seafloor; however, since the lines in the water column and not along seafloor are the focus for this visualization, the overlap issue will not affect the identified spacing.
Rotor diameter (i.e., blade length)	82 m/269 ft	For a representative 8 MW turbine.
Tower height (i.e., distance from sea surface to top of blade pointing straight up)	194 m/636 ft	For a representative 8 MW turbine.
Watch circle radius	90 m/295 ft	Platform and attached lines/cable will move in a watch circle with up to a 90 m radius. Mooring lines and cable must have some slack to allow for this movement.

Parameter	Data For Visual Simulation	Justification
Catenary Mooring System		
# mooring lines per platform	Three	The most commonly estimated number of mooring lines in unsolicited lease requests and number of lines in existing Hywind installation.
Connection points	On platform sides 18 m/59 ft below sea surface, three connections spaced equidistant from each other	Realistic and conservative estimate in that it requires more mooring line in the water column than if the lines were connected at the bottom of the platform (48 m/157 ft depth).
Mooring line configuration	120° between each line with respect to the seafloor; 45° from vertical with respect to the water column	Unsolicited lease requests and Hywind installation have mooring lines that are equiangular with respect to the seafloor anchor circle. Though anchor radius is large, the vertical angle of the mooring line in the water column does not change much based on water depth. Most of the mooring line would be lying on the seafloor to reduce vertical load on the anchors. Only Hywind installation has data on the specific vertical angle of mooring lines coming off the platform (42° from vertical); project plans indicate that the angle would not be greater than 45° from vertical.
Mooring line length in water column	964 m/3163 ft/0.6 mi	Assuming a maximum 45° angle of the mooring line from the platform and no curve in the line, the length of line in the water column would be 964 m. This is a conservative estimate as it means more line in the water column than if the vertical angle were smaller. Straight lines were assumed for the purpose of calculating length, but the visualization will reflect the more realistic catenary curve shape.
Mooring line material	High modulus polyethylene (HMPE) rope at platform and in water column, chain near anchor attachment	Materials based on unsolicited lease requests. Synthetic rope is more economical than chain, though chain would be used for stability, to offset some ballast in the platform, and to connect to the anchor.
Mooring line diameter	112 mm	Materials based on unsolicited lease requests. Specs found through online market research. Estimated that HMPE rope would be the mooring line material present at typical whale swimming depths--chain would be used closer to the seabed.
Mooring line mass	8.2 kg/m	Materials based on unsolicited lease requests. Specs found through online market research. Estimated that HMPE rope would be the mooring line material present at typical whale swimming depths--chain would be used closer to the seabed.
Inter-Array Cables (excludes offshore substation and export cable to shore)		
Cable type	33 kV	Typical cable type. See Hywind cable spec sheet for reference (appended).
Cable configuration	"Daisy chain" - single cable along turbine rows	Based on NREL expertise and existing Hywind Scotland Pilot Park installation.
Connection points	Center of bottom of platform	Generic configuration for the purpose of this study.

Parameter	Data For Visual Simulation	Justification
Cable depth	100 m/328 ft at floats, 150 m at bottom of sag	Judgment based on depth of fishing activities, design economics (deeper cable = more cable = higher cost), and industry input to the Bureau of Ocean Energy Management.
Cable length	>1114 m/3655 ft plus additional cable for sagging between buoyance modules.	Connection point to platform is at 48 m depth. Need 102 m to get cable down to designated maximum suspension depth, 820 m horizontal to next platform, 102 m up to connection point = 1024 m of cable, plus 90 m for watch circle (only one watch circle instead of two because it is unlikely that two platforms would be pushed in opposite directions) = 1,114 m. Additional cable length would be needed for sagging between buoyancy modules. Empirical data on suspended cables are generally lacking, so these are rough estimates.
Cable diameter	169 mm	Based on Hywind Scotland Pilot Park installation.
Cable mass	50.5 kg/m/33.9 lb/ft	Based on Hywind Scotland Pilot Park installation.
Cable float system	Generic cylindrical buoyancy module	Trelleborg renewbles distributed buoyancy modules referenced as example.
Number of floats along cable	10	Based on industry input to the Bureau of Ocean Energy Management.. Floats would be placed in two groups along cable. Largest float in Trelleborg cable float system design tool results chosen.
Cable float diameter	1.87 m/6.1 ft	Based on results.
Cable float length	1.622 m/5.3 ft	Based on Trelleborg cable float system design tool results.

