Assessment of Offshore Wind Energy Leasing Areas for Humboldt and Morro Bay Wind Energy Areas, California

Aubryn Cooperman, Patrick Duffy, Matt Hall, Ericka Lozon, Matt Shields, and Walter Musial

National Renewable Energy Laboratory

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April 2022

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List of Acronyms

AEP	annual energy production
BOEM	Bureau of Ocean Energy Management
D	rotor diameter
FLORIS	Flow Redirection and Induction in Steady State (wake modeling tool)
GCF	gross capacity factor
GW	gigawatt
GWh	gigawatt-hour
IEA Wind	International Energy Agency Wind Technology Collaboration Programme
km	kilometer
kV	kilovolt
m	meter
MN	meganewton
m/s	meter per second
MW	megawatt
MWh	megawatt-hour
NCF	net capacity factor
nm	nautical mile
NREL	National Renewable Energy Laboratory
PGA	peak ground acceleration
sq. mi.	square miles
TLP	tension-leg platform
TurbOPark	Turbulence Optimized Park (wake model)
TWh	terawatt-hour
WEA	wind energy area

Executive Summary

In this report, the National Renewable Energy Laboratory (NREL) assesses several options for delineating potential lease areas for the California wind energy areas (WEAs) of Morro Bay and Humboldt, designated in 2021. The options divide the WEAs into lease areas of approximately equal value while maintaining a capacity of at least a 1-gigawatt (GW) wind plant per lease area under most of the modeled scenarios. This analysis is intended to inform the Bureau of Ocean Energy Management (BOEM)'s proposed sale notice as it prepares to competitively auction lease areas to wind energy developers. NREL's analysis focuses on physical site characteristics and their effects on technology selection and energy generating potential. Assessments of potential interactions with the environment and competing uses are outside the scope of this analysis and are available from other sources, e.g., BOEM (2022a; 2022b).

Our analysis and delineation processes were as follows:

1. NREL researchers reviewed the nominations submitted by wind energy developers in response to the California Call for Information and Nominations (83 Fed. Reg. 53,096). NREL was granted confidential access to developers' descriptions of proposed projects to understand the scope and types of technology being considered.
2. To gain a more detailed understanding of the technology selection and potential challenges, NREL contacted wind energy developers who had submitted nominations. NREL interviewed representatives of five companies that responded to our request.
3. NREL reviewed published data and literature to assess the physical site characteristics of the Humboldt and Morro Bay WEAs.
4. NREL established that mooring configuration is a key variable in determining lease area power capacity because of the setback requirements between different anchor systems. We modeled four different mooring technologies (catenary, semi-taut, taut, and tension-leg platform) in depths representative of the California WEAs to estimate the range of mooring footprints.
5. For each WEA, NREL considered nearly a dozen possible delineation scenarios. In consultation with BOEM, we selected two options for delineating the Humboldt WEA into two lease areas, and four options for delineating the Morro Bay WEA: one option with two lease areas and three options with three lease areas each.
6. NREL assessed the generating potential for several example turbine layouts in each lease area and delineation option. These examples provide insights into the range of energy production that might be expected, but they do not represent detailed plant-level designs. The analysis considered the effects of turbine spacing, mooring system footprints, wake losses within and between adjacent wind plants, and other system losses.
7. NREL prepared this report summarizing our approach, results, and key findings.

The site characteristics and modeled wind plant performance metrics used to evaluate the delineation options are presented in Table ES-1.

Table ES-1. Parameters Used for Lease Area Evaluation

Site Characteristics	Wind Plant Parameters
Bathymetry (meters [m])	Maximum nameplate capacity (megawatts [MW])
Annual average wind speed (meters per second [m/s])	Turbine spacing (rotor diameters [D])
Wind direction (degrees)	Mooring system footprint (m)
Distance from land-based infrastructure (kilometers [km])	Wake losses (%)
Total area (km^2)	Capacity factor (%)
Geotechnical and geophysical hazards	Annual energy production (gigawatt-hours [GWh])

The proposed delineation options for the Humboldt and Morro Bay WEAs are shown in Figures ES-1 and ES-2, respectively.[1] In Humboldt (Figure ES-1), the two options for dividing the WEA into two lease areas are labeled B and C (option A, the full WEA, was not analyzed in detail).

[1] BOEM defines offshore boundaries in terms of Outer Continental Shelf lease blocks and aliquots. Each aliquot is a 1,200 meter (m) by 1,200 m square and each lease block contains 16 aliquots in four rows of four, with some exceptions related to the projection of a rectangular grid onto spherical coordinates. For more details, see https://www.boem.gov/oil-gas-energy/mapping-and-data.

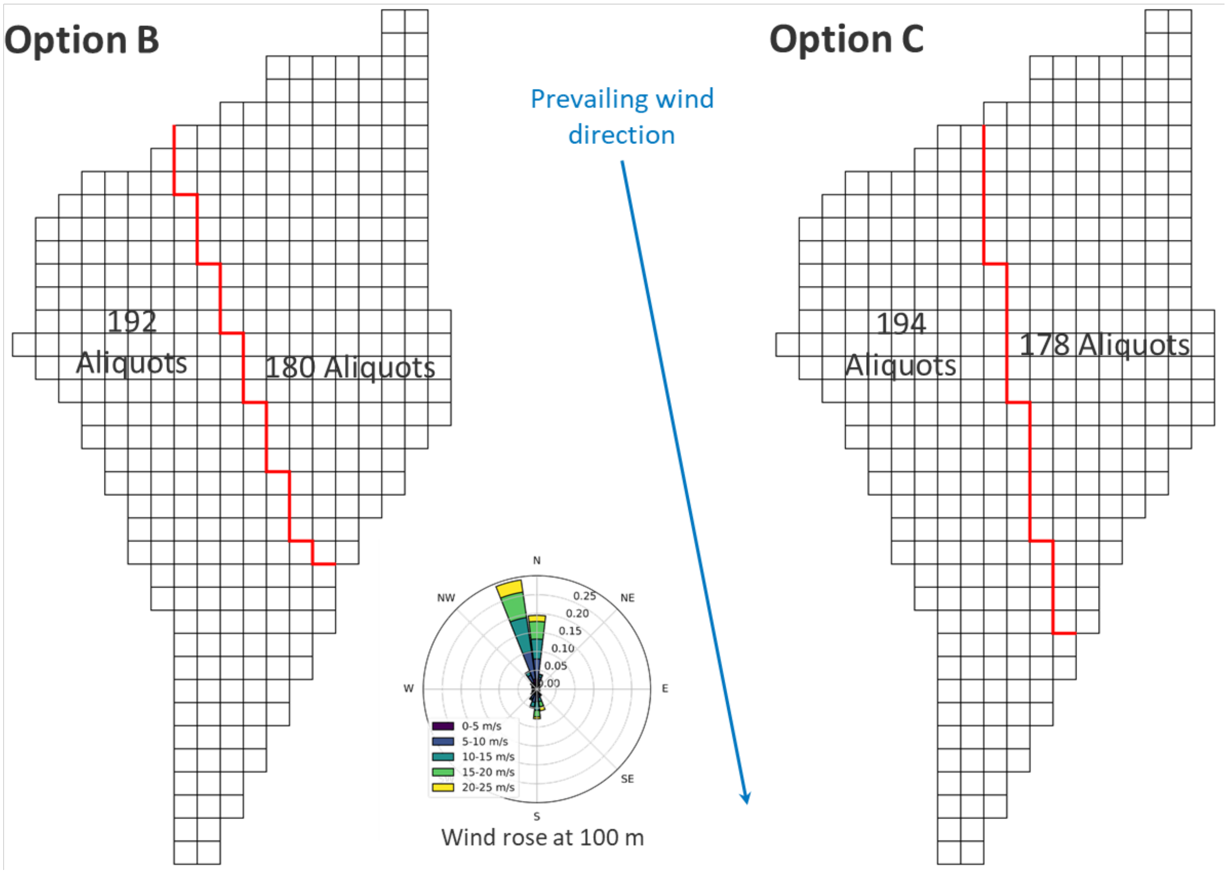

Figure ES-1. Proposed delineation options for the Humboldt wind energy area

Both options in Humboldt divide the WEA along a boundary roughly aligned with the prevailing wind direction to minimize potential wake losses between lease areas. We identified more challenging physical site conditions in the southwest part of the WEA due primarily to steep slopes and increased the area in those lease areas to compensate.

The shape and alignment of the Morro Bay WEA did not allow for efficient division of the WEA along the prevailing wind direction, so we prioritized delineation options that minimized the boundary length and maximized the usable area of each lease area (Figure ES-2). The option with two lease areas is labeled 2a, and the options with three lease areas are 3a, 3b, and 3c.

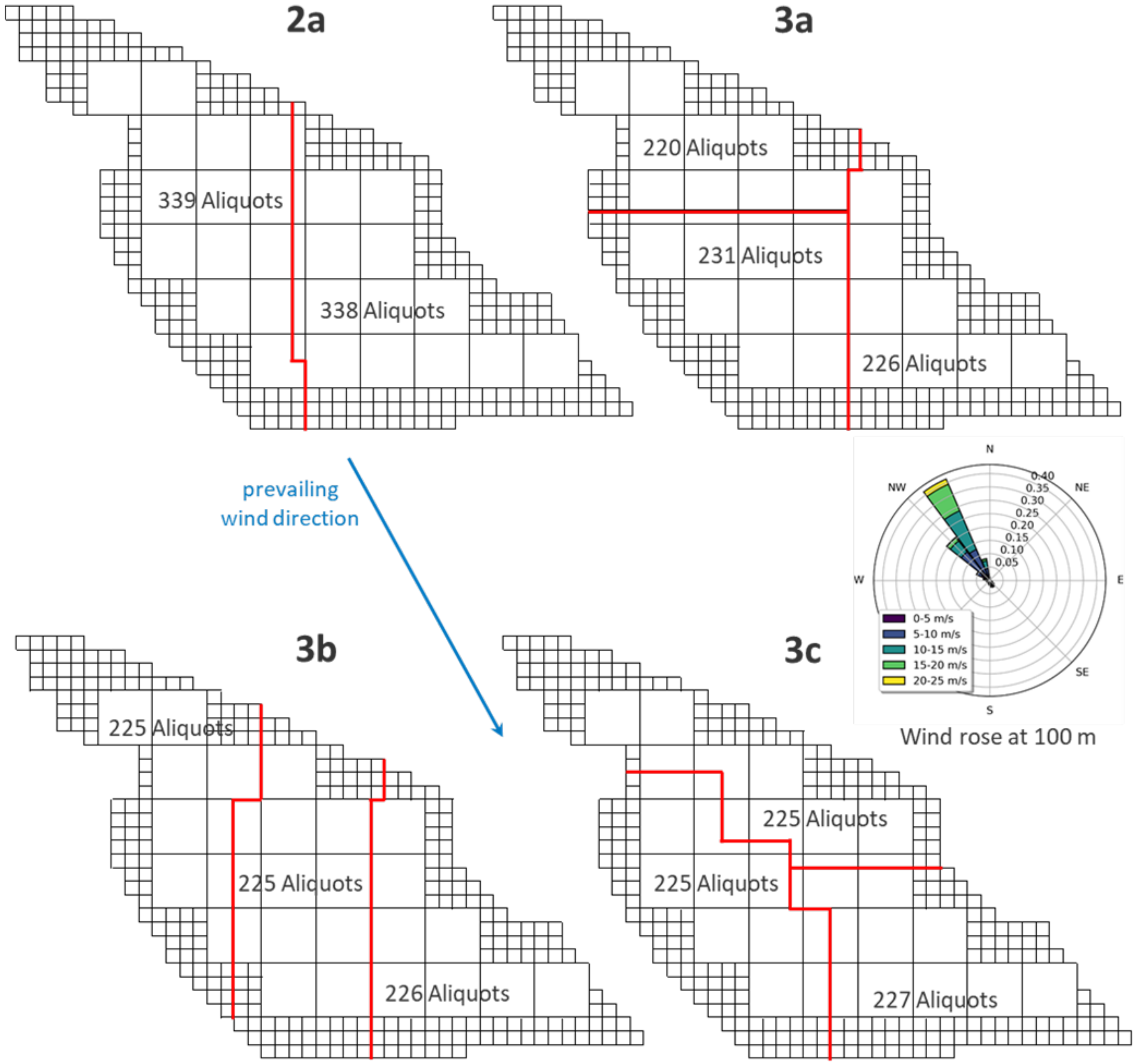

Figure ES-2. Proposed delineation options for Morro Bay wind energy area

The physical parameters and modeled wind plant performance for each delineation option are summarized in Tables ES-2 to ES-7. All the analyses assume 15-megawatt (MW) turbines in a rectangular grid layout. We consider two turbine spacing configurations: uniform 1 nautical mile (nm) by 1 nm (1.9 kilometers [km] by 1.9 km), and 4 rotor diameters by 10 rotor diameters (4D by 10D; 1 km by 2.4 km). The minimum distance between a lease area boundary and a turbine depends on the choice of mooring technology. A tension-leg platform (TLP) uses vertical tendons that minimize the horizontal spread of the moorings, whereas catenary moorings require the largest footprint among the alternatives that we considered. We analyzed wake losses and annual energy production for each lease area using TLP and catenary mooring setbacks to provide a reasonable upper and lower bound on the wind plant capacity and losses.

Table ES-2. Humboldt WEA Delineation Analysis for Option B

Humboldt: Delineation Option B		
Parameter	**NE Lease Area**	**SW Lease Area**
Total area (km^2)	259	276
Average wind speed at 100 m (m/s)	10.3	10.6
Average depth (m)	736	774
Depth range (m)	537–1,017	606–1,137
Average seafloor gradient (degrees)	1.7	2.5
Average distance from Eureka (km)	44	46
4D × 10D Turbine Spacing with TLP Mooring		
Wake losses with both lease areas (%)	7.0%	6.8%
Net capacity factor (%)	49.4%	49.4%
Potential capacity (MW)	1,455	1,590
Annual energy production (GWh)	6,291	6,884
4D × 10D Turbine Spacing with Catenary Mooring		
Wake losses with both lease areas (%)	6.5%	6.1%
Net capacity factor (%)	49.6%	49.8%
Potential capacity (MW)	1,155	1,140
Annual energy production (GWh)	5,019	4,973
1 nm × 1 nm Turbine Spacing with TLP Mooring		
Wake losses with both lease areas (%)	6.0%	5.8%
Net capacity factor (%)	49.8%	50.0%
Potential capacity (MW)	1,020	1,080
Annual energy production (GWh)	4,454	4,728
1 nm × 1 nm Turbine Spacing with Catenary Mooring		
Wake losses with both lease areas (%)	5.5%	5.2%
Net capacity factor (%)	50.1%	50.3%
Potential capacity (MW)	735	765
Annual energy production (GWh)	3,228	3,370

Table ES-3. Humboldt WEA Delineation Analysis for Option C

Humboldt: Delineation Option C		
Parameter	**NE Lease Area**	**SW Lease Area**
Total area (km^2)	256	279
Average wind speed at 100 m (m/s)	10.3	10.6
Average depth (m)	723	786
Depth range (m)	537–1,017	614–1,137
Average seafloor gradient (degrees)	1.6	2.6
Average distance from Eureka (km)	43	47
4D × 10D Turbine Spacing with TLP Mooring		
Wake losses with both lease areas (%)	7.1%	6.7%
Net capacity factor (%)	49.3%	49.5%
Potential capacity (MW)	1,470	1,590
Annual energy production (GWh)	6,347	6,892
4D × 10D Turbine Spacing with Catenary Mooring		
Wake losses with both lease areas (%)	6.4%	6.1%
Net capacity factor (%)	49.6%	49.8%
Potential capacity (MW)	1,035	1,155
Annual energy production (GWh)	4,500	5,038
1 nm × 1 nm Turbine Spacing with TLP Mooring		
Wake losses with both lease areas (%)	6.1%	5.7%
Net capacity factor (%)	49.8%	50.0%
Potential capacity (MW)	1,020	1,110
Annual energy production (GWh)	4,449	4,862
1 nm × 1 nm Turbine Spacing with Catenary Mooring		
Wake losses with both lease areas (%)	5.6%	5.2%
Net capacity factor (%)	50.1%	50.3%
Potential capacity (MW)	750	750
Annual energy production (GWh)	3,290	3,303

Table ES-4. Morro Bay WEA Delineation Analysis for Option 2a

Morro Bay: Delineation Option 2a		
Parameter	**NW Lease Area**	**E Lease Area**
Total area (km^2)	488	487
Average wind speed at 100 m (m/s)	9.7	9.4
Average depth (m)	1,107	1,003
Depth range (m)	988–1,284	884–1,273
Average seafloor gradient (degrees)	1.5	0.9
Average distance from Morro Bay (km)	102	81
Average distance from Port Hueneme (km)	330	310
4D × 10D Turbine Spacing with TLP Mooring		
Wake losses with both lease areas (%)	7.8%	8.7%
Net capacity factor (%)	46.7%	46.3%
Potential capacity (MW)	2,835	2,790
Annual energy production (GWh)	11,603	11,307
4D × 10D Turbine Spacing with Catenary Mooring		
Wake losses with both lease areas (%)	7.4%	8.2%
Net capacity factor (%)	47.0%	46.6%
Potential capacity (MW)	2,325	2,325
Annual energy production (GWh)	9,563	9,482
1 nm × 1 nm Turbine Spacing with TLP Mooring		
Wake losses with both lease areas (%)	7.0%	6.4%
Net capacity factor (%)	47.5%	47.2%
Potential capacity (MW)	2,055	1,905
Annual energy production (GWh)	8,544	7,870
1 nm × 1 nm Turbine Spacing with Catenary Mooring		
Wake losses with both lease areas (%)	5.8%	6.3%
Net capacity factor (%)	47.7%	47.5%
Potential capacity (MW)	1,500	1,545
Annual energy production (GWh)	6,273	6,428

Table ES-5. Morro Bay WEA Delineation Analysis for Option 3a

Morro Bay: Delineation Option 3a			
Parameter	**NW Lease Area**	**SW Lease Area**	**E Lease Area**
Total area (km^2)	317	333	325
Average wind speed at 100 m (m/s)	9.7	9.6	9.4
Average depth (m)	1,095	1,082	988
Depth range (m)	953–1,271	964–1,284	884–1,165
Average seafloor gradient (degrees)	1.1	1.6	0.9
Average distance from Morro Bay (km)	103	94	77
Average distance from Port Hueneme (km)	336	319	306
4D × 10D Turbine Spacing with TLP Mooring			
Wake losses with all lease areas (%)	6.3%	8.9%	8.6%
Net capacity factor (%)	47.5%	46.2%	46.3%
Potential capacity (MW)	1,680	1,830	1,845
Annual energy production (GWh)	6,988	7,401	7,491
4D × 10D Turbine Spacing with Catenary Mooring			
Wake losses with all lease areas (%)	5.7%	8.4%	7.7%
Net capacity factor (%)	47.8%	46.4%	46.8%
Potential capacity (MW)	1,275	1,710	1,440
Annual energy production (GWh)	5,337	6,955	5,901
1 nm × 1 nm Turbine Spacing with TLP Mooring			
Wake losses with all lease areas (%)	5.1%	7.7%	6.8%
Net capacity factor (%)	48.1%	46.8%	47.2%
Potential capacity (MW)	1,215	1,470	1,215
Annual energy production (GWh)	5,118	6,027	5,028
1 nm × 1 nm Turbine Spacing with Catenary Mooring			
Wake losses with all lease areas (%)	4.4%	6.7%	6.1%
Net capacity factor (%)	48.5%	47.3%	47.6%
Potential capacity (MW)	825	1,155	930
Annual energy production (GWh)	3,504	4,784	3,880

Table ES-6. Morro Bay WEA Delineation Analysis for Option 3b

Morro Bay: Delineation Option 3b			
Parameter	**NW Lease Area**	**C Lease Area**	**E Lease Area**
Total area (km^2)	324	325	325
Average wind speed at 100 m (m/s)	9.7	9.6	9.4
Average depth (m)	1,126	1,051	988
Depth range (m)	988–1,271	953–1,284	884–1,165
Average seafloor gradient (degrees)	1.7	1.1	0.9
Average distance from Morro Bay (km)	105	91	77
Average distance from Port Hueneme (km)	335	319	306
4D × 10D Turbine Spacing with TLP Mooring			
Wake losses with all lease areas (%)	6.7%	9.1%	8.7%
Net capacity factor (%)	47.3%	46.1%	46.3%
Potential capacity (MW)	1,800	1,905	1,845
Annual energy production (GWh)	7,461	7,689	7,478
4D × 10D Turbine Spacing with Catenary Mooring			
Wake losses with all lease areas (%)	5.7%	7.2%	6.6%
Net capacity factor (%)	47.8%	47.1%	47.3%
Potential capacity (MW)	1,410	1,260	1,215
Annual energy production (GWh)	5,904	5,195	5,037
1 nm × 1 nm Turbine Spacing with TLP Mooring			
Wake losses with all lease areas (%)	6.1%	7.9%	7.8%
Net capacity factor (%)	47.6%	46.7%	46.7%
Potential capacity (MW)	1,350	1,500	1,440
Annual energy production (GWh)	5,629	6,135	5,896
1 nm × 1 nm Turbine Spacing with Catenary Mooring			
Wake losses with all lease areas (%)	4.8%	6.1%	6.0%
Net capacity factor (%)	48.2%	47.6%	47.7%
Potential capacity (MW)	900	975	930
Annual energy production (GWh)	3,803	4,066	3,884

Table ES-7. Morro Bay WEA Delineation Analysis for Option 3c

Morro Bay: Delineation Option 3c			
Parameter	**NW Lease Area**	**SW Lease Area**	**E Lease Area**
Total area (km^2)	324	324	327
Average wind speed at 100 m (m/s)	9.7	9.6	9.4
Average depth (m)	1,058	1,100	1,007
Depth range (m)	899–1,264	988–1,284	884–1,209
Average seafloor gradient (degrees)	0.8	1.8	1.0
Average distance from Morro Bay (km)	99	97	77
Average distance from Port Hueneme (km)	333	322	305
4D × 10D Turbine Spacing with TLP Mooring			
Wake losses with all lease areas (%)	6.1%	8.9%	8.8%
Net capacity factor (%)	47.6%	46.2%	46.2%
Potential capacity (MW)	1,695	1,845	1,830
Annual energy production (GWh)	7,065	7,464	7,408
4D × 10D Turbine Spacing with Catenary Mooring			
Wake losses with all lease areas (%)	5.4%	8.0%	8.3%
Net capacity factor (%)	47.9%	46.6%	46.5%
Potential capacity (MW)	1,320	1,470	1,575
Annual energy production (GWh)	5,543	6,007	6,414
1 nm × 1 nm Turbine Spacing with TLP Mooring			
Wake losses with all lease areas (%)	4.9%	7.3%	7.2%
Net capacity factor (%)	47.1%	47.0%	48.2%
Potential capacity (MW)	1,260	1,260	1,335
Annual energy production (GWh)	5,319	5,188	5,504
1 nm × 1 nm Turbine Spacing with Catenary Mooring			
Wake losses with all lease areas (%)	4.2%	6.4%	6.2%
Net capacity factor (%)	48.6%	47.4%	47.6%
Potential capacity (MW)	855	945	1,035
Annual energy production (GWh)	3,639	3,926	4,312

The results in Tables ES-2 to ES-7 show that a 1-GW wind power plant can be installed in all the proposed lease areas for each delineation under most turbine spacing and mooring technology assumptions. The exception is the 1 nm spacing with catenary moorings, which results in plant capacities of 700 MW to 900 MW in most lease areas. The range of wake losses among the cases assessed is 4.2% to 9.1%. The lowest wake losses are found for wind plants in the northwest corner of the Morro Bay WEA with low total capacities, whereas high wake losses are found in the center and southwest of the Morro Bay WEA for wind plants with high total capacities.

Key Findings

Quantitative assessment of delineation options

- We evaluated two options for delineating the Humboldt WEA into two lease areas and show that each can support a wind plant with a capacity of at least 1 GW under most mooring design and turbine spacing scenarios. The total generating capacity of the two Humboldt lease areas combined is between 1.5 and 3 GW for both delineation options.
- We evaluated three options for delineating the Morro Bay WEA into three lease areas that can hold a 1-GW wind plant under most mooring design and turbine spacing scenarios, and we evaluated one option for just two lease areas. The range of capacities for the full Morro Bay WEA is between 3 and 5 GW for all delineation options.
- The factors we considered that affect the value of the lease areas are provided in Table ES-1; of these, the most important parameters that affect lease area value are mooring technology type, water depth, inter-array wake losses, distance from ports and electric interconnection, geohazards, and surface area as determined by the number of aliquots. The number of aliquots were adjusted in the delineations to help balance some of the negative impacts for certain options. For example, the lease areas that are downstream in the prevailing wind direction are often given larger areas.
- Aside from turbine spacing, the nameplate capacity of a given lease area was most sensitive to the choice of mooring technology. At one extreme, tension-leg platforms require minimal space for the mooring system. At the other extreme, catenary mooring systems could require anchors spaced at 2000 m from the turbines, with an additional setback (on the order of 100 m) from the lease area boundary to the closest anchor point to allow clearance for anchor installation.
- The loss of useable lease area due to mooring system technology type becomes more significant in the deeper waters of the Pacific and is exacerbated in narrower lease areas with long edges. Catenary mooring lines, while feasible at these depths and a useful bounding case, are disadvantageous due to their large footprint and significant weight. In California, WEA site selection is challenging because avoidance of visual impacts drives sites away from shore, but the water depth rapidly becomes too deep for current floating wind technologies. These considerations lead to narrow WEAs that are longer in the direction parallel to shore—which is also the prevailing wind direction—and as a result they are likely to experience deep-array effects.
- Interarray wake effects were a key parameter in the delineation of the California WEAs, as they can increase wake losses by up to 30% in some cases. The effect on the various wind farms within a WEA is highly dependent on the wind farm location and the wind speed heading. The interarray effects can cause an energy deficit that is five times higher for downstream farms than upstream farms under some conditions.

Qualitative considerations for offshore wind development

- All the California lease areas assessed in this report are in relatively deep water, up to 1,300 m. Water depth adds cost to a project in several ways. Deeper water requires longer mooring lines and more complex logistics, which add cost. Longer mooring lines in turn lead to larger anchor circles that reduce the usable area and the total generating capacity of the lease area. Lease areas that are located on the western side of the WEAs, and further from shore, tend to have water depths that are significantly greater.
- The wind direction in California is extremely consistent from the north-northwest, which may enable tighter turbine spacing along the rows, perpendicular to the prevailing winds. To some extent, this can offset the lost capacity due to the mooring system space requirements.
- Potential obstacles including geohazards and undersea cables were considered. Geohazards included seismic effects (fault lines), steep slopes, and hard-rock bottom, which were identified using data drawn from published literature (Tajalli Bakhsh et al. 2020). Further work is needed to collect and analyze more detailed, site-specific data. Although some obstacles are known to be present, they did not generate major concerns based on interviews with developers, and most developers indicated that most geohazards identified could be mitigated and would not be a barrier to development in general.
- The Pacific is known for its higher seismic risk relative to other sites on the U.S. Outer Continental Shelf. We found that there is a significantly higher seismic risk in Humboldt than in Morro Bay based on expected ground accelerations. It is not yet known what the impact of a major earthquake would be to floating wind turbines, but it is likely that the impacts would be limited to the anchors, which would experience shaking and possible displacement. Vertical load moorings may be more susceptible to liquefaction and this consideration should be incorporated in the design process as liquefaction could result in reduced load carrying capacity.
- The availability of bulk transmission access will play a large role in establishing the value of the lease areas. This factor will be more important in differentiating between Morro Bay and Humboldt WEAs than among the lease areas within these WEAs. Morro Bay has much better access to existing transmission infrastructure due to the retirements of the Morro Bay power plant and Diablo Canyon Power Plant. Humboldt WEA can only reasonably export about 150 MW before major transmission upgrades are needed (Daneshpooy and Anilkumar 2022).
- Suitable port access is essential to support offshore wind energy development in the California WEAs. Because Humboldt and Morro Bay are separated by approximately 500 miles, there will need to be a port in each region. In Humboldt, the port of Humboldt Bay is well suited to be upgraded to handle offshore wind construction and maintenance. For Morro Bay, the exact location of the port is not yet known, but possible options include Port Hueneme or a new port at Diablo Canyon. The distance to the port has some impact on the cost of energy at the site but will not be the primary driver.

Limitations of the current analysis

- NREL developed the CA20 resource data for this analysis, which indicated extremely high average wind speeds at Humboldt and excellent resource characteristics at Morro Bay. In subsequent comparisons with the limited lidar measurements obtained from buoys deployed at Morro Bay and Humboldt, we found a relatively high bias, indicating that the CA20 data may overestimate actual wind speeds at hub height. This problem is being investigated, but the reader is cautioned that the uncertainty in the data is higher than expected. Nevertheless, this finding did not impact the delineation strategy or the results of this report.

- Our assessment of generating potential uses medium-fidelity tools to estimate likely ranges of energy production. It is not optimized to maximize power output, nor does it account for plant-level siting considerations such as cable routing, substation placement, or avoidance of specific obstacles (e.g., rocks). More precise estimates of wind plant performance require detailed site assessments and layout optimization that would be conducted after leases are awarded and detailed project parameters are known.

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1 Introduction

The Bureau of Ocean Energy Management (BOEM) is coordinating efforts among tribal, state, and local governments and federal agencies to identify the most appropriate areas for commercial wind energy leasing off the shore of California. BOEM initially identified three California Call Areas, designated Humboldt, Morro Bay, and Diablo Canyon, in an October 2018 Call for Information and Nominations (83 Fed. Reg. 53,096). BOEM's process for identifying areas included consideration of wind speed, water depth, marine life, and other ocean users. BOEM excluded National Marine Sanctuaries, nearshore areas with high levels of fishing activity, locations with existing undersea cables, vessel traffic lanes near the Santa Barbara Channel, and areas that could be identified with high concentrations of sensitive species.

The Humboldt Call Area was designated as a wind energy area (WEA) in July 2021. After consultation with the U.S. Department of Defense regarding fleet activities off the central coast, the Morro Bay Call Area was altered by removing some aliquots in the northern portion and adding extensions to the east and west of the original area.[2] The extension areas were published in a separate Call for Information and Nominations that was issued in July 2021 (86 Fed. Reg. 40,869). In November 2021, major portions of the original Morro Bay Call Area and the West Extension were designated as the Morro Bay WEA. As of March 2022, the Diablo Call Area had not been designated as a WEA and is not actively being studied. This report provides options for the delineation of lease areas in the Humboldt and Morro Bay WEAs.

The Humboldt WEA (Figure 1) is a 536 square kilometer (km^2; 207 square mile [sq. mi.]) stretch of ocean located northwest of Eureka, California, that comprises 372 BOEM aliquots. The Humboldt WEA is approximately 35 km from shore at its closest point and 55 km from shore at its farthest point.

The Morro Bay WEA (Figure 2) is located due west of Cambria, California, northwest of Morro Bay. It consists of 718 BOEM aliquots covering 975 km^2 (376 sq. mi.). The WEA is approximately 32 km from shore at its closest point and 60 km from shore at its farthest point.

The National Renewable Energy Laboratory (NREL) is providing scientific and technical services to BOEM under an interagency agreement that defines the purpose of this report: to provide technical assistance in delineating potential lease areas from the California WEAs that can be competitively auctioned to wind energy developers. The analysis summarized in this report is intended to help BOEM maximize efficient offshore wind energy resource use and ensure fair return to the government for use of the lease areas by assessing options for viable ways to divide the WEAs into auctionable commercial lease areas of approximately equal value. This report provides several delineation options for BOEM to consider. BOEM will make the final decision on lease area delineation, taking the information herein into consideration.

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[2] BOEM defines offshore boundaries in terms of Outer Continental Shelf lease blocks and aliquots. Each aliquot is a 1,200 meter (m) by 1,200 m square and each lease block contains 16 aliquots in four rows of four, with some exceptions related to the projection of a rectangular grid onto spherical coordinates. For more details, see https://www.boem.gov/oil-gas-energy/mapping-and-data.

NREL has performed similar analyses for offshore wind lease areas on the Atlantic coast, in Massachusetts, Rhode Island, New Jersey, and Maryland (Musial, Elliott, et al. 2013; Musial et al. 2013a; 2013b; Musial, Parker, et al. 2013). A similar approach was used for the delineation of offshore lease areas in California; however, additional considerations were required to understand the unique challenges for floating offshore wind systems in the deep waters of the Pacific region. NREL analyzed the likely costs of floating offshore wind in California in a previous study (Beiter et al. 2020).

The goal of NREL's analysis is to delineate potential lease areas that are technically and economically feasible for wind energy development. The scope of our analysis is limited to factors affecting technical feasibility and does not include other factors such as environmental assessment or consideration of competing uses. These factors informed BOEM's initial designation of the WEA and are addressed in the environmental assessments for each WEA (BOEM 2022a; 2022b). We considered several physical site characteristics in each WEA and did not identify any features that would make wind energy development infeasible. Site characteristics such as water depth, seafloor slope, and distance to land-based infrastructure will impact the cost of development at each location. Our objectives for each WEA were to subdivide it into potential lease areas of approximately equal value and to demonstrate that at least 1 gigawatt (GW) can be deployed in each lease area.

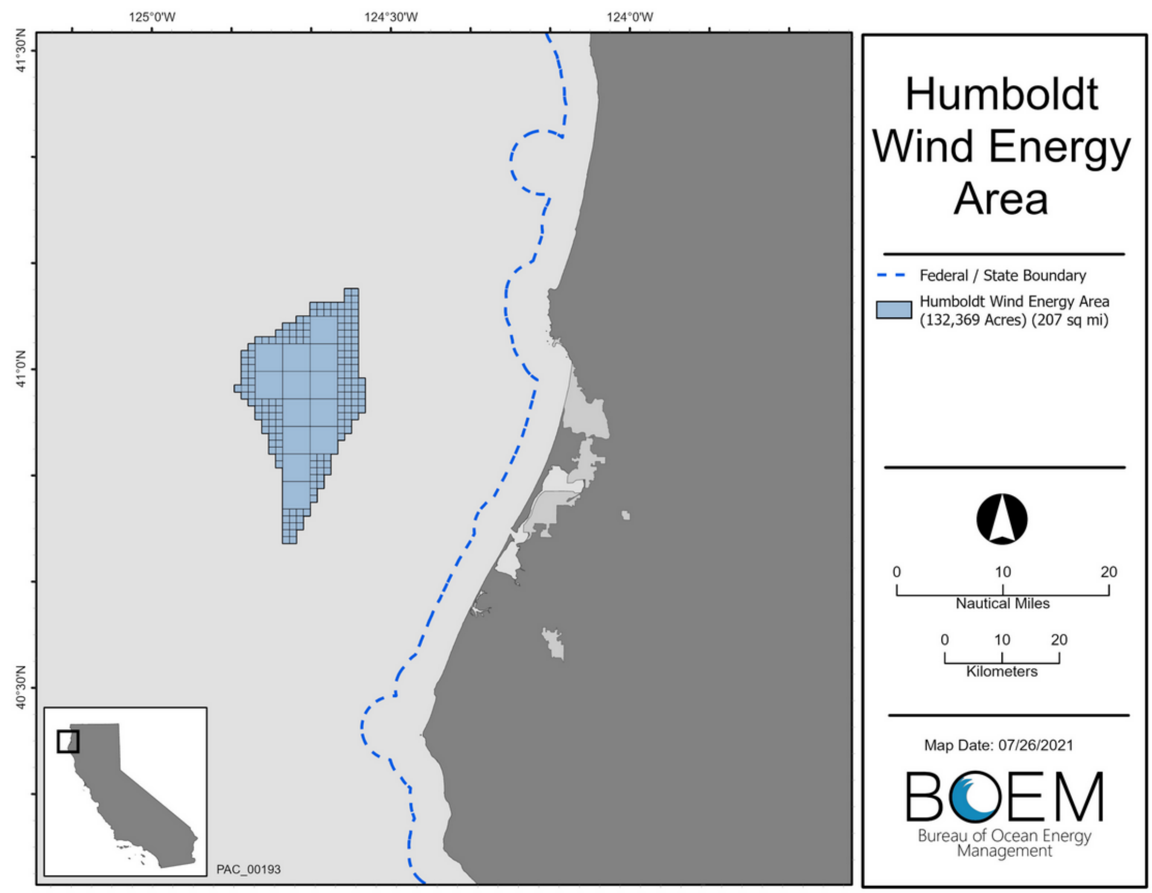


Figure 1. Humboldt wind energy area (WEA). The smaller squares within the WEA represent BOEM aliquots and the larger squares are lease blocks encompassing 16 aliquots each. *Image from BOEM (https://www.boem.gov/renewable-energy/state-activities/california)*

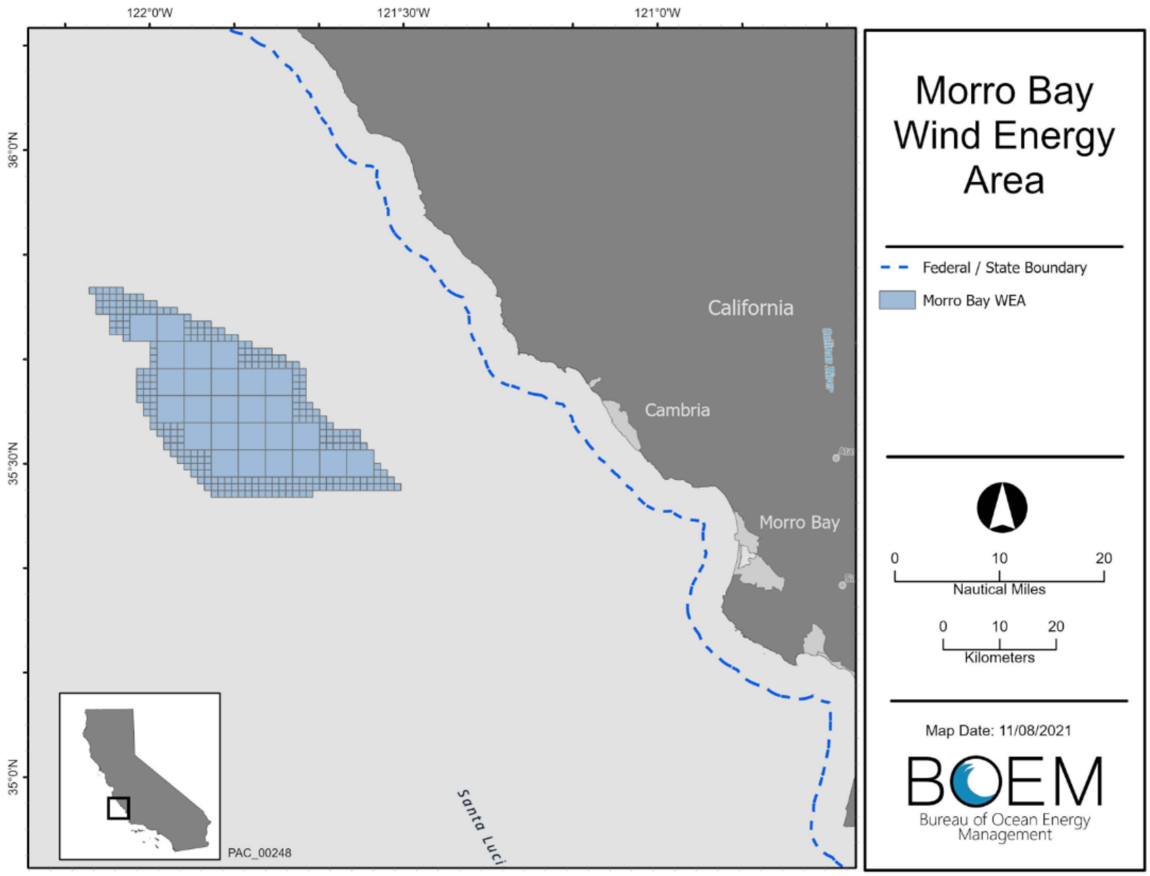


Figure 2. Morro Bay WEA. The smaller squares within the WEA represent BOEM aliquots and the larger squares are lease blocks encompassing 16 aliquots each. *Image from BOEM*

2 Nominations Review

In response to the October 2018 call, 10 developers submitted nominations for wind energy development in the Humboldt Call Area and 11 submitted nominations for Morro Bay. An additional six developers submitted nominations for the East and West Extensions to the Morro Bay Call Area in response to the July 2021 call. The nominations contain varying levels of detail regarding proposed development, ranging from brief statements of interest and qualifications to in-depth reviews of site characteristics and initial project outlines. NREL reviewed the nominations and then contacted developers to obtain more detail regarding the technical aspects of project development, including project size, technology selection, environmental and siting considerations, and land-based infrastructure needs.

We were interested in understanding developers' perspectives on the Call Areas so that we could better assess how site characteristics affect the value of potential lease areas for offshore wind development. Developers' perspectives also informed and validated the selection of plant and turbine capacity, layout, and mooring options that we used to model the generation potential of each lease area.

2.1 Technology Selection

Developers are still in the early stages of technology selection. Water depths in both WEAs are 550 meters (m) or more, which greatly exceeds typical depths for fixed-bottom foundations of 60 m or less. Although floating substructures will be required, there is currently no consensus on which substructure type is the best choice for development. Figure 3 presents three examples of floating substructures for offshore wind turbines, but other types (e.g., barge) are also possible, and designs continue to evolve as new concepts are developed and demonstrated. The spar shown at left in Figure 3 requires a deep-draft harbor or protected assembly location; without ready access to either of those, developers do not consider it a feasible option for the California WEAs. The semisubmersible design, shown in the center of Figure 3, and similar variants are feasible because they have shallow drafts when fully assembled that allow them to be towed between standard port facilities and the turbine's location within the wind project. They are connected to the seabed using either catenary, taut, or semi-taut mooring lines, which are described in more detail in Section 4.3. The illustration on the right of Figure 3 is a tension-leg platform (TLP) that is connected to the seabed by vertical tendons. The installation process for TLPs is more complex and expensive than for other floating substructures because they are inherently unstable until the tension legs are attached. They also have more complex anchoring requirements because of the high loads on the vertical tendons. As a result of these engineering challenges, they have not yet been demonstrated for offshore wind turbines. However, the small footprint of TLPs on the seabed could be advantageous in deep water, and several designs have been proposed for wind turbines that may avoid typical TLP drawbacks.

Figure 3. Examples of floating substructure types: spar (left), semisubmersible (center), and tension-leg platform (right). *Illustration by Joshua Bauer, NREL*

The exact size of turbines to be installed in the California WEAs is unknown as of the publication of this report. Developers tend to prefer the largest commercially available turbines at the time of construction because increasing the turbine rating tends to decrease per-unit costs for the same total plant size (Shields et al. 2021). Nominations submitted in 2019 identified 8 to 15 megawatts (MW) as a potential range of turbine ratings, whereas interviews conducted in 2020 anticipated rated powers ranging from 12 to 15 MW, reflecting recent announcements from turbine manufacturers. Most turbine manufacturers have announced they are developing prototypes in the 12 to 15 MW range that are expected to be commercially available beginning in 2022–2024, with examples in Table 1. While turbines larger than 15 MW may be available by the time projects in California are built in the early 2030s, 15 MW is likely to reflect the market installed average at that time. Musial et al. (2021) document a lag of approximately 6 to 8 years between the installation of a new prototype and widespread adoption of turbines of that size.

Table 1. Representative Turbine Sizes

Turbine	Rated Capacity	Rotor Diameter	Hub Height	Commercial Availability
GE Haliade-X	12–14 MW	220 m	150 m	2022
SG 14-222 DD	14–15 MW	222 m	Site-specific	2024
Vestas V236-15.0	15 MW	236 m	Site-specific	2024
IEA Wind 15-MW	15 MW	240 m	150 m	N/A
MingYang MySE16.0-242	16 MW	242 m	Site-specific	2024

2.2 Transmission and Grid Interconnection

Developers identified power offtake and transmission as the key risks for project development in the Humboldt WEA. The existing transmission capacity in Humboldt County is limited and upgrades will be costly—estimates range from to $1.4 billion to $2.8 billion for land-based transmission upgrades to support a 1.8-GW wind plant (Severy and Jacobson 2020). The timeline for permitting and constructing new transmission is as long or longer than that of an offshore wind plant, and if transmission upgrades are not in place when a wind plant is capable of generating power, the wind plant relying on that transmission line will be unable to deliver power to the grid and earn revenue.

The transmission grid is more accessible in the Morro Bay region than along the north coast. Two potential points of interconnection that have been identified near the Morro Bay WEA are substations at Morro Bay and Diablo Canyon. The Morro Bay substation is located at the site of a former thermal generation power plant. The Diablo Canyon substation is approximately 20 km south of Morro Bay and currently serves the 2.2-GW Diablo Canyon nuclear power plant that is scheduled to be retired in 2025. Both substations are close to the coast, are connected to high-voltage transmission lines, and are likely to have available capacity to accept new generation.