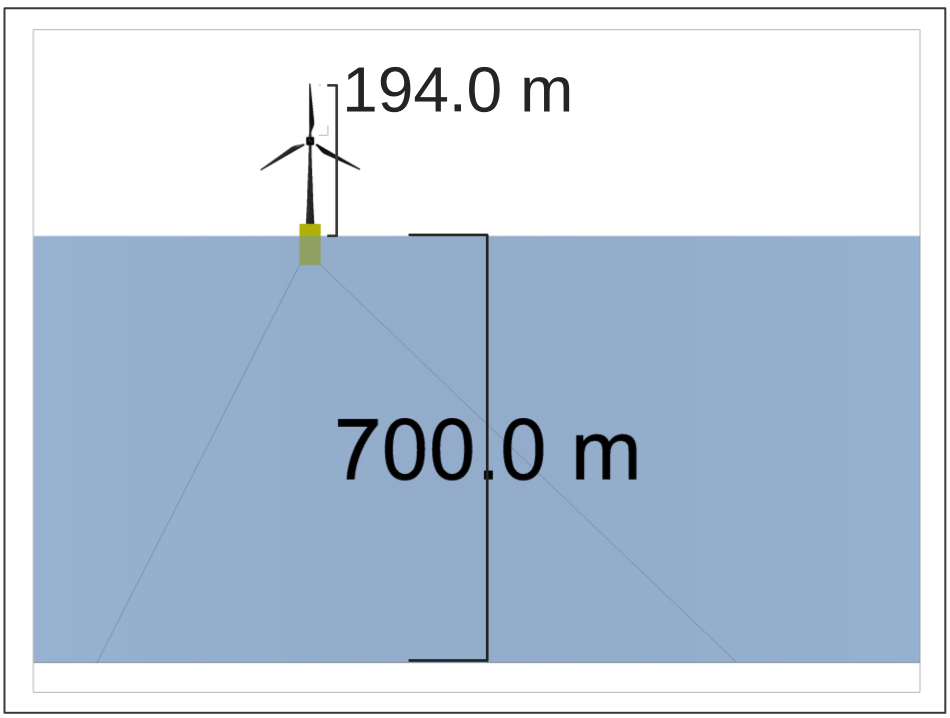

Figure C 1. Depth Profile of One Offshore Wind Platform in 700 m of Water. Turbine size is based on Vestas website specification of a 8 MW turbine.

A single turbine platform has three cables connected it to the seabed (Figure C.1). Three platforms in profile are visualized in Figure C.2 to show how the mooring lines are laid out. Each row of three platforms were offset from the next row by 410 m (Figure C.3).

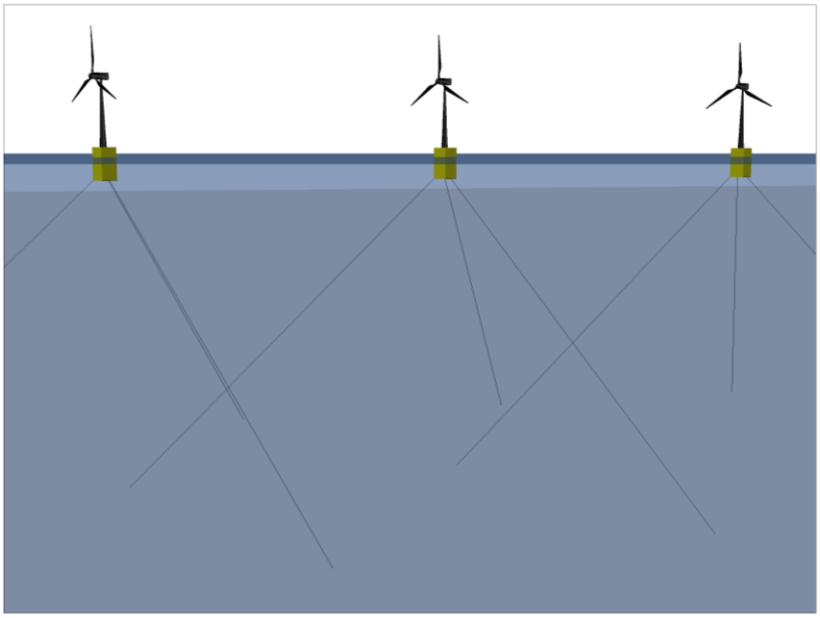

Figure C 2. Three Platforms in Profile Show How the Mooring Lines Look in a Single Row of Turbines