2.3 Project Size

Developers proposed a wide range of plant capacities for projects within each WEA. Figure 4 summarizes the proposed capacities, including multiple plant sizes in some cases to reflect phased development—for example, initial construction of a 400-MW plant followed by expansion to 2 GW. The median proposed plant capacity was 1 GW in both areas. Constraints on transmission in the Humboldt region influenced some developers' proposals of smaller plant capacities in the Humboldt WEA. These represent pilot projects of 5 to 10 turbines that could be built without expanding transmission capacity. In both WEAs, proposed capacities at the upper end of the range assume that a single project occupies the full WEA. Developers' initial estimates of the generating potential for the full WEA are based on power capacity densities of 2.5–5 MW/km^2, leading to a total power generating potential of between 1.3 and 2.6 GW in Humboldt and between 2.4 and 4.9 GW in Morro Bay.

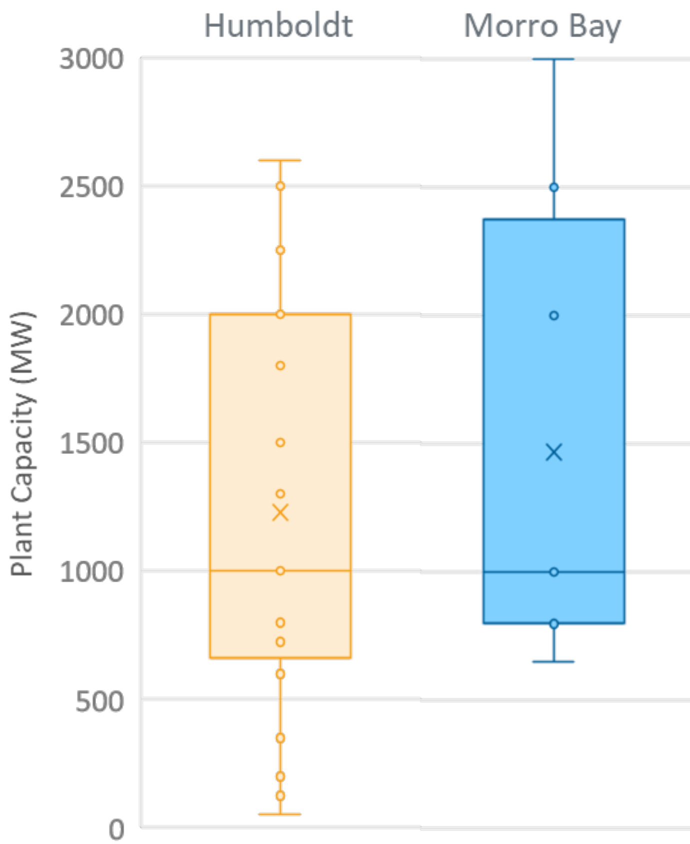


Figure 4. Plant power capacity proposals for full or partial WEAs from nominations and developer interviews. Each circle represents a proposed plant capacity; horizontal lines in each color, from bottom to top, indicate the minimum, 25th percentile, 50th percentile, 75th percentile, and maximum; and × marks the mean capacity.

2.4 Plant and Turbine Spacing

Optimized layouts require detailed siting studies that have not yet been carried out; however, developers identified wake losses and mooring footprints as factors that are likely to influence layout. No geohazards were identified that appear likely to prevent development, although some physical site conditions could influence the placement of individual turbines and anchors; these are discussed in Section 3.

Turbine spacing is strongly influenced by the prevailing wind direction, which determines how wakes propagate and affect downstream turbines. In both Morro Bay and Humboldt, winds most frequently blow from the north-northwest, with occasional winds from the south and infrequent winds from other directions (refer to Figure 7 and Figure 8). Wake losses can be reduced by increasing the separation between turbines in the prevailing wind direction (approximately north-south). Wake losses are likely to be minimal in the direction perpendicular to the prevailing wind, so tighter spacing allows for a higher total installed capacity. Assuming a rectangular grid layout with spacing based on the turbine rotor diameter (D), nominations and developer interviews suggested that turbine spacings of 7D–10D would be considered along the prevailing wind direction and 3D–7D in the perpendicular direction.

A second driver of turbine spacing constraints is the mooring system design. Some developers indicated that separation distances due to mooring footprints in deep water could be greater than typical distances for wake loss mitigation. Mooring footprints are considered in more detail in Section 4.3.

2.5 Environmental and Siting Considerations

Several site-specific considerations may impact project design. Developers mentioned possible hazards, including seismic terrain, interaction with wildlife such as marine mammals, and kelp entrapment adding weight to mooring lines. Cable-crossing protocols will need to be implemented to manage situations when cables transmitting power and/or data from each wind plant intersect with cables from another wind plant or with subsea telecommunications cables. New telecommunication cable routes pass through portions of both WEAs and could impact the siting of turbines, anchors, and subsea cables.

2.6 Project Timeline

Developers estimated that the timeline from lease auction to wind plant commissioning could take from 5 to 9 years, with the shortest estimates corresponding to smaller plant capacities. The main factor affecting developers' estimates of the commercial operation date was the timing of the lease auction.

2.7 Port Infrastructure

The Humboldt Bay Harbor District is the closest port to the Humboldt WEA, and developers identified it as the most likely base for assembly, operations, and maintenance. The harbor district is investing in improvements that are intended to support fabrication and assembly of offshore wind components. A detailed assessment of the port capabilities and potential improvements to support offshore wind can be found in Porter and Phillips (2020).

The city of Morro Bay has a harbor that one developer identified as a potential base for routine operations and maintenance; however, fabrication and assembly would require a larger port to handle offshore wind vessels and staging of major components. The ports of Hueneme, Long Beach, and Los Angeles were assessed to determine their suitability for offshore wind installation in Porter and Phillips (2016). The ports are capable of handling larger vessels and components but would require additional investment to accommodate staging and assembly of offshore wind turbines. It is also possible to consider building a new port that could be located at the Diablo Canyon site to gain closer proximity to the WEA and lower cost.

3 Physical Site Assessment

The aim of the physical site assessment is to characterize the WEAs based on average annual wind speeds at hub height, average annual wind directions, bathymetry, surface area, distance from shore, and proximity to relevant geographic infrastructure such as service ports, potential construction ports, and grid connections. This section highlights some of the possible impacts of these site characteristics for potential wind energy installations, with several maps to identify the spatial distribution of the relevant attributes.

3.1 Wind Resource

As part of a larger effort for BOEM, NREL has updated the resource data contained in the Wind Integration National Dataset (WIND) Toolkit with a 20-year time series compiled from ensemble runs of the Weather Research and Forecasting numerical weather prediction model (Optis et al. 2020). The new data set represents a longer time series (20 years versus 7 years) and utilizes a newer atmospheric model that was validated with lidar wind speed measurements on the Atlantic coast and surface-level measurements from buoys offshore California. After the new data set was generated, floating lidars were deployed within the Morro Bay and Humboldt WEAs. Comparison of the new lidar data with modeled results for the same time period has identified a positive bias in the modeled results, which is larger in Humboldt than Morro Bay. NREL is continuing to investigate the differences between the measured and modeled values.

Figure 5 and Figure 6 show the annual average wind speeds in the Humboldt and Morro Bay regions, respectively. Mean wind speeds at a height of 100 m are between 9.75 meters per second (m/s) and 11.0 m/s within the Humboldt WEA and between 9.0 m/s and 10.0 m/s in the Morro Bay WEA. Wind roses taken from the ensemble data at the centroid of each WEA show the directionality of the wind at 100 m and 150 m above mean sea level and are provided in Figure 7 and Figure 8. The wind blows primarily from the north-northwest with little difference between potential hub heights of 100 m and 150 m. The prevailing winds in Humboldt come from about 15° northward of those in Morro Bay.

Figure 9 illustrates the temporal variation in the wind resource. During the day, wind speeds in both regions tend to dip slightly in the morning and peak in the midafternoon to early evening. This diurnal trend might be complementary with solar energy resources, which peak in the middle of the day. The average wind speed in Morro Bay reaches a lower minimum and the difference between the minimum and maximum wind speeds is larger, producing a steeper rise to the evening peak. Average wind speeds in Humboldt are more consistent throughout the day, although there is some seasonal variation with the highest wind speeds observed in the summer.

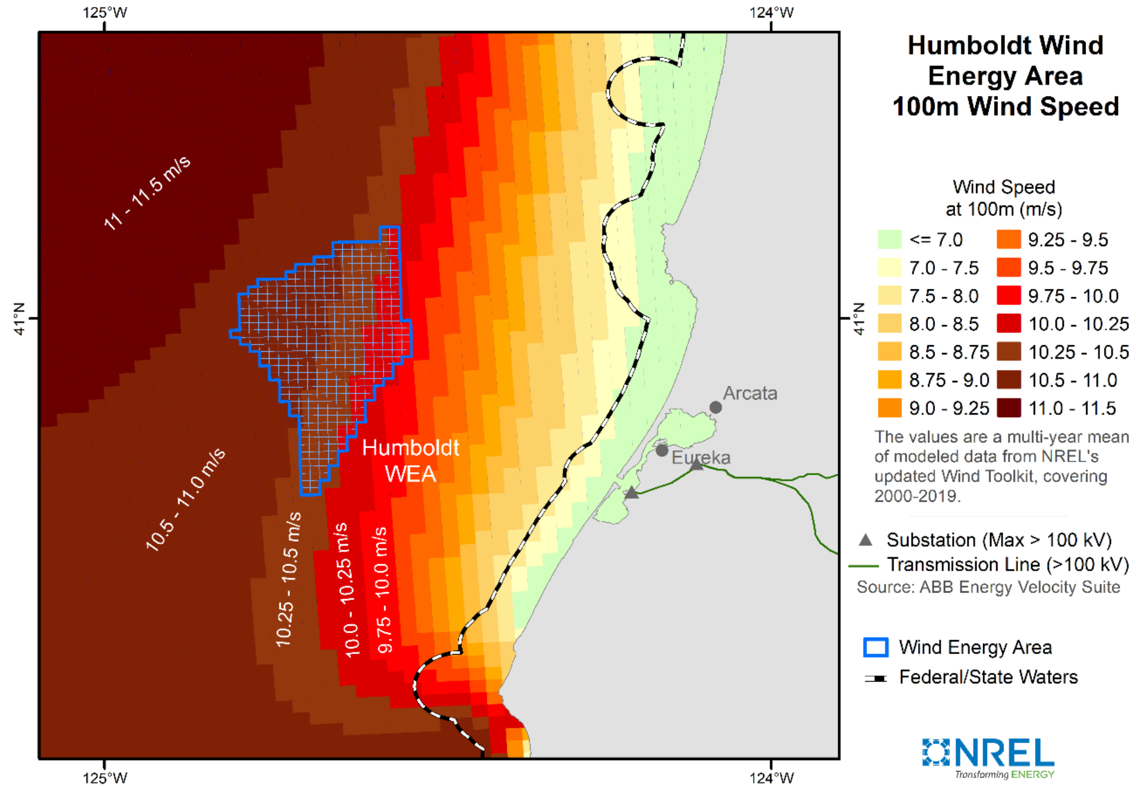


Figure 5. Annual mean wind speed at 100 m above mean sea level in the Humboldt WEA and surrounding region

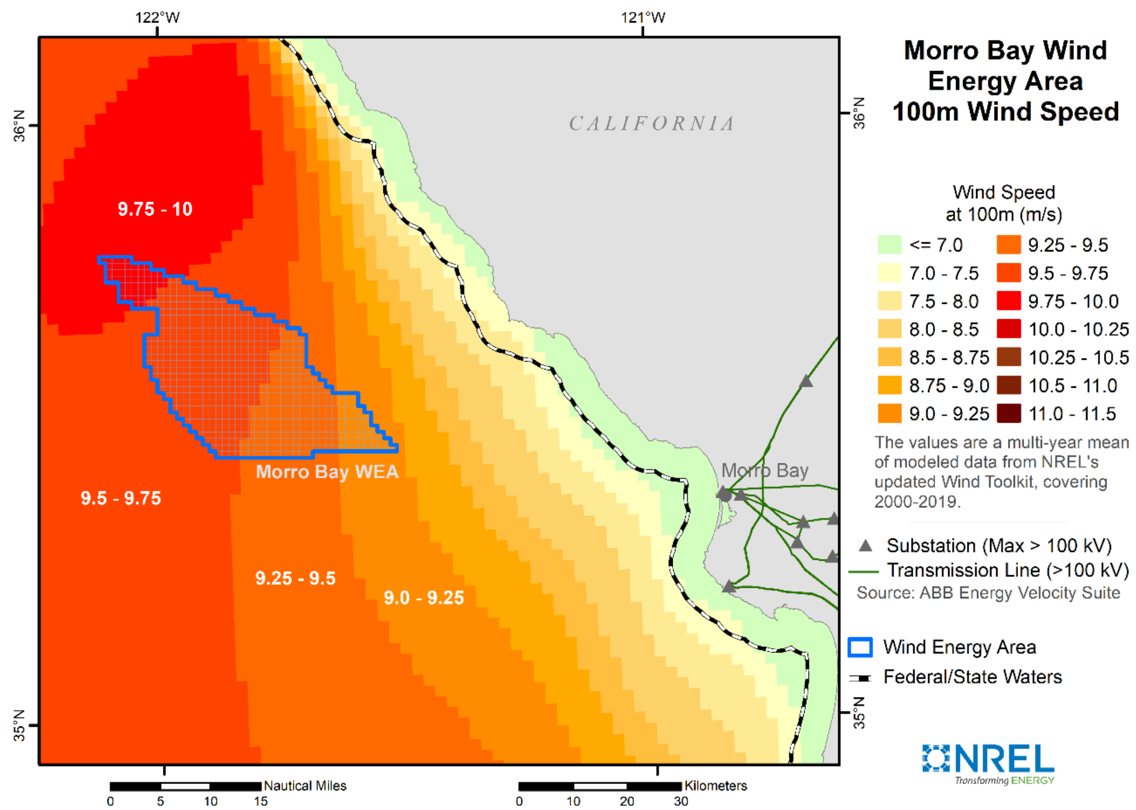


Figure 6. Annual mean wind speed at 100 m above mean sea level in the Morro Bay WEA and surrounding region

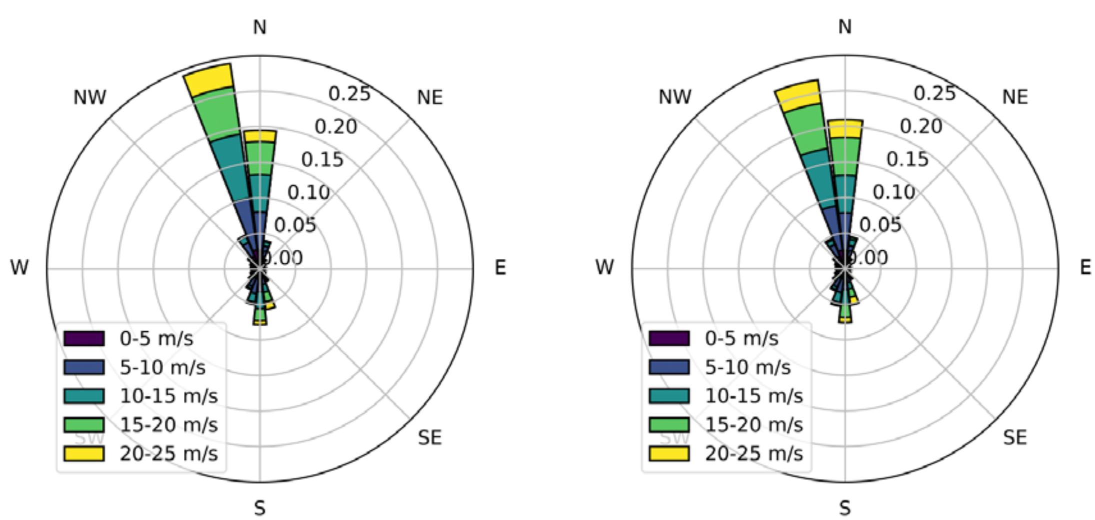


Figure 7. Wind roses at 100 m (left) and 150 m (right) above mean sea level at the centroid of the Humboldt WEA. *Image from wind resource data from the updated NREL WIND Toolkit, 2000–2019 (Optis et al. 2020)*

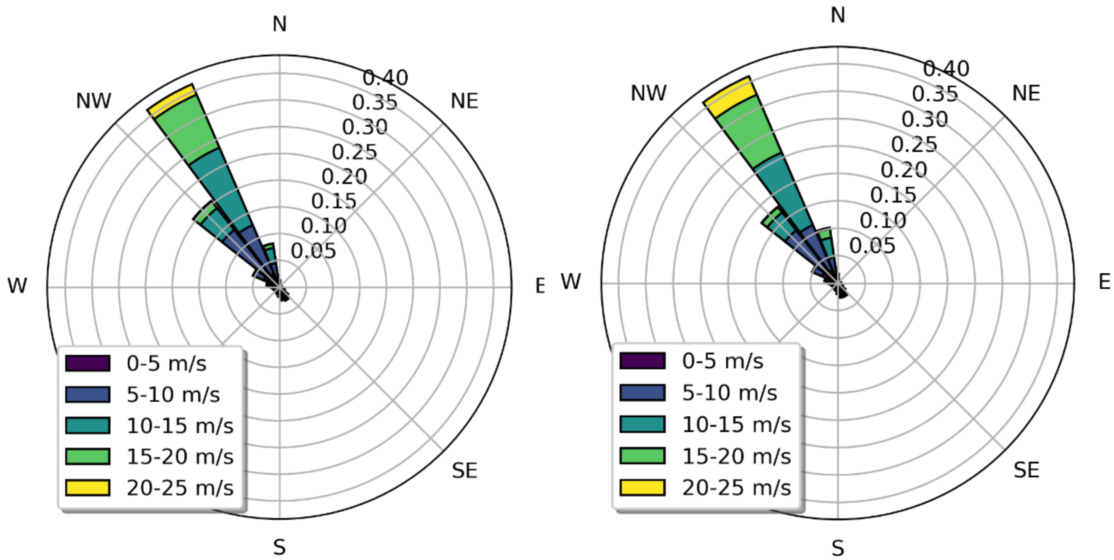


Figure 8. Wind roses at 100 m (left) and 150 m (right) above mean sea level at the centroid of the Morro Bay WEA. *Image from wind resource data from the updated NREL WIND Toolkit, 2000–2019 (Optis et al. 2020)*

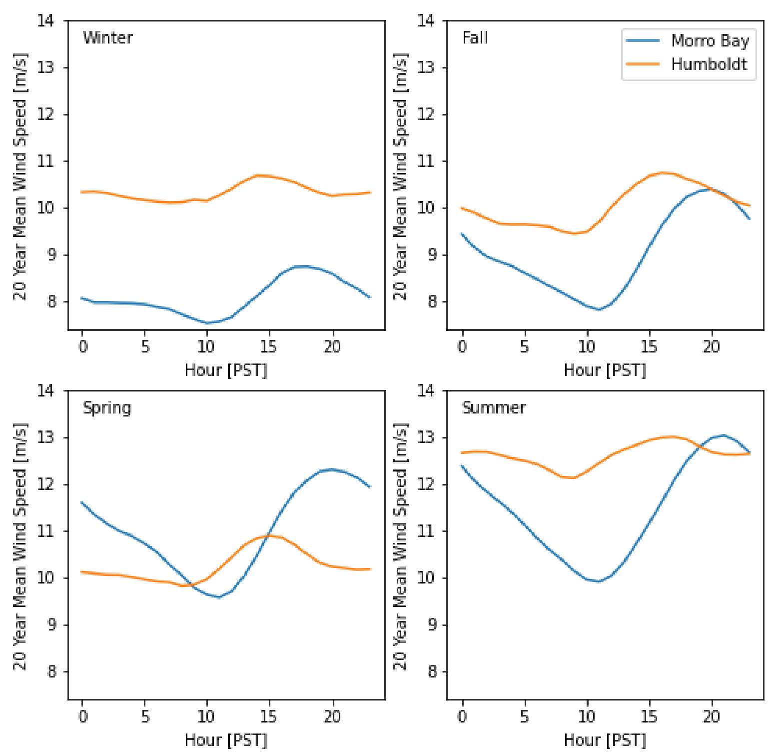


Figure 9. Seasonal diurnal wind speed profiles at 150 m for the Morro Bay and Humboldt WEAs

3.2 Bathymetry and Seafloor Characteristics

The conditions of the seafloor are of significant interest to project developers, as they dictate the design of the offshore wind turbine mooring and anchoring system. Maps showing the bathymetry of the Humboldt and Morro Bay WEAs and surrounding ocean are provided in Figure 10 and Figure 11. Bathymetry data were taken from the U.S. Coastal Relief Model (National Geophysical Data Center 2003a; 2003b) and were also used to calculate the seafloor gradient, which impacts the selection of the turbine anchoring system, the degree of sediment motion and scour, and the likelihood of landslides in the region. Seafloor gradients are shown in Figure 12 and Figure 13.

The water depths of the Humboldt WEA are primarily between 550 and 1,000 m, with increasing depths reaching 1,100 m toward the western boundary. This is where the gradients steepen and approach or exceed 4°, which can greatly increase the risk of slope instability and submarine landslides as well as make anchor placement more challenging. Several localized areas with sharp gradients are noticeable within the WEA boundaries, which would require more detailed surveying and construction planning by an offshore wind developer. Overall, the slopes within the central area of the WEA are relatively uniform. The Morro Bay WEA has deeper water depths between 800 and 1,300 m; however, the seabed gradients are generally smaller than in Humboldt.

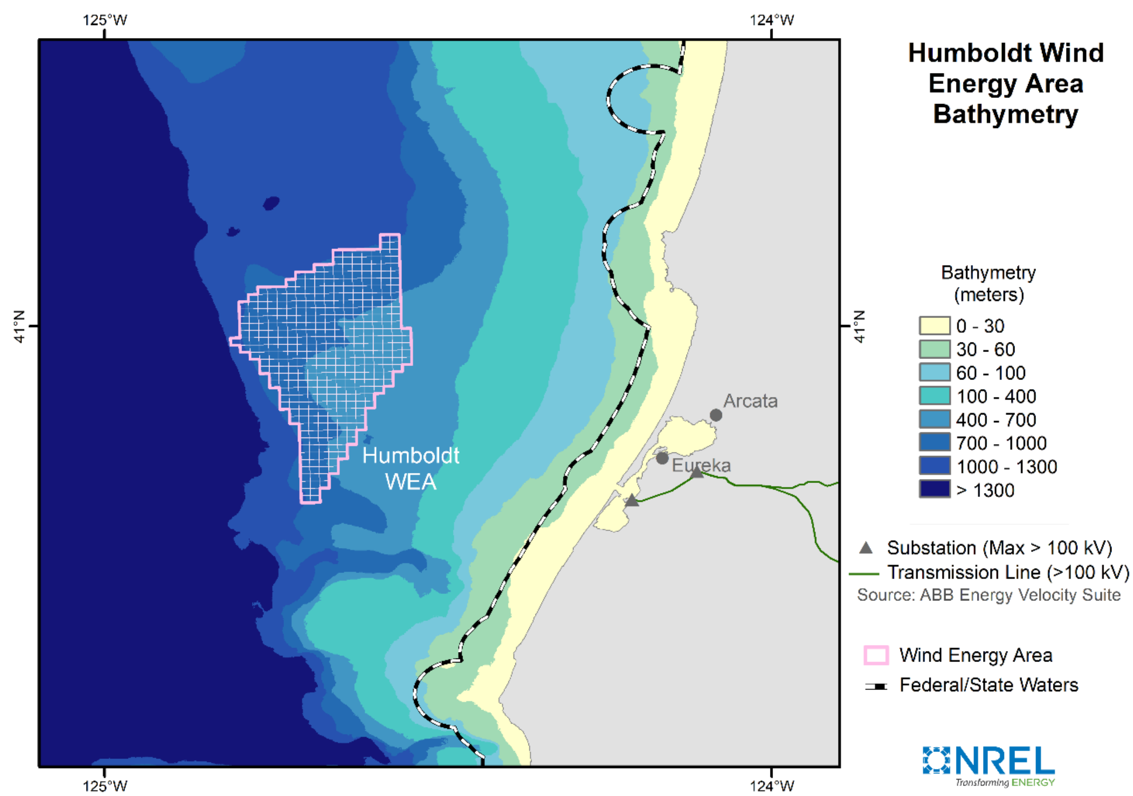


Figure 10. Bathymetry of the Humboldt WEA and surrounding region

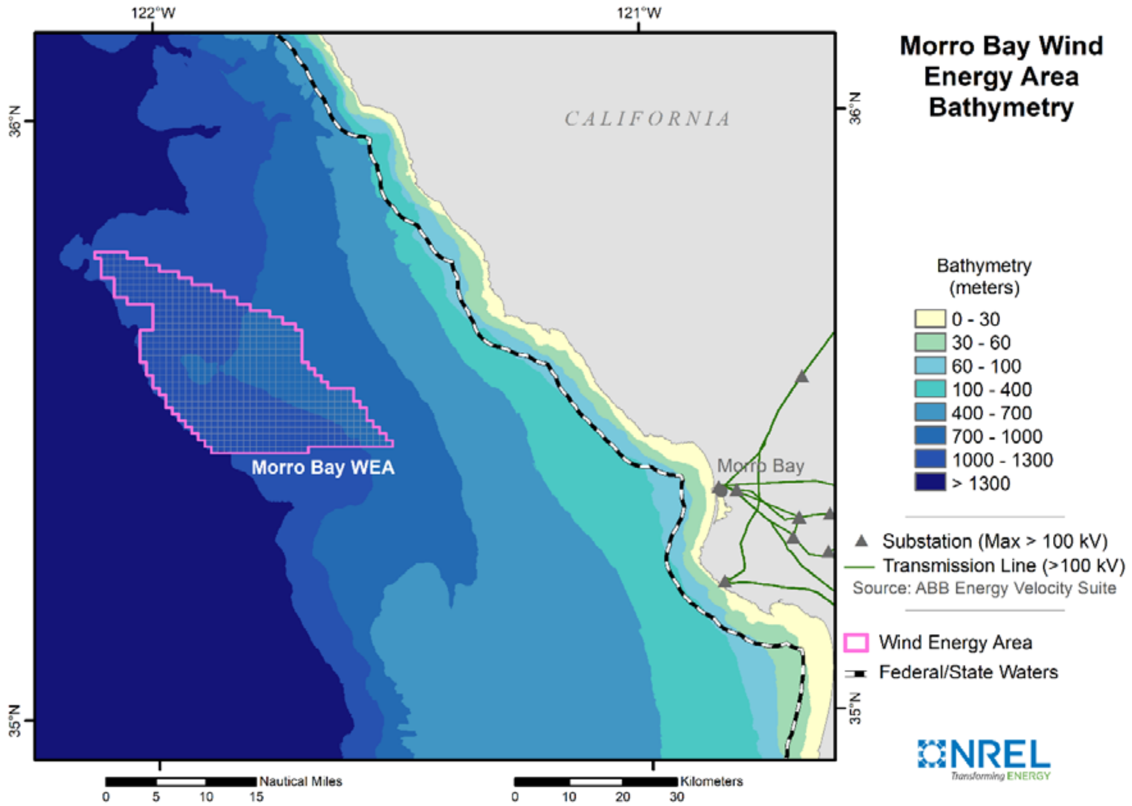


Figure 11. Bathymetry of the Morro Bay WEA and surrounding region

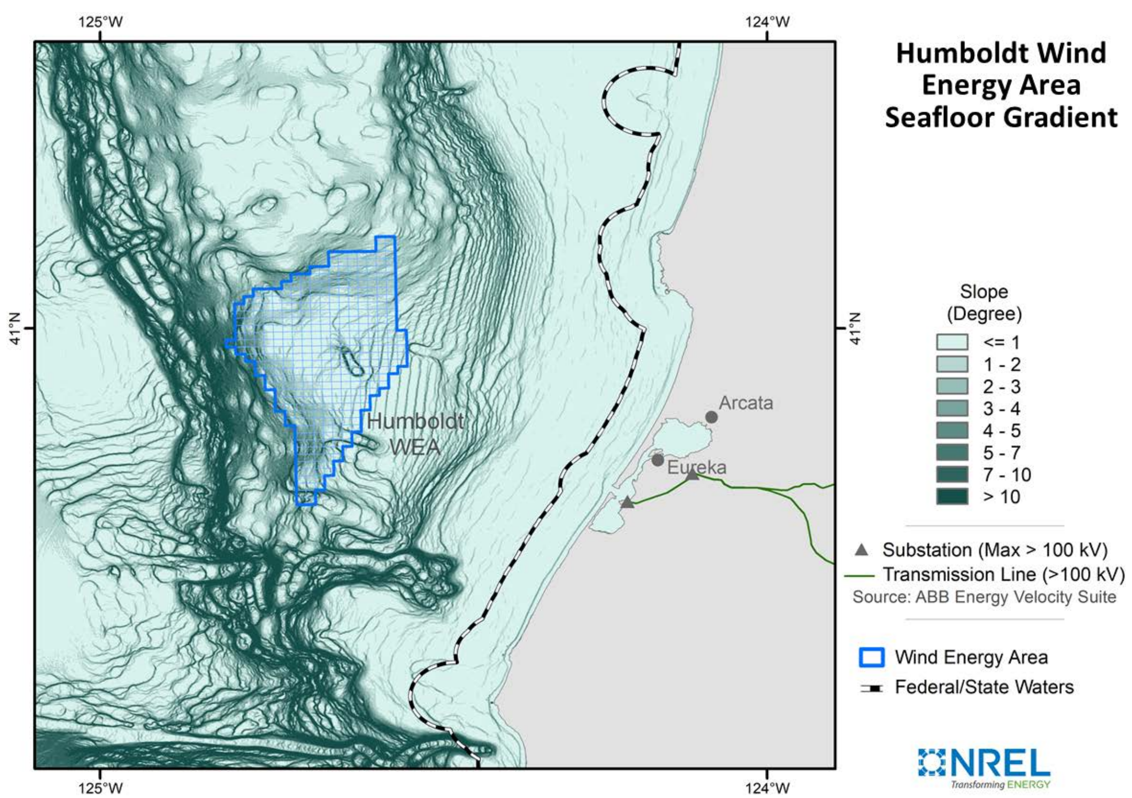


Figure 12. Seafloor gradients of the Humboldt WEA and surrounding region

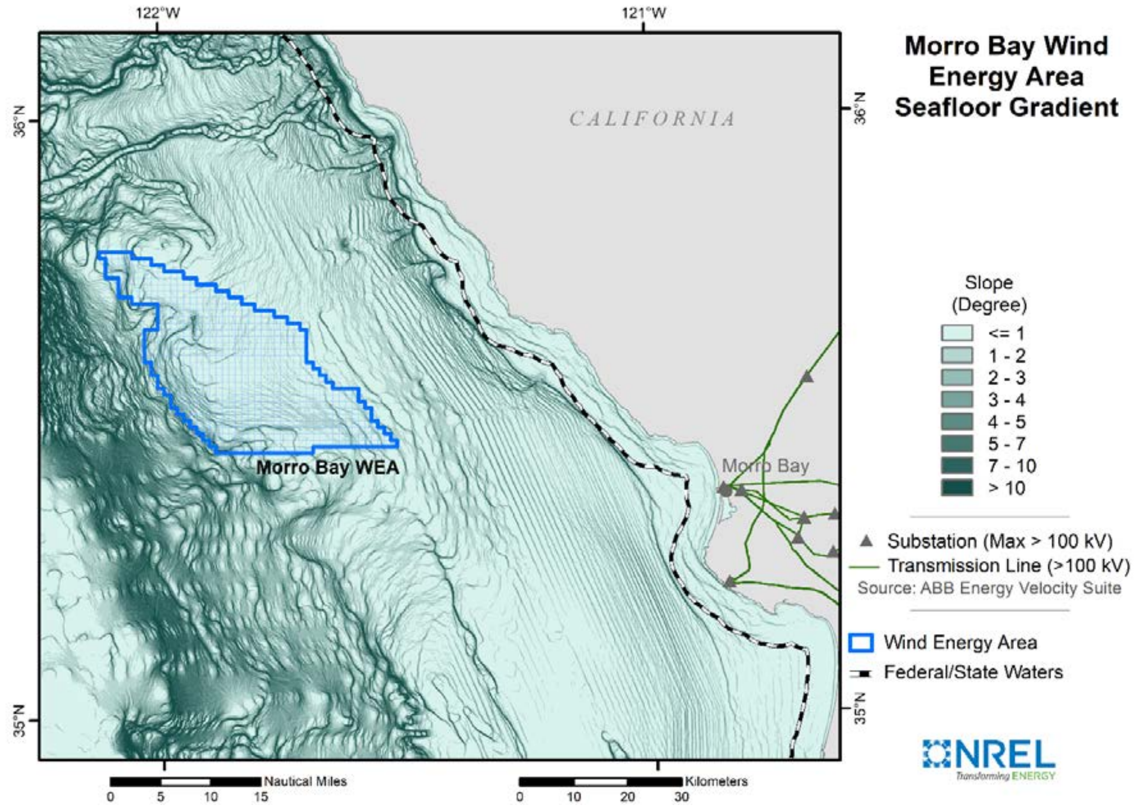


Figure 13. Seafloor gradients of the Morro Bay WEA and surrounding region

There are limited data available to characterize the seafloor in the Humboldt and Morro Bay WEAs. A broad survey of the geology, bathymetry, and seafloor characteristics relevant to wind energy development in the California WEAs was carried out by the RPS Group (Tajalli Bakhsh et al. 2020). Along the north coast, the best data currently available come from a survey conducted by the Active Tectonics and Seafloor Mapping Lab at Oregon State University (Goldfinger et al. 2014). These data have significant uncertainty as they were intended to provide baseline seafloor geology information at a regional scale with only some areas of more detailed, higher resolution data that are largely outside the WEA. A more recent multiagency data collection effort was conducted in the Morro Bay region; the sediment data from that survey will inform assessments of the Morro Bay WEA once they are fully analyzed (Cochrane et al. 2022). Soil classifications inferred from the available data are shown in Figure 14 and Figure 15. In the Humboldt WEA, the soil type is primarily mud/muddy sand, although pockets of hard soil/rock/rock mix exist, which may impact the choice of floating wind turbine anchors and subsea cable designs or burial strategies in these areas. In the Morro Bay WEA, the substrate is primarily classified as mud in the regions covered by available data.

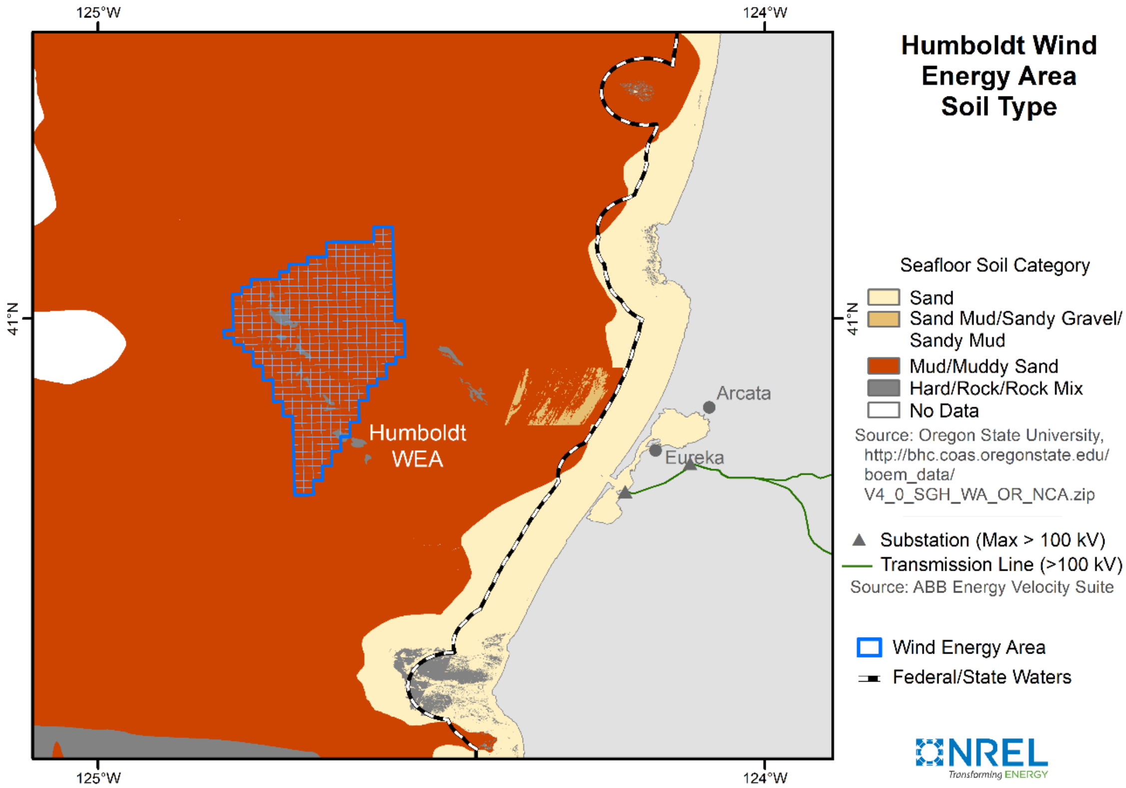


Figure 14. Soil types of the Humboldt WEA and surrounding region

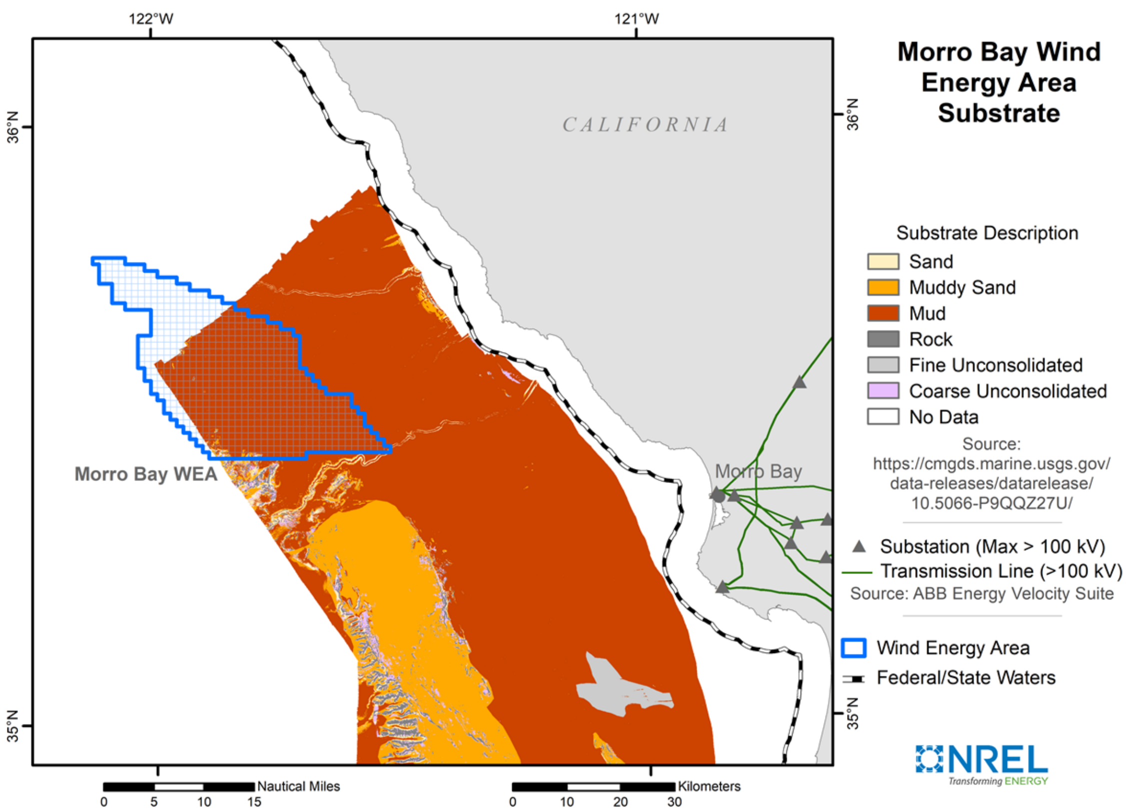


Figure 15. Soil types of the Morro Bay WEA and surrounding region

3.3 Seismic Conditions

The California coast is known as a region of seismic activity with many mapped fault lines, and the Morro Bay and Humboldt WEAs are no exception. The increased likelihood of major earthquakes near these fault lines represents an inherent risk to offshore wind project developers. While the presence of faults is an important consideration, an additional metric is required to quantify the overall suitability of the site for offshore wind development. Again, following the analysis presented in Tajalli Bakhsh et al. (2020), the seismic hazard is evaluated via the peak ground acceleration (PGA), which is the maximum ground acceleration magnitude recorded in historical earthquake records. The key metric is the PGA for a 10% probability of exceedance in 50 years—in other words, the expected ground acceleration that would be experienced in the region during a 500-year earthquake. The PGA may not be a major contributor to loads, but it could induce soil liquefaction (especially in areas with steeper seafloor gradients) and reduce anchor load carrying capacity. Figure 16 and Figure 17 identify major quaternary fault lines and peak seafloor accelerations (expressed as a percentage of gravitational acceleration) in the Humboldt and Morro Bay regions.

The data show that several fault lines are present within the WEA boundaries, which may impact offshore wind project development by dictating the location and/or orientation of mooring lines or submarine cables. Furthermore, the PGA values in Humboldt of between 30% and 40% of gravitational acceleration are relatively high and are considered to be in the lower half of the suitability range for offshore wind development (Tajalli Bakhsh et al. 2020). PGA values in the Morro Bay WEA are lower, between 6% and 10% of gravitational acceleration. Developers will need to take this seismic risk into consideration as part of their initial design basis and take steps to ensure that anchors can adequately resist these conditions.

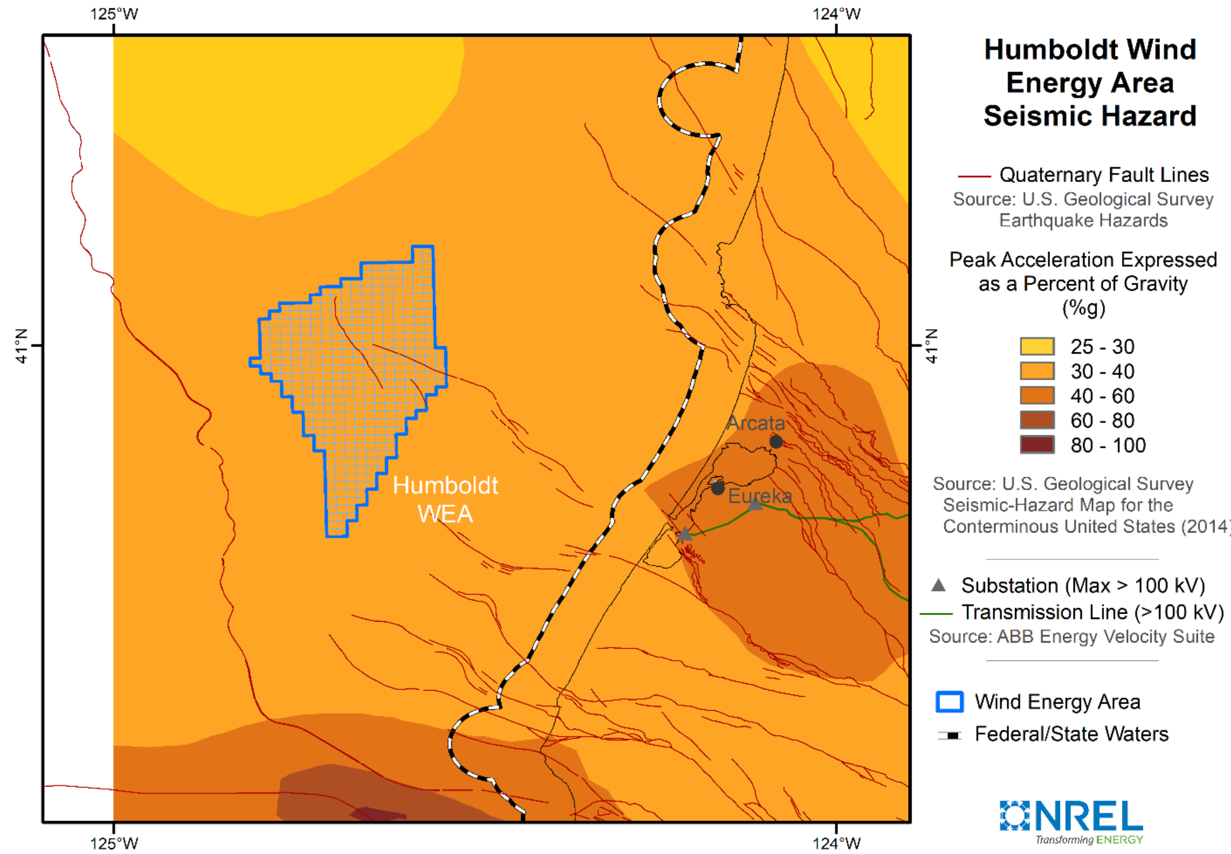


Figure 16. Seismic hazard and quaternary fault lines of the Humboldt WEA and surrounding regions. Seismic hazard is evaluated by considering the peak acceleration of the seafloor.