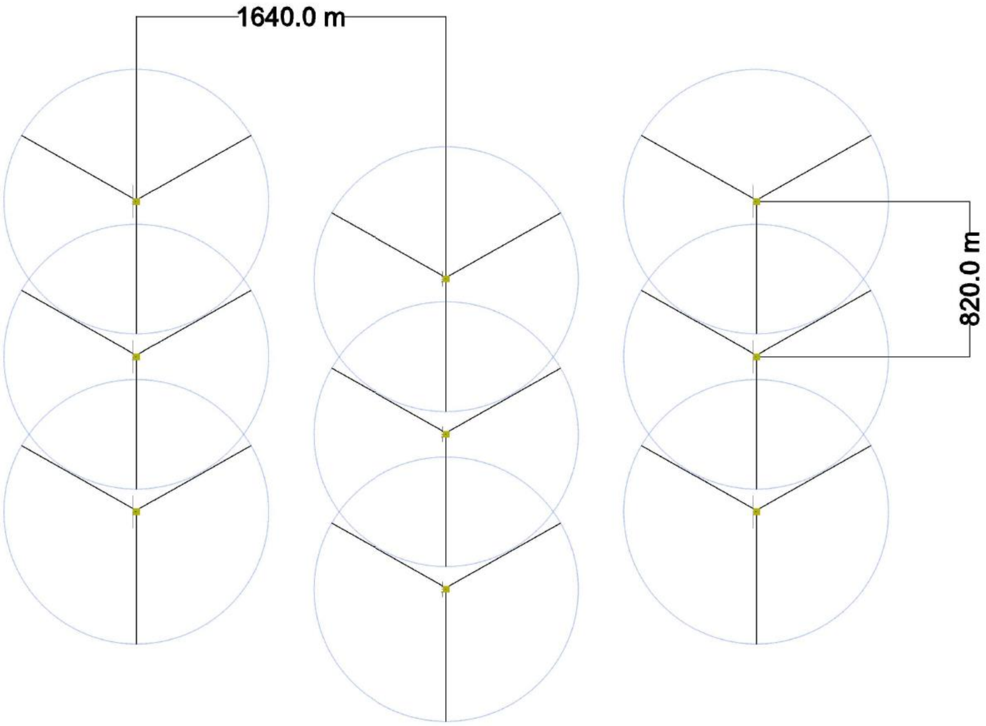

Figure C 3. Scale Drawing of Wind Farm Array. Light blue circles represent the effective diameter of the turbine platform based on where the mooring lines are connected to the seabed.

Appendix D

Animation and Production Inputs

Table D 1. Speed Input Parameters Used for Each Animated Scene

Clip Number	Clip Description	Speed Input Parameters
1	California Coast Migration Routes	No speed input parameters
2	Flythrough of offshore wind farm	Wind turbine rotation: 10 rpm Boat Speed: 20 knots
3	Bird's eye view	Wind turbine rotation: 10 rpm
4	Side view of two turbines	Wind turbine rotation: 10 rpm
5	Mother and calf approaching wind farm	Wind turbine rotation: 10 rpm Whale traveling speed: 1.05 m/s
6	Mother begins diving	Whale diving speed: 2.5 m/s
7	Mother forages for krill	Whale foraging speed: 4.0 m/s
8	Scale during dive	No speed input parameters
9	Mother crosses in front of mooring line	Whale diving speed: 2.7 m/s
10	Mother crosses in front of buoy and cable	Whale diving speed: 2.2 m/s
11	Mother ends dive and return to calf	Whale diving speed: 1.4 m/s
12	Mother and calf cross wind farm	Wind turbine rotation: 10 rpm Whale traveling speed: 1.05 m/s
13	Sunset	Wind turbine rotation: 10 rpm

Table D 2. Text Overlay for Each Scene (still under review). Overlayed animation created with Adobe After Effects also are described.

Clip Number	Clip Description	Text	Text 2	Other Animation
1	California Coast Migration Routes	Each year, humpback whales travel along the U.S. west coast to northern feeding grounds	Some females have their calves with them	Arrows point to regions where humpbacks migrate
2	Flythrough of offshore wind farm	In the future, these whales may encounter a new technology: floating wind turbines		None
3	Bird's eye view	The floating turbine platforms would be anchored to the seabed using mooring lines		Animation of mooring lines from bird's eye view
4	Side view of two turbines	Buoyed cables would connect rows of platforms to transmit the electricity generated		Mooring lines and inter-array cables are emphasized Text Animation: water depth: 700 m platform spacing: 820 m turbine height: 194 m whale: 13 m
5	Mother and calf approaching wind farm	We created this animation to visualize the scale of the humpback mother and calf swimming through a hypothetical floating wind farm		None
6	Mother begins to dive	The mother dives to forage while her calf stays near the surface		None
7	Mother passes near mooring lines	The mooring lines would be fairly taut to keep the platform from moving around too much	The electrical cables could be suspended more loosely in the water column using floats	None
8	Feed for Krill	Humpbacks rarely dive deeper than 120 meters to feed (Dolphin, 1987)	The electrical cable here is suspended at 100-150 meters depth	None
9	Scale of farm	The spacing between platforms, mooring lines, and cables is not expected to restrict whale movement		None
10	Mother crosses in front of buoy and cable	The mother may encounter the electrical cables and floats during her feeding dives	Each float shown here is almost 2 meters in diameter and about 1.6 meters long	None
11	Mother ends dive and returns to calf			None

12	Mother and calf cross wind farm	When the mother and calf are swimming near the surface, they should not encounter mooring lines or cables	None
13	Sunset	Learn more at at https://www.boem.gov/Pacific-Completed-Studies/ https://tethys.pnnl.gov/humpback-whales-and-floating-offshore-wind-farm-animation	BOEM Logo, PNNL Logo

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Prepared for the **Bureau of Ocean Energy Management**
under an Interagency Agreement with the U.S. Department of Energy
CONTRACT DE-AC05-76RL01830

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