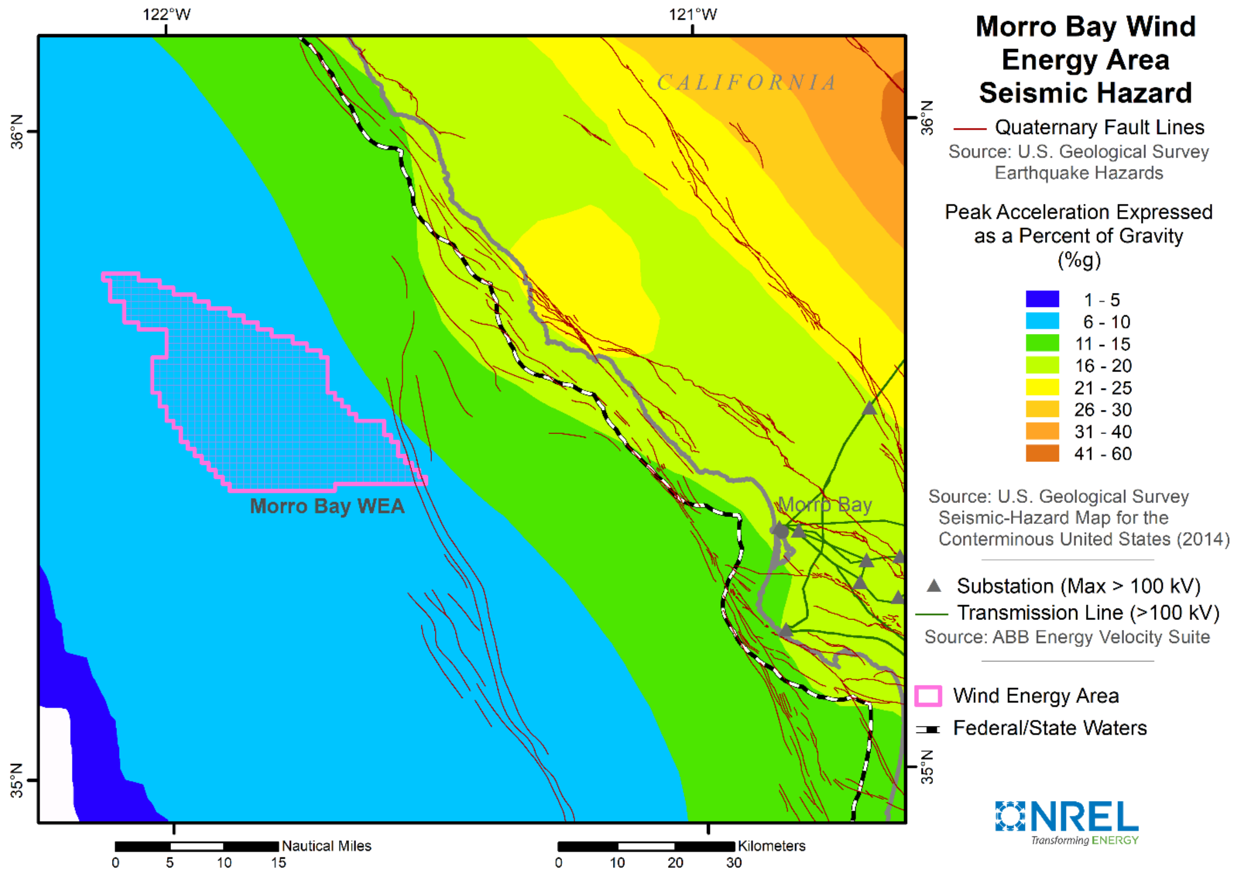


Figure 17. Seismic hazard and quaternary fault lines of the Morro Bay WEA and surrounding region. Seismic hazard is evaluated by considering the peak acceleration of the seafloor.

3.4 National Marine Sanctuaries

California is home to a range of marine wildlife species and has a number of marine protected areas to encourage conservation. The Monterey Bay National Marine Sanctuary is adjacent to the northern two-thirds of the Morro Bay WEA along its eastern boundary, between the WEA and the coast (Figure 18). An additional area to the south and east of the Morro Bay WEA has been proposed for sanctuary designation as the Chumash Heritage National Marine Sanctuary. A final decision on the proposed sanctuary is anticipated in 2024 or 2025.

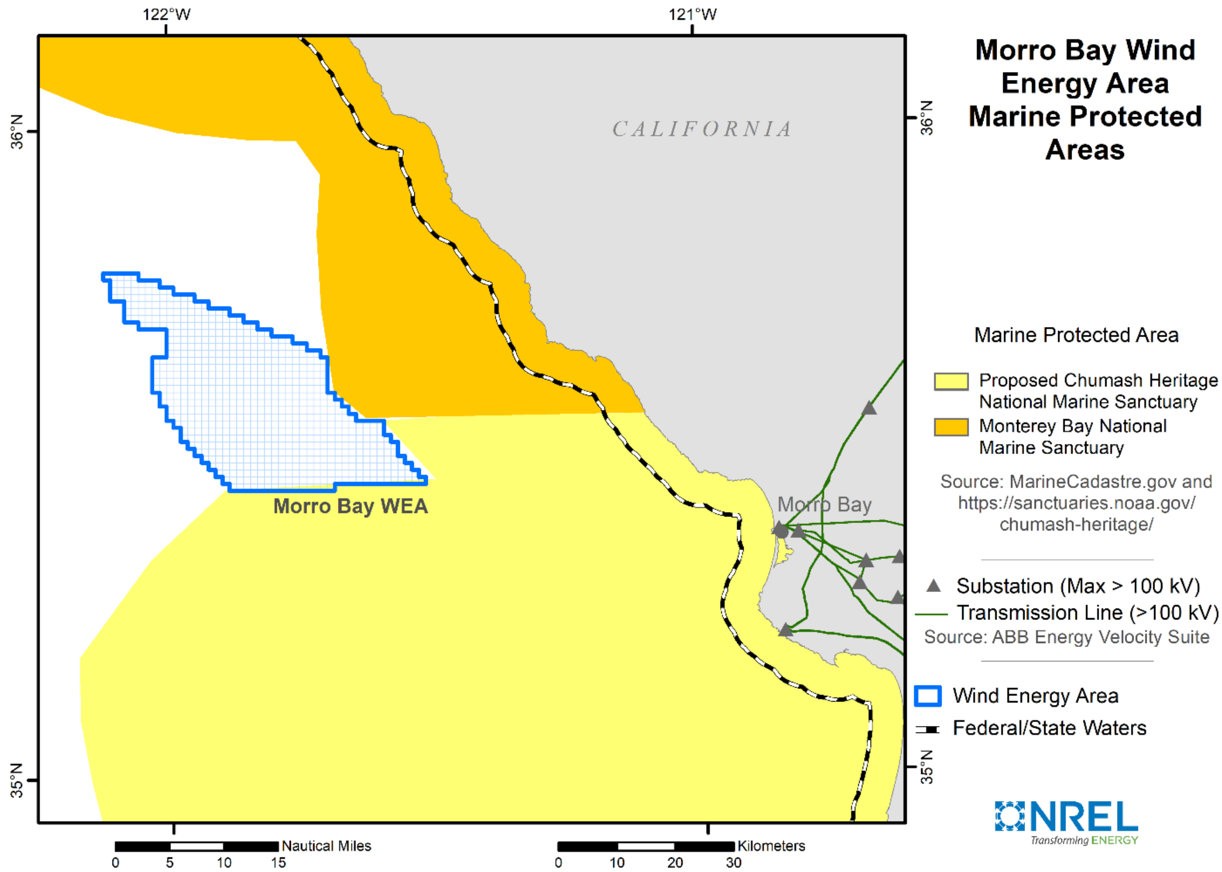


Figure 18. Locations of current and proposed national marine sanctuaries near Morro Bay WEA

3.5 Proximity to Relevant Infrastructure

3.5.1 Ports

The majority of relevant infrastructure that would likely serve the Humboldt WEA is located in the Humboldt Bay/Eureka area, as identified in Table 2. The Port of Humboldt Bay is the only deep-water port in the region with substantial infrastructure that could support offshore wind energy development and is a likely assembly port for potential projects in the Humboldt WEA. Additional investment would likely be needed to develop larger quays and improved bearing capacity, although the port does have significant area for turbine and substructure staging and assembly, including dry land and space for floating components. The Port of Humboldt Bay has no overhead clearance limitations, but its channel depth of less than 15 m is not sufficient for spar-type foundations with drafts of 70–85 m (Porter and Phillips 2016). Support for operations and maintenance for an active offshore wind farm in the Humboldt WEA could be based in the Port of Humboldt Bay or Crescent City Harbor District to the north, but the Port of Humboldt Bay is approximately 70 km closer to the WEA.

There are several ports that could potentially support offshore wind energy development in the Morro Bay WEA (Table 3). They are larger and farther away from the Morro Bay WEA than Humboldt Bay is from the Humboldt WEA. Port Hueneme is the closest existing port among those identified by Porter and Phillips (2016) as potential fabrication, construction, and assembly ports. Port Hueneme is approximately 300 km from the WEA. It has unlimited overhead clearance (air draft), adequate berth and navigation channel depth, access to railways, and land that could potentially be leased for the development of offshore wind support facilities. Port Hueneme currently supports other commercial and defense activities that would likely compete with offshore wind activities for access to facilities. The ports of Long Beach and Los Angeles were also identified as potential offshore wind ports by Porter and Phillips (2016). They are farther away from the Morro Bay WEA than Port Hueneme and offshore wind development would have to compete with a wide range of other commercial activities for access to port facilities.

The Port of Morro Bay is likely too small to support the assembly of offshore wind components, but it could potentially provide a base for operations and routine maintenance (Porter and Phillips 2016). The port is between 60 and 120 km from the Morro Bay WEA at its closest and farthest points, respectively.

The possibility of developing a new port at the site of the Diablo Canyon Power Plant is discussed in a study from the California Polytechnic State University in San Luis Obispo (Hamilton et al. 2021). If a port were constructed at Diablo Canyon, it could potentially support assembly, operations, and maintenance for floating offshore wind turbines. The distance to the port would be in the range of 75 to 135 km from the Morro Bay WEA.

With many potential port options, offshore wind energy development in the Morro Bay region would benefit from a more in-depth assessment of options than is presented here. A future study examining the costs and benefits of different port options could identify solutions that make optimal use of existing facilities and/or target investment in new facilities.

3.5.2 Grid Interconnection

Transmission lines leaving the Humboldt Bay area connect to the California Independent System Operator grid. All transmission infrastructure in this area is owned by Pacific Gas & Electric. While several electrical substations exist in the Humboldt Bay area, only two of them are rated above 100 kilovolts (kV). Both are included in the Humboldt-specific maps shown in Figure 10–Figure 16; the western substation is the Humboldt Bay substation located near the Humboldt Bay Power Plant, and the eastern marker represents the Humboldt substation (in the town of Eureka). The substations are rated at 115 kV. The Humboldt Bay substation is connected to both the town of Eureka and the Humboldt substation via several 60–70 kV transmission lines; while this means that upwards of 100 kV can be transmitted out of the Humboldt Bay substation, not all of it would feed into the grid connection at the Humboldt substation. If offshore wind generating capacity exceeds approximately 150–200 MW, new transmission will be required to export power to other regions (Pacific Gas and Electric Company 2020; Daneshpooy and Anilkumar 2022).

The closest site to the Morro Bay WEA with access to the transmission system is the Morro Bay substation at the location of the retired Morro Bay Power Plant. The distance to the substation is approximately 60 km from the nearest point of the WEA and 120 km from the farthest point. The substation is connected to 230-kV transmission lines carrying electricity to the east, northeast, and southeast. Another potential interconnection location is the Diablo Canyon Power Plant, 16 km south of Morro Bay, which is scheduled to be retired in 2025.

Table 2. Relevant Infrastructure for Offshore Wind Development Near Humboldt WEA

Infrastructure	Classification	Distance (km)
Humboldt Bay Harbor District	Assembly port Operations/service port	35
Crescent City Harbor District	Operations/service port	105
Humboldt Bay Substation (115 kV)	Grid interconnection point	35
Humboldt Substation (115 kV)	Grid interconnection point	43

Table 3. Relevant Infrastructure for Offshore Wind Development Near Morro Bay WEA

Infrastructure	Classification	Distance
Port Hueneme	Assembly port Operations/service port	290–350 km
Ports of Los Angeles / Long Beach	Assembly ports	390–450 km
Morro Bay Harbor	Operations/service port	60–120 km
Morro Bay Substation (230 kV)	Grid interconnection point	60–120 km
Diablo Canyon Substation (500 kV)	Grid interconnection point	75–135 km

3.5.3 Subsea Cables

Any offshore wind development will need to be cognizant of existing subsea infrastructure and negotiate cable crossing agreements with the owners of other subsea cables. Several telecommunication cables are located just south of the Morro Bay WEA, and a cable under construction for installation in 2023 will pass through several aliquots at the southern edge of the Morro Bay WEA (Alcatel Submarine Networks 2021). Two proposed telecommunication routes intersect the southern third of the Humboldt WEA.

4 Preliminary Lease Area Delineation

In this section we consider several alternatives for delineating lease areas in the Humboldt and Morro Bay WEAs. Each delineation option is intended to divide the WEA into two or three lease areas of approximately equal value, based on consideration of the wind resource and other site characteristics.

4.1 Proposed Lease Areas

Figure 19 shows the two proposed options for dividing the Humboldt WEA into two lease areas. Parallel alignment of the delineation boundary with the prevailing wind direction was a primary consideration for both options to minimize the potential for wakes from a wind farm in one lease area impacting turbines in the adjacent lease area. Providing access to port and potential points of interconnection near Eureka (east of the WEA) were also important considerations.

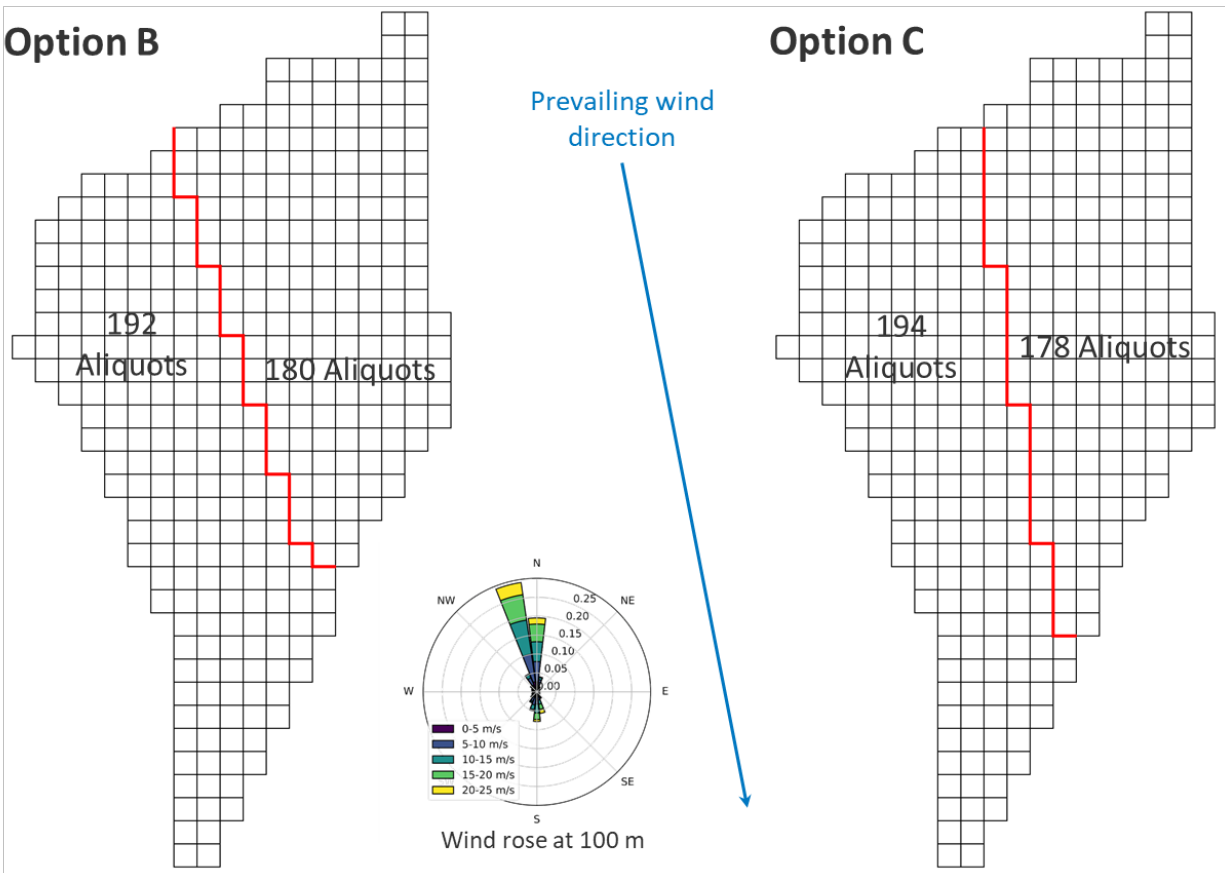


Figure 19. Proposed delineation options for Humboldt WEA: B (left) and C (right)

The proposed options for delineating the Morro Bay WEA are shown in Figure 20. Option 2a has two lease areas and the other three options each have three lease areas. In contrast to the Humboldt WEA, the longest dimension of the Morro Bay WEA is nearly parallel to the prevailing wind direction. Although delineating along the prevailing wind direction could reduce the impact of wakes from neighboring wind plants, in Morro Bay it would result in very narrow lease areas with long boundaries and limited space for wind turbine placement perpendicular to the prevailing wind; therefore, we considered different approaches to delineating this area that could provide more space to accommodate larger mooring footprints and allow for higher power capacity in those scenarios. Options 2a and 3b are divided along lines oriented north-to-south, which allow for shorter, straighter boundaries and provide each lease area with access to relatively unobstructed wind along the northern edge. Option 3a minimizes the length of edges between adjacent lease areas to allow efficient use of the space within each lease area for wind turbine placement. Option 3c roughly follows the prevailing wind direction to delineate the southwest lease area, but the boundary between the east and northwest areas is a straight east-west line that creates two more compact lease areas. Each of these delineation options aims to distribute potentially advantageous or disadvantageous physical site characteristics between lease areas as equally as possible while maintaining cohesive lease area boundaries. The following section compares the distribution of site characteristics between proposed lease areas in more detail.

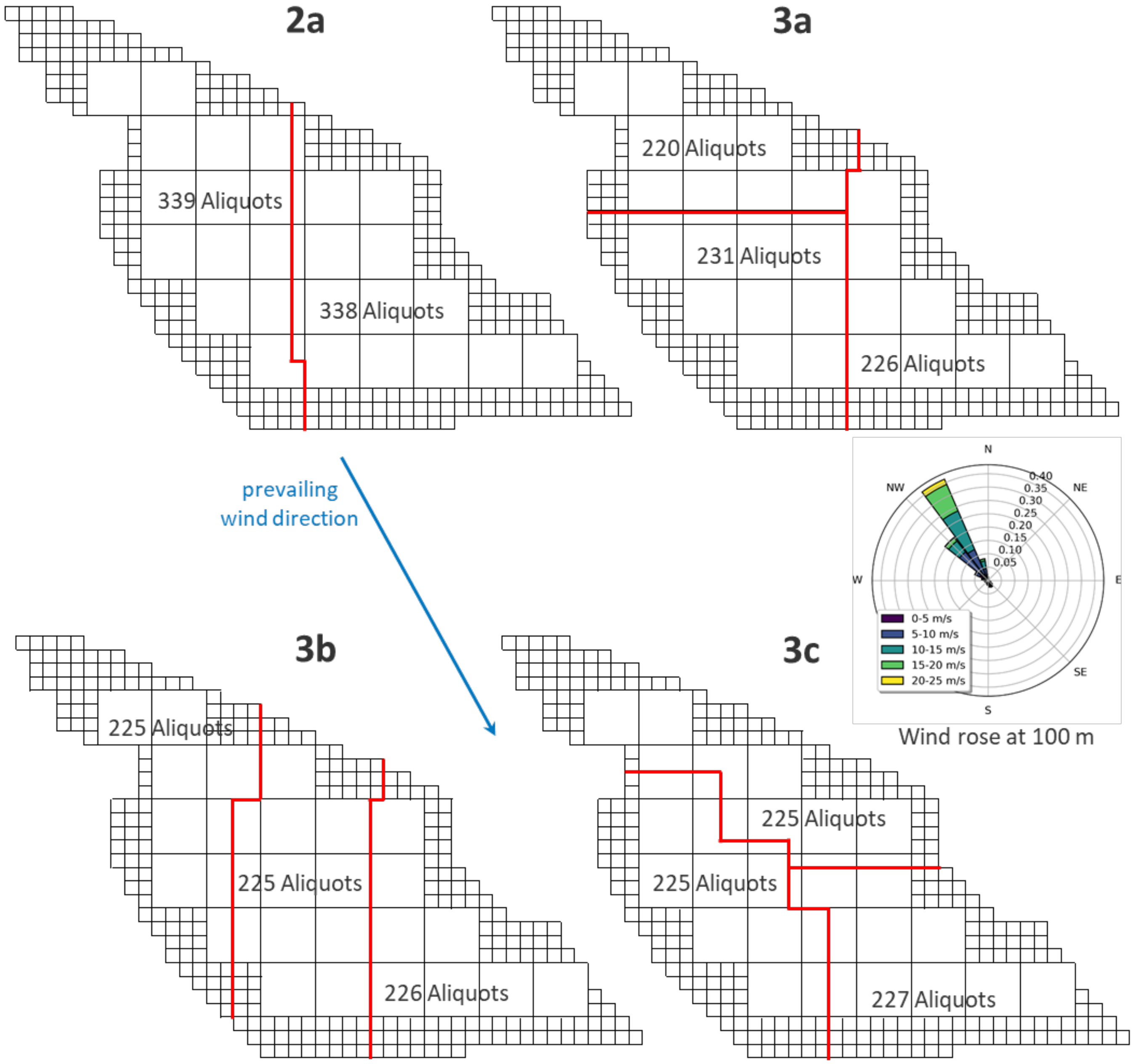


Figure 20. Proposed delineation options for Morro Bay WEA: 2a (top left), 3a (top right), 3b (bottom left), and 3c (bottom right)

4.2 Physical Site Characteristics

Each aliquot was characterized based on the following attributes:

- **Wind speed**: the 20-year mean wind speed at a height of 100 m, in meters per second (Optis et al. 2020)
- **Depth**: mean water depth within each aliquot, in meters (National Geophysical Data Center 2003a; 2003b)

- **Mean slope**: mean seabed slope within each aliquot, in degrees (calculated from the U.S. Coastal Relief Model)
- **Distance to land-based infrastructure**: distance to closest potential points of interconnection to the electric grid and ports that could support assembly and operations and maintenance, in kilometers. Locations used for this calculation were Eureka (for the Humboldt WEA) and Morro Bay and Port Hueneme (for the Morro Bay WEA).
- **Hard rock**: presence of hard, rocky substrate in available seafloor data
- **Cable**: presence of a planned subsea telecommunications cable route.

Although additional physical parameters may be relevant to site selection, such as benthic habitat areas, sediment depth, currents, wave climate, and bathymetric features, we lacked data to quantify the effects of these factors on specific aliquots. Table 4 and Table 5 summarize the distribution of site characteristics between lease areas in the Humboldt and Morro Bay WEAs, respectively.

Table 4. Summary of Physical Parameters: Number of Aliquots Impacted for Humboldt WEA

Option	Lease Area[a]	Avg. 100-m Wind Speed	Avg. Dist. to Eureka	Cable	Hard Rock	Water Depth (m)				Avg. Seafloor Slope	
						500–700	700–900	900–1,100	1,100–1,300	0–4°	>4°
		m/s	km	# aliquots		# aliquots				# aliquots	
B	NE	10.3	44	0	0	81	70	29	0	173	7
	SW	10.6	46	16	52	47	125	19	1	156	36
C	NE	10.3	43	2	0	91	62	25	0	171	7
	SW	10.6	47	14	52	37	133	23	1	158	36

[a] NE = northeast lease area; SW = southwest lease area

In both delineations B and C for the Humboldt WEA, the southwest lease area has the advantage of higher average wind speeds that are expected to result in higher annual energy production (AEP) and capacity factors, depending on the specifications of the installed wind turbines. The southwest areas also have several disadvantages, including a slightly longer distance to Eureka, most or all of the aliquots that intersect with a planned telecommunications cable route, all of the known areas of hard, rocky seafloor, and more aliquots with a mean slope greater than 4°. To compensate for these disadvantages, the proposed southwest lease area has 12 more aliquots than the northeast area in option B and 16 more aliquots in option C. The distribution of water depths does not strongly favor one lease area over the other.

Table 5. Summary of Physical Parameters: Number of Aliquots Impacted for Morro Bay WEA

Option	Lease Area[a]	Avg. 100-m Wind Speed	Avg. Dist. to Hueneme	Avg. Dist. to Morro Bay	Cable	Water Depth (m) 700–900	900–1,100	1,100–1,300	Avg. Seafloor Slope 0–4°	>4°
	-	m/s	km	km	# aliquots					
2a	NW	9.7	330	102	0	0	157	182	323	16
	E	9.4	310	81	11	5	295	38	338	0
3a	NW	9.7	336	103	0	0	108	112	215	5
	SW	9.6	319	94	0	0	144	87	220	11
	E	9.4	306	77	11	5	200	21	226	0
3b	NW	9.7	335	105	0	0	73	152	215	10
	C	9.6	319	91	0	0	179	47	220	6
	E	9.4	306	77	11	5	200	21	226	0
3c	NW	9.7	333	99	0	2	134	89	223	2
	SW	9.6	322	97	0	0	123	102	211	14
	E	9.4	305	77	11	3	195	29	227	0

[a] NW = northwest lease area; E = east lease area; C = central lease area; SW = southwest lease area

In the Morro Bay WEA, physical characteristics that could lower the value of some aliquots are not concentrated in a single lease area and therefore the proposed delineation options all consist of lease areas of nearly equal size. The east area in each delineation has the lowest mean wind speeds and contains all the aliquots that intersect a planned telecommunications cable route; offsetting those disadvantages, this area is also closer to land-based infrastructure, has the least deep water, and the fewest aliquots with slopes greater than 4°. The northwest area in each delineation option has the highest mean wind speeds and the best exposure to the prevailing winds, which reduces the potential for wake losses from neighboring wind plants. Disadvantages for the northeast lease areas include the longer distance to land-based infrastructure, deeper water depths, and more steeply sloped aliquots, especially in options 2a and 3b. Wind speeds and distances to infrastructure for the central and southwest lease areas fall between the values in the east and northwest areas, as does the distribution of water depths in options 3a and 3b. The southwest lease area contains majority of the aliquots with slopes steeper than 4° and in option 3c it also has the most aliquots deeper than 1,100 m.

4.3 Impact of Mooring System Footprint

Floating wind turbines are connected to the seabed via mooring lines and anchors. Depending on the choice of substructure and mooring system, the radius from the turbine location to the anchor can become significant. Because anchors must be placed within the boundaries of the seabed lease, turbines cannot be located closer to the boundary than the radius defined by the footprint of the mooring system. In this analysis, we consider the space required by four different mooring configurations:

- **Catenary**. Mooring lines are made of chain or wire rope and follow a curve that is described mathematically as a "catenary" from the point where they connect to the turbine to the point where they land on the seabed due to their weight. They then extend for an additional length along the seabed before reaching their anchors, allowing the use of drag embedment anchors, which are typically more affordable than anchors designed for vertical forces. Because of their curved profile and need for length on the seabed, catenary moorings generally have the longest lines and the largest anchor spacings.

- **Semi-taut**. Mooring lines typically use taut synthetic rope combined with heavier components and are affected by both weight and rope elasticity. The semi-taut mooring configuration used in this study uses taut synthetic rope for most of the depth range connected to a length of chain that follows a catenary curve near the seabed. This configuration maintains a length of chain along the seabed, allowing the use of drag embedment anchors while achieving smaller anchor spacings than catenary moorings.
- **Taut**. Mooring lines are typically made of synthetic rope and have minimal contact with the seabed, relying on rope elasticity for their compliance. As a result, they require anchors that can withstand both vertical and horizontal loads. In this analysis we chose a 55° angle between the mooring line and the seabed to represent a minimal anchor spacing option for semisubmersible and spar platform types.
- **Tension-leg platform (TLP)**. Designs use high-tension mooring lines oriented vertically with anchors designed to withstand high vertical loads (e.g., suction pile anchors). The distance between anchors is approximately equal to the width of the floating platform, representing the minimum possible mooring footprint. These designs require a specific platform type with extra buoyancy rather than using semisubmersible or spar platforms.

4.3.1 Background

The purpose of this analysis is to estimate likely anchor spacing distances for floating wind turbines in water depths representative of California lease areas. Anchor spacing is the horizontal radius from the turbine location at which anchors are located. This spacing affects wind farm layout and especially how close turbines can be positioned to the lease area boundaries. When positioning turbines in the array, a margin inside the boundaries is needed to accommodate the anchor spacing plus room for anchor installation. Drag-embedment anchors require a distance on the order of 100 m along the seabed for their installation, depending on seabed and anchor variables.

The water depths in the California lease areas, which range from 550 m to 1,300 m, make a variety of mooring system configurations and anchor spacings possible. Catenary mooring systems, which use chain in a relatively slack profile (Figure 21d), are a traditional choice for shallower waters and may be reasonable around 500 m of depth. Taut mooring systems (Figure 21b) typically use synthetic rope that provides some elasticity. They are most efficient in deep water because they minimize weight and anchor spacing. Semi-taut mooring systems (Figure 21c) combine the previous two approaches, with a taut rope-based segment attached to a catenary-shaped chain segment near the seabed. More complex variants of these mooring configurations are also possible but generally have characteristics that fall in between the above configurations with respect to anchor spacing. The previous three configurations are applicable to semisubmersible and spar-type substructures, whereas TLPs use vertical moorings (Figure 21a) that are anchored directly below the points of connection to the floating platform.

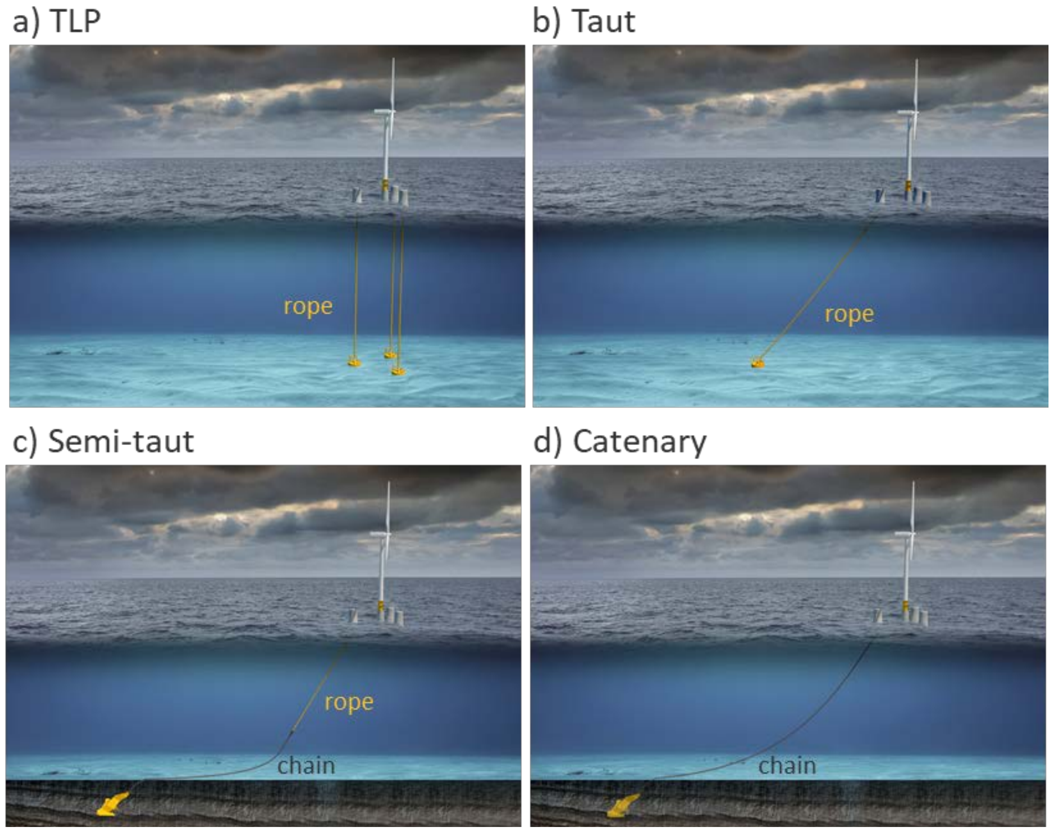


Figure 21. Four typical mooring line configurations. *Illustration by Joshua Bauer, NREL*

Authoritative information characterizing the mooring systems for floating wind turbines in deep water is scarce. No floating wind projects have yet been deployed in waters as deep as those in California, and existing offshore oil and gas examples are of limited value because their mooring design considerations differ significantly. Furthermore, the published literature does not contain studies that detail floating wind mooring systems in deep-water ranges. Although the basic configuration types are known, the specific sizing choices—including anchor spacing—require new analysis.

4.3.2 Analysis

To estimate likely anchor spacings, preliminary mooring system sizing analyses were performed for catenary, taut, and semi-taut mooring system configurations across a range of water depths and anchor spacings. A mooring system design optimization algorithm was used to determine the most cost-effective mooring system design under each depth and anchor-spacing condition while respecting key technical design requirements. These requirements are based on accommodating wind forces and wave-induced motions representative of the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) 15-MW reference wind turbine and the VolturnUS-S reference semisubmersible platform (Allen et al. 2020). The analyses use the quasi-static mooring system model MoorPy (Hall et al. 2021) and mooring design tools under development at NREL, which will be published at a later date. Additionally, several spot checks were performed using the state-of-the-art floating wind turbine simulator OpenFAST (Jonkman and Sprague n.d.) to verify the mooring system design process.

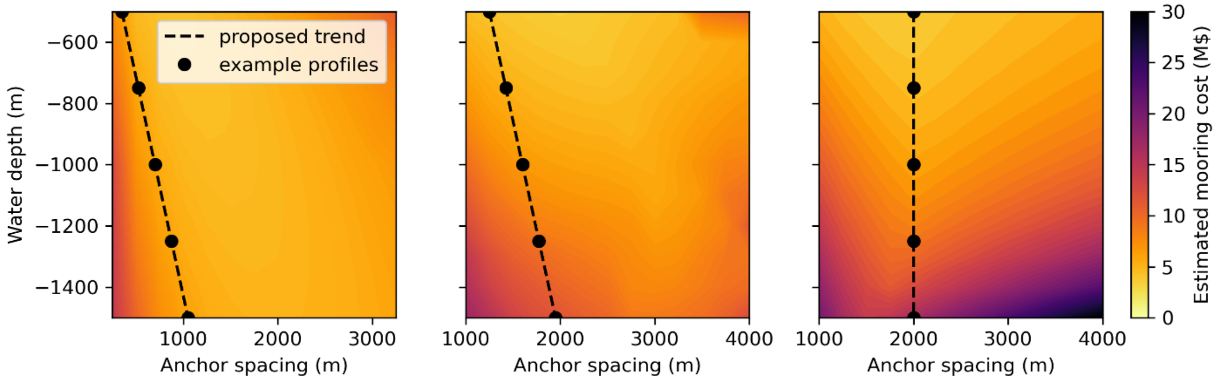
A design optimization was set up for each mooring system configuration and applied across the water-depth and anchor-spacing parameter ranges. At each point in these ranges, the optimizer searches for values of mooring design variables (line lengths and diameters) that minimize the estimated mooring system cost while meeting engineering requirements. The first requirement is that the mooring system achieve a certain target offset of 100 m or less under the maximum expected steady horizontal load (taken to be the turbine's rated thrust of 2.6 meganewtons [MN]). The second requirement is that, if an additional 10 m offset is applied due to extreme wave-induced motions, the mooring line tensions stay within 60% of the mooring lines' minimum breaking load, consistent with typical safety factors. For the catenary and semi-taut configurations, which feature drag-embedment anchors, an additional requirement is that at least 30 m of chain always stays on the seabed to prevent vertical anchor forces. For the taut configuration, the mooring line must never lie horizontally on the seabed to prevent rope abrasion and maintain adequate line tension.

Figure 22 shows, for each mooring configuration, a heat map of the estimated minimum mooring system cost across the water-depth and anchor-spacing ranges. The cost assumptions come from industry estimates used in previous work (Hall et al. 2022) and account for component and installation costs. The lightest areas of the figures represent the lowest mooring system cost. The most cost-effective anchor spacing increases with depth for the taut and semi-taut configurations but is nearly constant around 2,000 m for the catenary configuration. These trends reflect the differences in what drives the design across the three configurations. Taut and semi-taut configurations feature rope that is relatively lightweight and therefore can be easily extended to accommodate deeper waters. The catenary configuration relies on chain, for which weight becomes a significant load on the system as the lines get longer.

A line is drawn on top of each heat map that represents a proposed trend for likely anchor spacings as a function of depth. The choice of these trends will be explained later. Five points along the line indicate depth-spacing value pairs at which example profiles will be illustrated in in Section 4.3.3 (Figure 26).

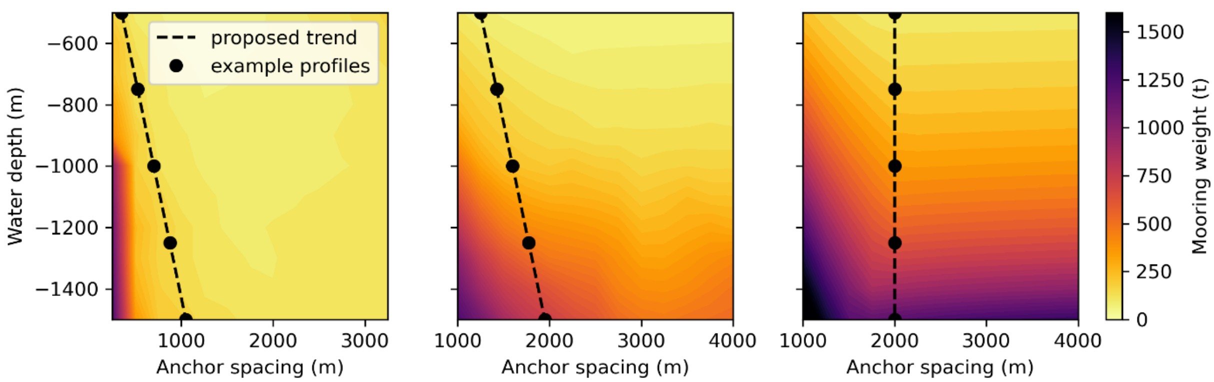
Figure 23 shows heat maps of the calculated suspended weight of the mooring system, which needs to be resisted by the floating platform's buoyancy. This weight is an important metric when considering design trade-offs because it directly affects the floating platform's size and cost. The weight heat maps have similar trends as the cost heat maps, reflecting that the mooring system weight and cost are closely related. Comparing across configurations, there is a noticeable increase in weight going from taut to semi-taut to catenary configurations at all but the shallowest depths.

Figure 24 shows heat maps of the required line diameters in the mooring designs. For the taut configuration, the reported diameter is of the rope and is not of particular concern except around the lowest anchor spacings where the diameters become extreme and impractical.



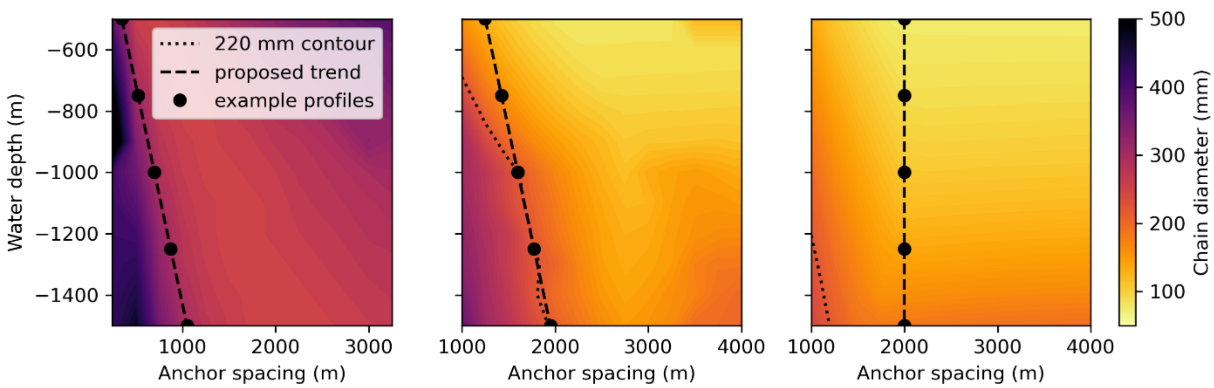
(a) Taut (b) Semi-taut (c) Catenary

Figure 22. Calculated minimum mooring system cost as a function of water depth and anchor spacing



(a) Taut (b) Semi-taut (c) Catenary

Figure 23. Calculated suspended mooring system weight as a function of water depth and anchor spacing



(a) Taut (rope diameter) (b) Semi-taut (chain diameter) (c) Catenary (chain diameter)

Figure 24. Calculated mooring line diameter as a function of water depth and anchor spacing

For the catenary configuration, the chain diameter is very similar to the weight heat map. For the semi-taut configuration, the chain diameter gets relatively large at lower anchor spacings. The dotted line shows the boundary at which a diameter above 220 millimeters (mm) is required, which is an important constraint to consider because 220 mm is the largest chain width currently manufactured. Although this limitation could be circumvented by using smaller chain with the addition of clump weights to provide the required larger weight, we keep it as a practical guideline for the purposes of the present study.

4.3.3 Proposed Anchor Spacing Trends

The analysis results show how important mooring system characteristics vary with depth and anchor spacing. From that information, trends for reasonable anchor spacings as a function of water depth can be proposed for each mooring configuration.

The results for catenary mooring lines show that an anchor spacing of around 2,000 m is most favorable across the full depth range in the California WEAs. Lesser anchor spacings require heavier and more costly lines, while greater spacings simply add more mooring line along the seabed, adding cost without changing performance. This gives the simple constant trend:

$$\text{Catenary spacing} = 2{,}000 \text{ m}$$

Semi-taut mooring lines can have lesser anchor spacings than catenary mooring lines while also having lower cost and weight over the depth range. In the current study, the limiting factor on reducing anchor spacing is when the required chain diameter meets the maximum manufacturable size of 220 mm. This gives a minimum anchor spacing of around 1,950 m at 1,500 m water depth. Assuming larger chain does not become available and clump weights are not used as an alternative (this is a conservative assumption for assessing the maximum anchor spacing), this 220 mm chain size limitation is likely to determine the anchor spacing decision. Anchor spacings larger than this value would likely be undesirable because of the large reduction they impose on the lease area capacity.

In the less-deep portions of the California lease areas, cost and system performance considerations may outweigh chain size limitations to determine anchor spacing. Therefore, anchor spacing values will likely fall somewhere between the 220 mm chain size contour (a relatively small anchor spacing) and the minimum-mooring-cost anchor spacing (which is relatively large). Figure 24b shows the 220 mm chain size contour diverging from our proposed trend line for water depths below 1,000 m.

With the above depth factors in mind, the proposed trend line approximates the 220 mm chain size contour in the deepest waters and provides a balance between cost and chain size in less deep waters:

$$\text{Semi-taut spacing} = 0.7 \times \text{depth} + 900 \text{ m}$$

Taut mooring lines have a straight profile and therefore lend themselves to an anchor spacing that is proportional to water depth. A depth-spacing trend with the same slope as the semi-taut case corresponds to a mooring line inclination angle of 55°. This is steeper than typical taut mooring line angles for oil and gas structures, but the analysis results show that it gives lower mooring system costs and weight than the semi-taut configuration while having significantly smaller anchor spacing. Considering that having a smaller minimum anchor spacing helps bound the range of possibilities, this gives a good trend for the anchor spacing of the taut configuration:

$$\text{Taut spacing} = 0.7 \times \text{depth}$$

Figure 25 shows the three selected anchor spacing trends. Figure 26 shows the mooring line profiles calculated by the design algorithm at five points along the trendline for each of the mooring configurations.

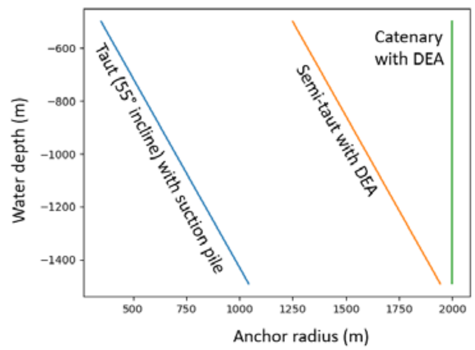


Figure 25. Selected anchor spacing versus water depth trends for the three mooring line configurations using a suction pile or drag-embedment anchor (DEA)

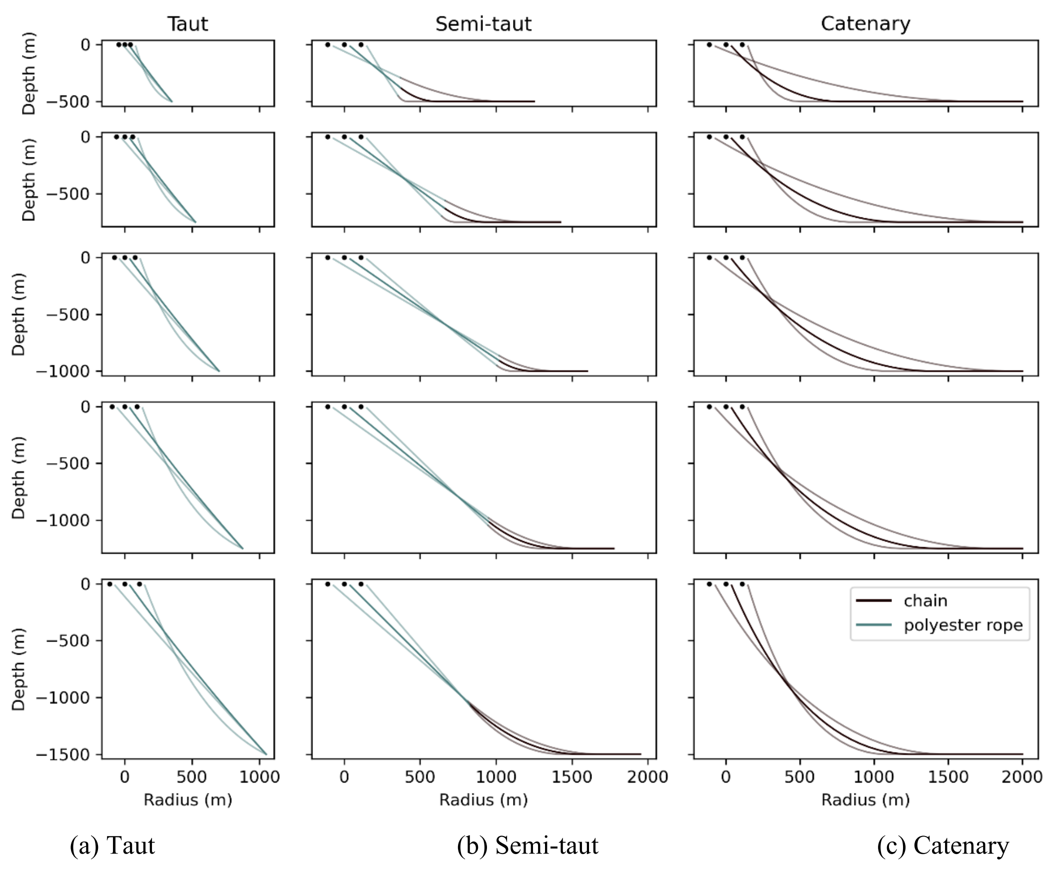


Figure 26. Calculated mooring line profiles along the trendlines showing undisplaced and extreme displaced states

4.3.4 Additional Margin for Anchor Installation

An additional lease area consideration for the mooring system is the distance required to install drag-embedment anchors. This drag-embedment distance extends radially beyond the anchor location and is a function of the soil type, anchor type, and required holding capacity. These relationships are given in anchor performance curves from manufacturers. The curves from the Vryhof Stevpris Mk6 anchor (Vryhof 2018), the latest version of a common anchor for floating wind systems, are used to estimate the required drag-embedment distance.

An OpenFAST simulation of the optimal mooring system on the trendline at 1,000 m water depth, with the VolturnUS-S semisubmersible and IEA Wind 15-MW reference turbine, was simulated to check the mooring system behavior. All responses were as expected in a severe wind and wave case. From this analysis, the peak anchor tension was estimated at 3.8 MN. API RP-2SK specifies a safety factor of 1.5 for drag-embedment anchors (Shu et al. 2018). The corresponding required anchor capacity is 580 tonnes.

Using this required anchor capacity, and assuming full anchor embedment to achieve 100% holding capacity, applying the relations in the Vryhof Manual results in the drag distances shown in Table 6.

Table 6. Estimated Required Anchor Weight and Drag Distance for Three Soil Types

Soil Type	Anchor Weight (tonnes)	Drag Distance (m)
Soft clay	14	85
Medium clay	9	50
Sand and hard clay	7	25

Some additional distance may be needed as a margin when positioning the anchor for installation, or to compensate for uncertainties in soil type. The drag-embedment distance and any margins should be added to the spacing-depth trend mentioned previously.

The radius from turbine to anchor can be used to define a circle around each turbine indicating the minimum distance to a lease area boundary. However, strategic placement of the anchors on the circumference of that circle can reduce the effective minimum distance to the boundary, as illustrated schematically in Figure 27. Figure 27 also includes a setback for catenary and semi-taut moorings to account for the distance traveled by a drag-embedment anchor from initial placement to permanent embedment. The minimum distance from turbine to lease area boundary for each mooring type is indicated in Table 7. Without carrying out detailed modeling, we assumed a minimum distance of 100 m for TLPs to account for factors such as the platform diameter, motion of the TLP, and vessel activity during installation and operation.

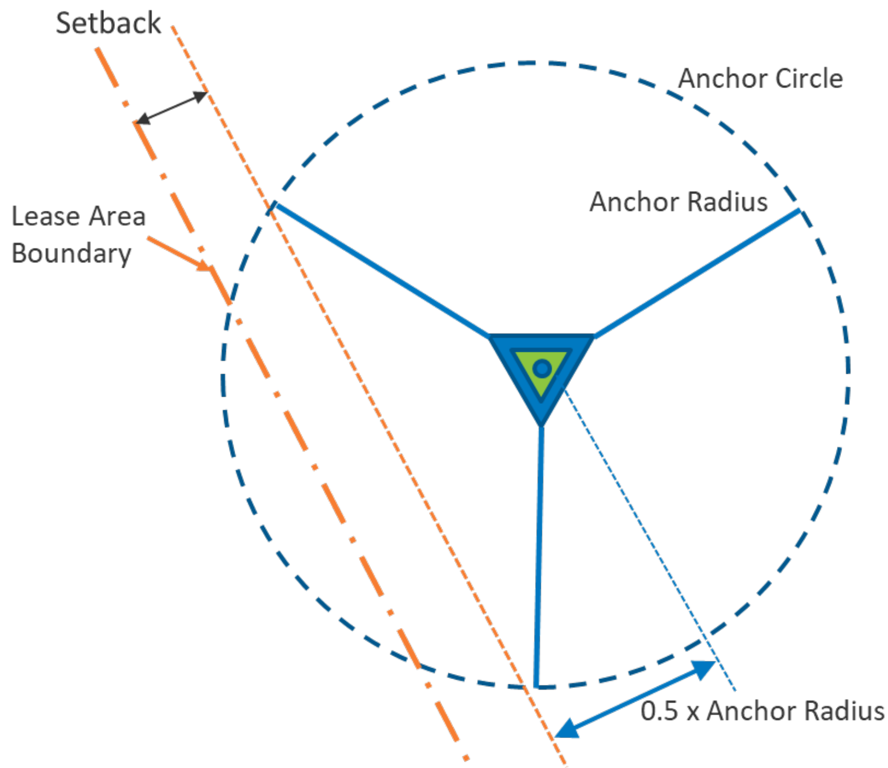


Figure 27. Conceptual diagram of anchor placement near lease area boundary. Setback and anchor radius vary by mooring type; Table 7 lists total distance for each type.

Table 7. Minimum Distances From Turbine to Lease Area Boundary by Mooring Type

Mooring Type	Minimum Turbine-to-Boundary Distance
Catenary	1,100 m
Semi-taut	0.35 × water depth + 500 m
Taut	0.35 × water depth
TLP	100 m

For the Humboldt WEA, implementing a minimum boundary distance by mooring type results in a 2.5% reduction in the area available for turbine placement for TLPs, an 8% reduction for taut moorings, a 19% reduction for semi-taut moorings, and a 25% reduction for catenary moorings. In the Morro Bay WEA, the corresponding reductions in available area are 2.0% for TLPs, 8% for taut, 16% for semi-taut, and 20% for catenary moorings. Dividing the WEA into two or more lease areas increases the total area along the boundaries (by adding a boundary between lease areas). Table 8 compares the total available area under different setback assumptions for each of the proposed delineations. The proposed lease areas in the Humboldt WEA are relatively long and narrow, which contributes to a larger reduction in available area compared with Morro Bay. The addition of a third lease area in some Morro Bay delineations also reduces the total available area compared with option 2a.

Table 8. Percentage of Total WEA Available for Wind Turbine Placement Within Lease Areas Under Different Mooring Technology Setback Assumptions for Delineation Options in Humboldt and Morro Bay

	Humboldt		Morro Bay			
	B	**C**	**2a**	**3a**	**3b**	**3c**
TLP	96%	96%	97%	97%	97%	97%
Taut	89%	90%	90%	89%	88%	88%
Semi-taut	72%	72%	79%	75%	74%	74%
Catenary	63%	64%	74%	70%	69%	69%

5 Lease Area Generating Potential and Wake Loss Analysis

In this section, we evaluate the generating potential and possible wake losses for the Humboldt and Morro Bay WEAs based on the delineations proposed in Section 4.1. We are particularly interested in assessing differences in wake losses between adjacent wind plants. Wakes from one wind farm can impact neighboring wind farms, reducing energy production and revenue (Lundquist et al. 2019). Under certain atmospheric conditions, velocity deficits from offshore wind turbine wakes may persist upwards of 50–90 km (Schneemann et al. 2020; Hasager et al. 2015; Pryor, Barthelmie, and Shepherd 2021). In the following subsections, we outline our methodology before presenting results of the generation and wake loss analyses.

5.1 Methodology

For a given delineation option we consider the amount of generating capacity that could be installed within the delineation's boundary based on choices of turbine technology, mooring system technology, and wind farm layout. Then we use NREL's wake modeling utility, FLORIS, which stands for FLOw Redirection and Induction in Steady State, to assess intra- and interarray wake losses before calculating total AEP (NREL 2021). Wake model options included with FLORIS are low-fidelity engineering wake models well-suited for evaluating energy production of many wind farm configurations because they are less computationally expensive than other flow modeling options (e.g., computational fluid dynamics simulations or direct numerical simulations). Even taking advantage of the engineering wake models available in FLORIS, the computational expense grows with the size of the wind farms being modeled, so we bound the range of possible wind farm configurations.

5.1.1 Turbine Technology Assumptions

Consistent with Beiter et. al (2020), we use the IEA Wind 15-MW reference turbine (Gaertner et al. 2020), but extend its cut-out wind speed from 25 m/s to 30 m/s. Tabular power curve data and documentation can be found on GitHub.[3]

5.1.2 Mooring System Technology Assumptions

The choice of mooring technology impacts the available area for turbine placement within a boundary because anchors and mooring lines must remain within the wind energy area or eventual lease area. Table 8 illustrates the lost area in each delineation resulting from respecting appropriate boundary setbacks for each of the mooring technology options. To reduce the number of wake loss scenarios to consider, we opt to present results for the mooring system technologies with the greatest and least impact on available area for turbine placement. These correspond to catenary and TLP mooring systems, respectively.

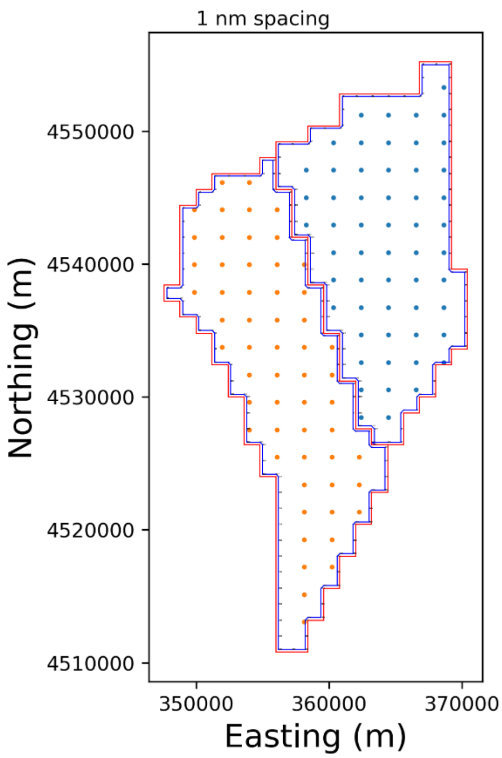
5.1.3 Wind Farm Layout Assumptions

Developers will likely optimize wind farm layouts considering soil conditions, geohazards, spatial distribution of the wind resource and wind plant performance, export and array cable routes, environmental factors, and legal regulations. Some of these decisions are informed by

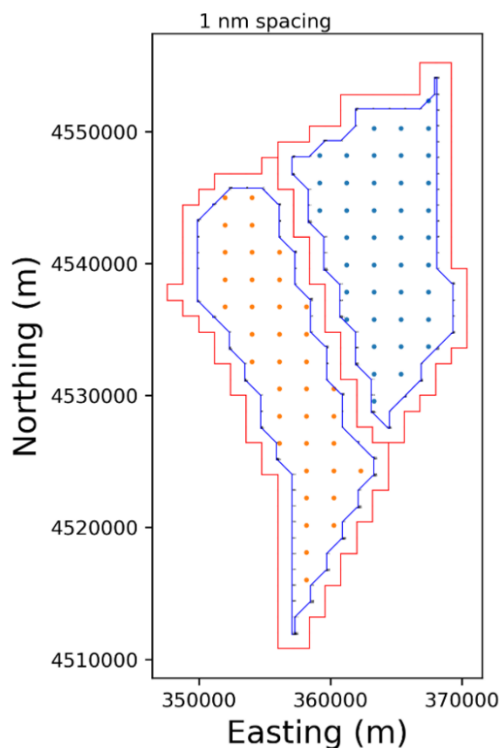
[3] Tabular power curve data and documentation available at: https://github.com/NREL/turbine-models.

studies that occur after the acquisition of a lease area. For the present study, we do not optimize layouts, but rather bound the range of possible configurations informed by developer feedback (refer to Section 2.4). With optimization, the capacity of the different delineations could increase by 30 MW to more than 300 MW in the most extreme cases.

We examine two layout configurations: a square grid with turbine spacings of 1 nm and a rectangular grid with turbines spaced 4D in the east-west direction and 10D in the north-south direction. The latter choice aligns the larger spacing more closely with the dominant wind direction offshore California. These layouts reflect developers' proposed spacings in New England and feedback from the nominations. We do not make any assumptions regarding the arrangement of mooring lines within the turbine array, except for assuming that the modeled spacings can be achieved (e.g., using staggered or shared mooring lines) even if the anchor spacing is larger than the turbine spacing. Figure 28 shows examples of the two turbine spacings filling Humboldt for delineation B.



(a)



(b)

Figure 28. Examples of turbine space filling in Humboldt: (a) delineation B with 1 nm spacing and TLP technology, (b) delineation B with 1 nm spacing and catenary technology. The red outer lines are the proposed lease area boundaries, and the blue inner lines indicate the mooring setback. The coordinate system is Universal Transverse Mercator in Zone 10.

5.1.4 Wake Modeling With FLORIS

NREL's FLORIS is a wind farm optimization tool with a focus on analyzing wakes and optimizing wind farm control (NREL 2021). For the purposes of this study, we leverage the wake modeling features to help assess wake losses and AEP for different delineations. The Turbulence Optimized Park (TurbOPark) wake model was selected for this analysis because it better captures wakes across longer distances between wind farms and represents some amount of blockage from the presence of the wind farm (Nygaard et al. 2020).

By bounding the number of mooring technology choices and wind farm layouts, we reduce the number of scenarios for wake analysis to 84. This still allows for investigation of the key trends and bounds the range of possible generation potential in the California wind energy areas. Table 9 summarizes the number of scenarios investigated.

Table 9. Summary of Scenarios Considered for Wake Analysis

Wind Energy Area	Number of Delineations	Wake Interaction Cases	Spacing Options	Mooring Technologies	Total No. Cases
Humboldt	2 with 2 areas	3 per delineation	1 nm × 1nm 4D × 10D	Catenary TLP	24
Morro Bay	1 with 2 areas 3 with 3 areas	3 or 4 per delineation	1 nm × 1nm 4D × 10D	Catenary TLP	60

For each delineation, the lease boundaries were adjusted to account for the appropriate mooring setbacks described in the previous section. Then, the adjusted area was filled with turbines using the two spacing options. Figure 28 shows examples of turbine space filling in Humboldt. FLORIS was used to calculate the wake losses for each farm, both individually and with adjacent farms. Figure 29 shows an example of the wakes for the combined NE and SW farms in Humboldt using 4D × 10D spacing and catenary technology. After running the combined cases in FLORIS, the wake losses were calculated for each farm (for example, NE and SW in Humboldt). Comparison of the results for each wind farm separately and combined show the effect of adjacent wind farms on wake losses for each area. Finally, the net AEP was calculated using the wake losses from the FLORIS analysis and additional losses shown in Table 10 for Humboldt and Morro Bay.

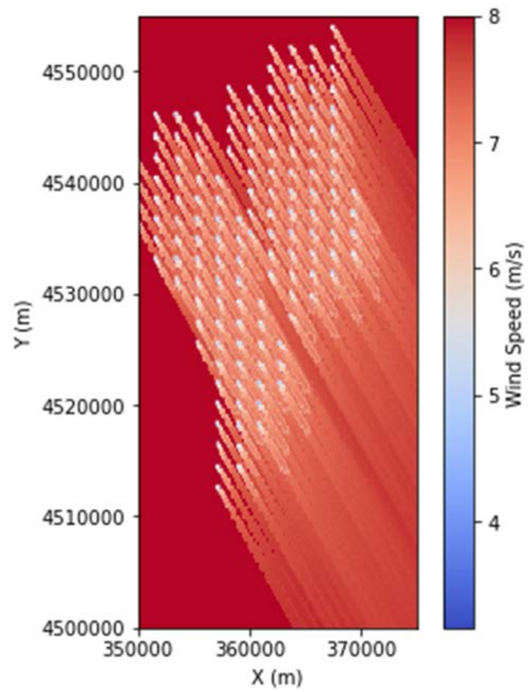


Figure 29. Humboldt wake losses for delineation B with 4D x 10D spacing and TLP technology with 8 m/s wind from 330º north-northwest. Lighter areas correspond to lower wind speeds in the wake of each turbine.

After calculating wake losses for each case we applied additional losses following Beiter et al. (2020) (refer to Table 10) to estimate the total losses and compute the net AEP. The additional losses include:

- **Environmental losses**: Shutdowns and performance degradation caused by atmospheric conditions such as extreme temperatures, lightning, hail, ice accumulation, and blade fouling from dirt, insects, and other airborne material.
- **Technical losses**: Losses related to turbine performance such as parasitic loads, rotor misalignment with the wind direction, and high-wind hysteresis (delayed return to operation).
- **Electrical losses**: Electrical power losses in the export cable between the wind plant and the point of interconnection to the onshore transmission system.
- **Availability losses**: Downtime due to grid outages, maintenance, or repair of the wind turbines or balance of system.

Table 10. Assumed Losses for AEP Calculation

Loss Category (% of gross production)	Morro Bay	Humboldt
Wake Losses	Calculated Using FLORIS	Calculated Using FLORIS
Environmental losses	1.6%	1.6%
Technical losses	1.2%	1.2%
Electrical losses	4.3%	3.9%
Availability losses	5.0%	5.0%

5.2 Results

5.2.1 Humboldt

Following the methodology laid out in the previous section, FLORIS cases were set up and analyzed for the two Humboldt delineations, B and C. Table 11 summarizes the generation potential for the two delineation options using the spacing and technology combinations with the highest and lowest densities. Full results are tabulated in Appendix A. The 1 nm spacing with catenary moorings has the lowest capacity among the options modeled and results in a capacity of 1,500 MW for both delineations. The 4D × 10D spacing with TLP technology has the highest capacity—3,045 MW and 3,060 MW for delineations B and C, respectively, which is approximately double the capacity of the 1-nm catenary case. For both B and C delineations, the net capacity factor is 50.2% for the 1 nm spacing with catenary technology. The 4D × 10D spacing with TLP technology has a slightly lower net capacity factor of 49.4% because the turbines are packed more tightly, resulting in higher wake losses.

Table 11. Humboldt WEA Generating Potential

Delineation	Spacing	Mooring Technology	Capacity [MW]	Capacity Density [MW/km^2]	Gross Generation [TWh][a]	GCF[b] [%]	Net Generation [TWh]	NCF[c] [%]
B	1 nm	Catenary	1,500	2.8	7.8	59.3	6.6	50.2
B	4D × 10D	TLP	3,045	5.7	15.8	59.3	13.2	49.4
C	1 nm	Catenary	1,500	2.8	7.8	59.3	6.6	50.2
C	4D × 10D	TLP	3,060	5.7	15.9	59.3	13.2	49.4

[a] TWh = terawatt-hour; [b] GCF = gross capacity factor; [c] NCF = net capacity factor

Figure 30 shows the wake losses for the two Humboldt delineation options, individually and with the other farm. As expected, the 4D × 10D spacing with TLPs has the highest wake losses because the turbines are packed most densely. The 1 nm with catenary moorings has the least dense turbine packing and results in the lowest wake losses. With all combinations of turbine spacing and technology, the northeast farm has a larger increase in wake losses caused by the adjacent farm. This is because the wind direction, shown in Figure 7, is headed slightly toward the east, causing the wakes of the southwest farm to impact the northeast farm more significantly. Also, the turbine positions are slightly offset east to west, positioning the southwest turbines outside of the direct wake of the northeast turbines.

Figure 31 shows the annual energy production results for Humboldt. Again, the 4D × 10D spacing with TLP moorings results in the largest AEP while the 1 nm spacing with catenary moorings results in the smallest AEP. The AEP is shown for the northeast farm and the southwest farm both individually and with the addition of the other farm. The effect of the adjacent farm on the AEP is minimal in these cases because the wake loss increases are less than 1% in all cases. With the TLP technology, the southwest farm has a higher AEP than the northeast farm for both B and C delineations. Catenary moorings reduce the usable area and lower the AEP. With the catenary technology, the southwest and northeast AEP is similar in most cases, except the 4D × 10D spacing for delineation C.

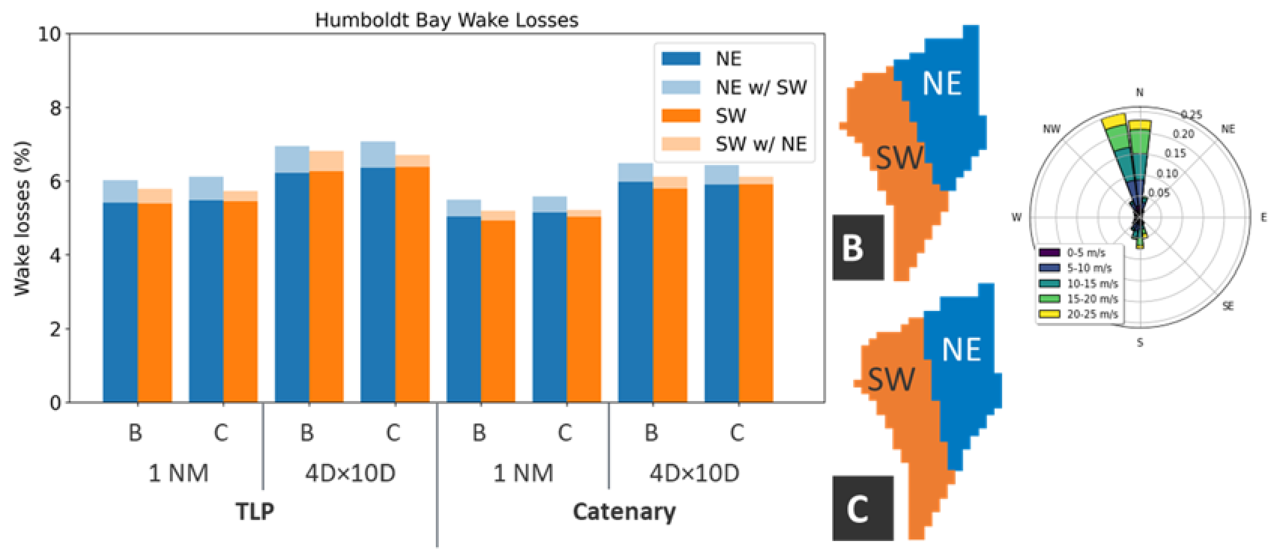


Figure 30. Wake losses in Humboldt WEA for delineation options B and C

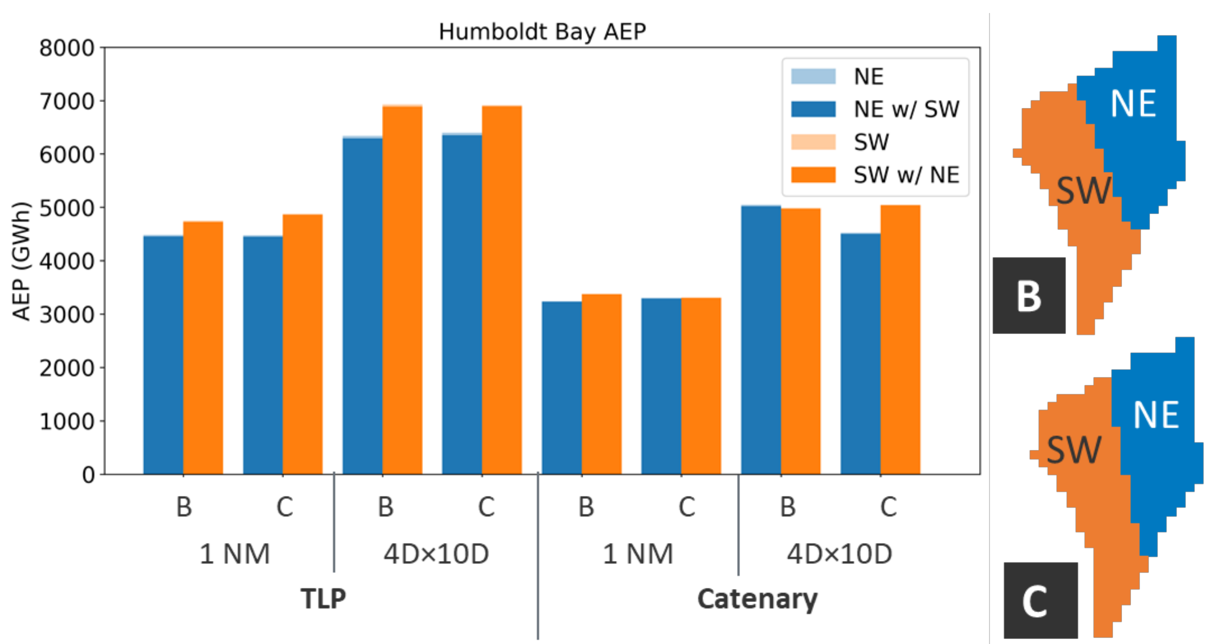


Figure 31. Annual energy production in Humboldt WEA for delineation options B and C

The combined AEP for the two farms is compared across both delineation options in Figure 32. The total AEP is almost equal between options B and C for all cases. Delineation option C has a slight advantage with TLP technology, while option B has a slight advantage with catenary moorings. These differences are more noticeable with 4D × 10D spacing, which is more sensitive to the mooring setbacks.

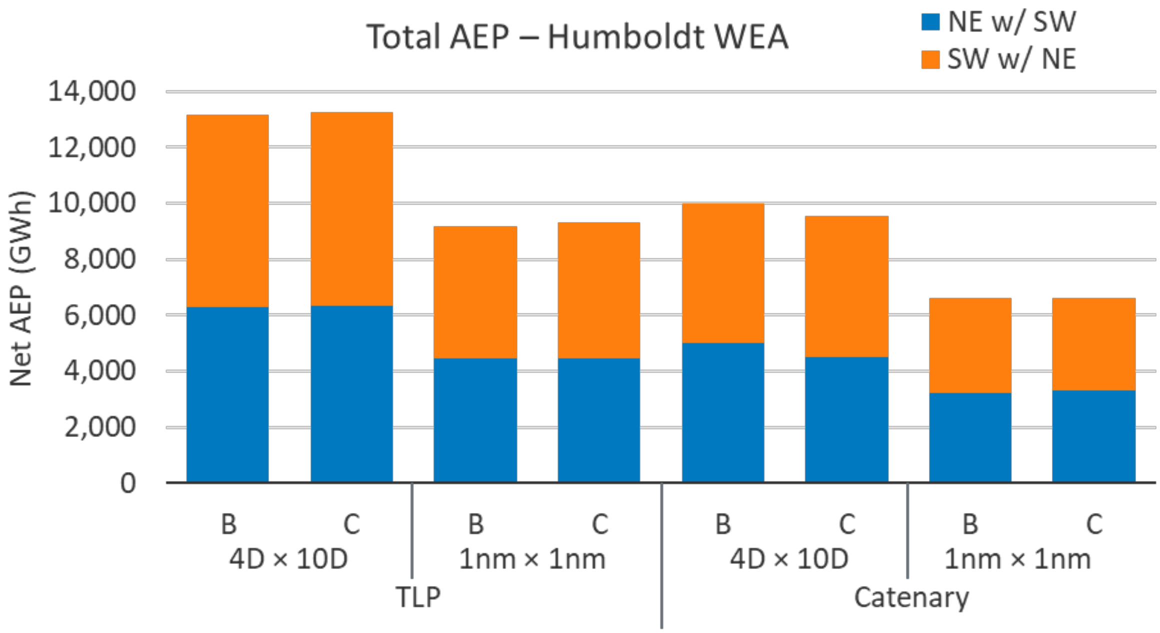


Figure 32. Combined annual energy production of both lease areas in the Humboldt WEA for delineation options B and C

5.2.2 Morro Bay

We used the same approach to analyze the four Morro Bay delineation options. Table 12 summarizes the generating potential for the four delineations using the most- and least-dense spacing and technology combinations. The 2a delineation has the largest capacity in both cases because its ratio of boundary length to area is lower than that of the delineations with three lease areas. Among the delineations with three areas, option 3a has the largest capacity for 1 nm spacing with catenary moorings and option 3b has the largest capacity for 4D × 10D spacing with TLPs. The table also shows the net capacity factor for each option. For the 1 nm with catenary combination, the net capacity factor ranges from 47.6% to 47.8%. Like in Humboldt, the 4D × 10D spacing with TLP combination lowers the net capacity factor by more than 1% because the turbines are more densely packed.

Table 12. Morro Bay WEA Generating Potential

Delineation	Spacing	Mooring Technology	Capacity [MW]	Capacity Density [MW/km^2]	Gross Generation [TWh]	GCF [%]	Net Generation [TWh]	NCF [%]
2a	1 nm	Catenary	3,045	3.1	15.8	57.4	12.7	47.6
	4D × 10D	TLP	5,625	5.8	29.2	57.4	22.9	46.5
3a	1 nm	Catenary	2,910	3.0	15.1	57.4	12.2	47.7
	4D × 10D	TLP	5,355	5.5	27.8	57.4	21.9	46.6
3b	1 nm	Catenary	2,805	2.9	14.6	57.4	11.8	47.8
	4D × 10D	TLP	5,550	5.7	28.8	57.4	22.6	46.5
3c	1 nm	Catenary	2,835	2.9	14.7	57.4	11.9	47.8
	4D × 10D	TLP	5,370	5.5	27.9	57.4	21.9	46.6

Wake loss results for the Morro Bay delineations are presented in two separate figures for readability. The 3a and 3c delineation wake losses are compared in Figure 33 because the area divisions are similar. For each farm, the wake losses are shown individually and with both adjacent farms. In the southwest and east lease areas, the wake losses increase by 1% to 2% with the addition of wind plants in the adjacent lease areas. This is because the winds in Morro Bay come primarily from the northwest, as shown in the wind rose, so the southwest and eastern farms are in the wake of the northwest farm. The northwest farm, however, shows only a small increase in wake losses with the addition of the other two farms. Figure 34 compares the 2a and 3b delineation options, which both have vertical divisions of the space. The eastern and central farms show 1% to 2 % increases in wake losses caused by the addition of adjacent farms. Again, the northwest farm's wake losses are relatively unaffected by the other farms, showing an increase of less than 0.5%.

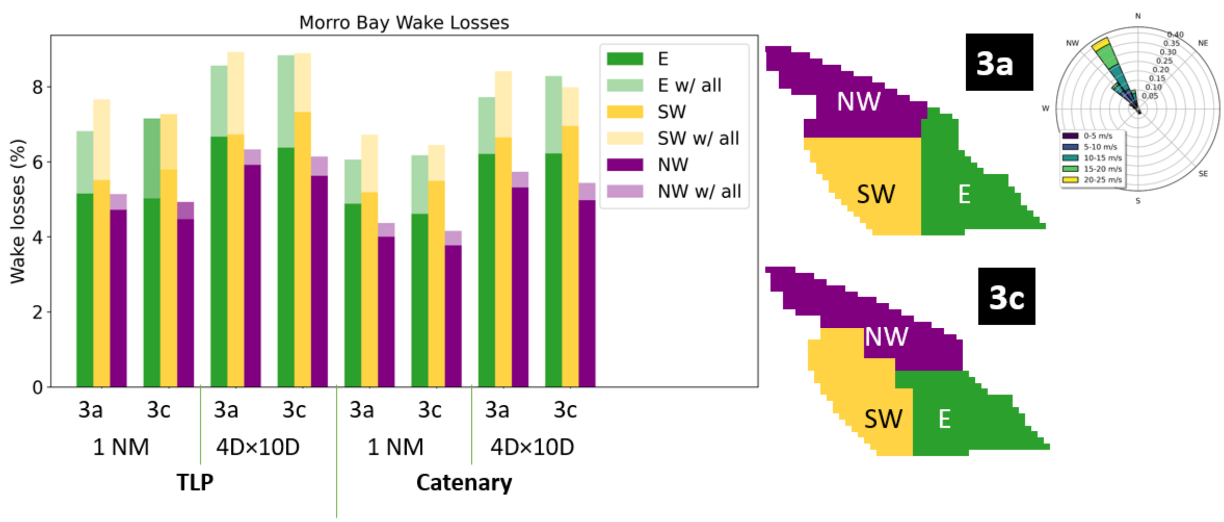


Figure 33. Wake losses in Morro Bay WEA for delineation options 3a and 3c

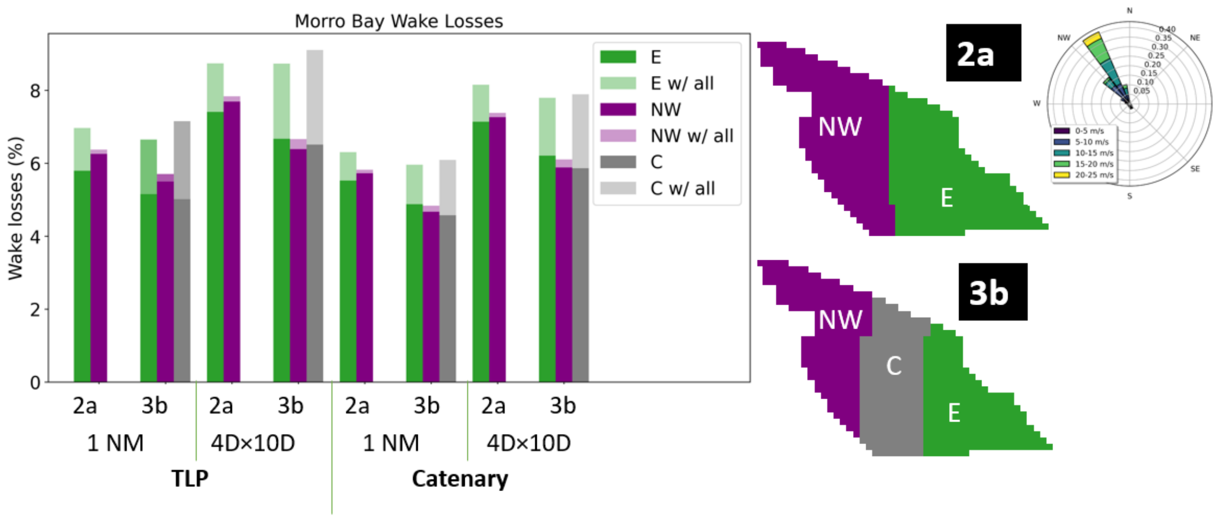


Figure 34. Wake losses in Morro Bay WEA for delineation options 2a and 3b

Figure 35 shows the annual energy production for delineations 3a and 3c. Corresponding to the wake loss results, the southwest and eastern farms show slight decreases in AEP caused by the adjacent farms while the northwest farm does not. In option 3a, the southwest farm has the highest AEP in most cases, except for the 4D × 10D TLP case. This is likely because the nearly rectangular shape of the southwest farm is the most efficient for space filling in most cases. In option 3c, AEP is more similar across the three farms, with the eastern farm coming out with the highest AEP by a small margin in all cases. Figure 36 shows the annual energy production for the 2a and 3b delineation options. For the 2a option, the AEP is similar between the eastern and northwestern farms. The northwestern farm has a slightly higher AEP in the cases with TLP technology, possibly because the northwestern corner is most sensitive to mooring setbacks. The 3c delineation option shows a slightly higher AEP for the central farm in most cases, except for the case with 1 nm spacing and TLP technology.

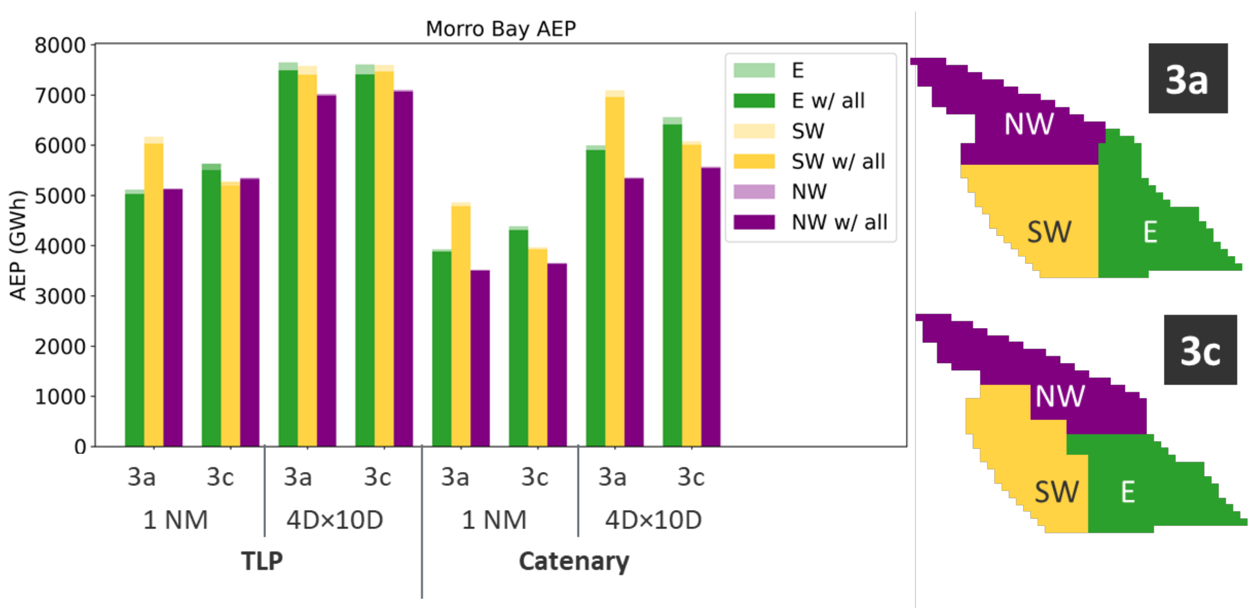


Figure 35. Annual energy production in Morro Bay WEA for delineation options 3a and 3c

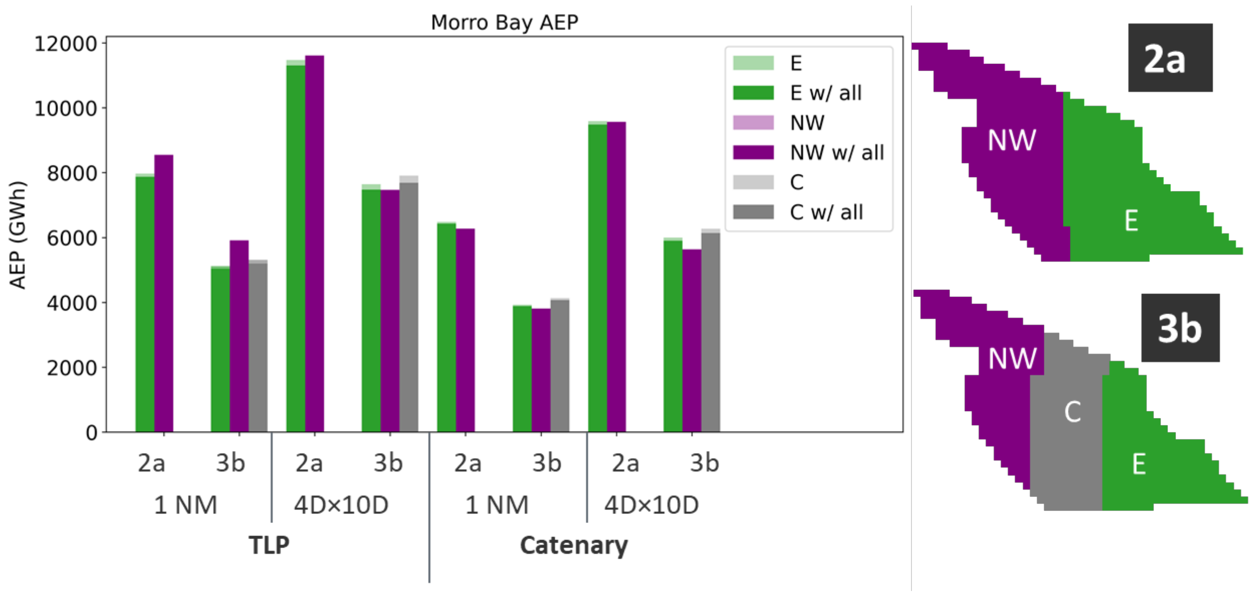


Figure 36. Annual energy production in Morro Bay WEA for delineation options 2a and 3b

Figure 37 shows the total AEP for the four delineation options in Morro Bay. For all technology and spacing combinations, option 2a has the highest overall AEP because there are fewer boundaries and more turbines. However, this result assumes that the two lease areas in option 2a would be completely filled. If developers chose to limit the installed capacity within each lease area to 1 GW only, then the total AEP in option 2a would be less than in the options with three lease areas. Among options 3a, 3b, and 3c, option 3b has the highest overall capacity with TLP technology and the lowest capacity with catenary moorings. The 3a and 3c capacities are similar, but option 3a has a slight advantage in all cases except 4D × 10D with TLP technology. These results show that the performance of the different delineation options is highly dependent on the chosen turbine spacing and mooring technology.

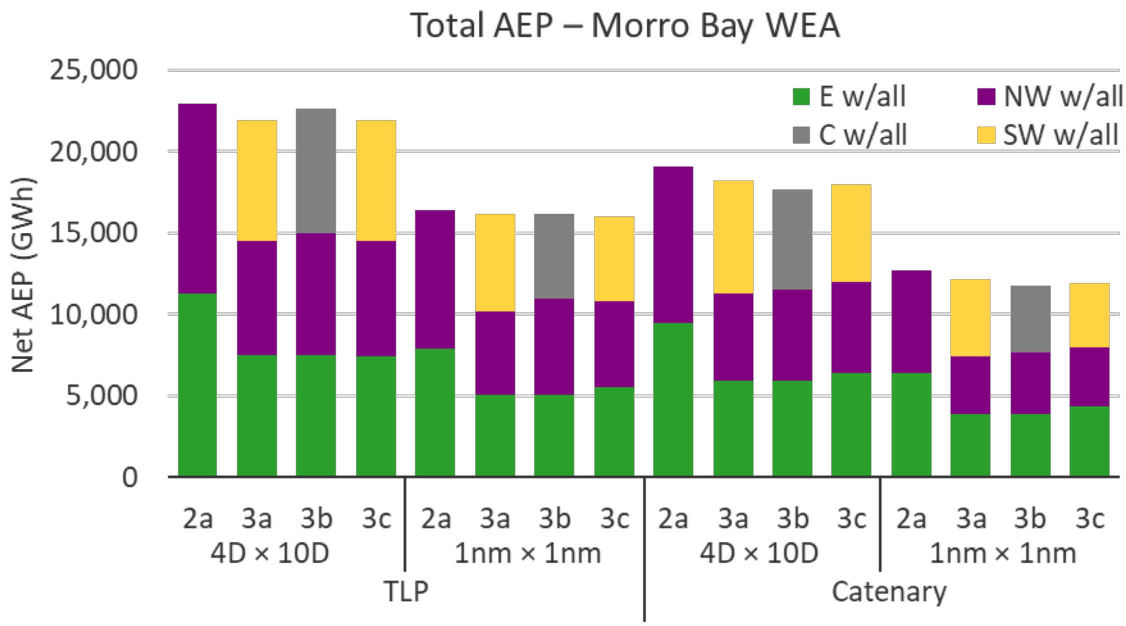


Figure 37. Combined annual energy production of all lease areas in the Morro Bay WEA for delineation options 2a, 3a, 3b, and 3c

Figure 38 shows the additional wake losses caused by the presence of adjacent wind farms. For Humboldt, the northeast lease area is more affected by turbines in the southwest lease area because the wind is coming from the northwest. The C delineation option shows a larger difference between the northeast and southwest lease areas because the delineation is more vertical. Morro Bay results show that the northwest lease area is consistently the least affected by adjacent wind farms because it is upstream. The southwest lease area has the highest additional wake losses for the 3a option, while the eastern lease area has the highest additional wake losses for the 3c option. Lastly, the central lease area has the highest additional wake losses for the 3b option. These results show that the impact of neighboring wind farms on wake losses is highly dependent on the position and orientation of each lease are relative to the wind direction.

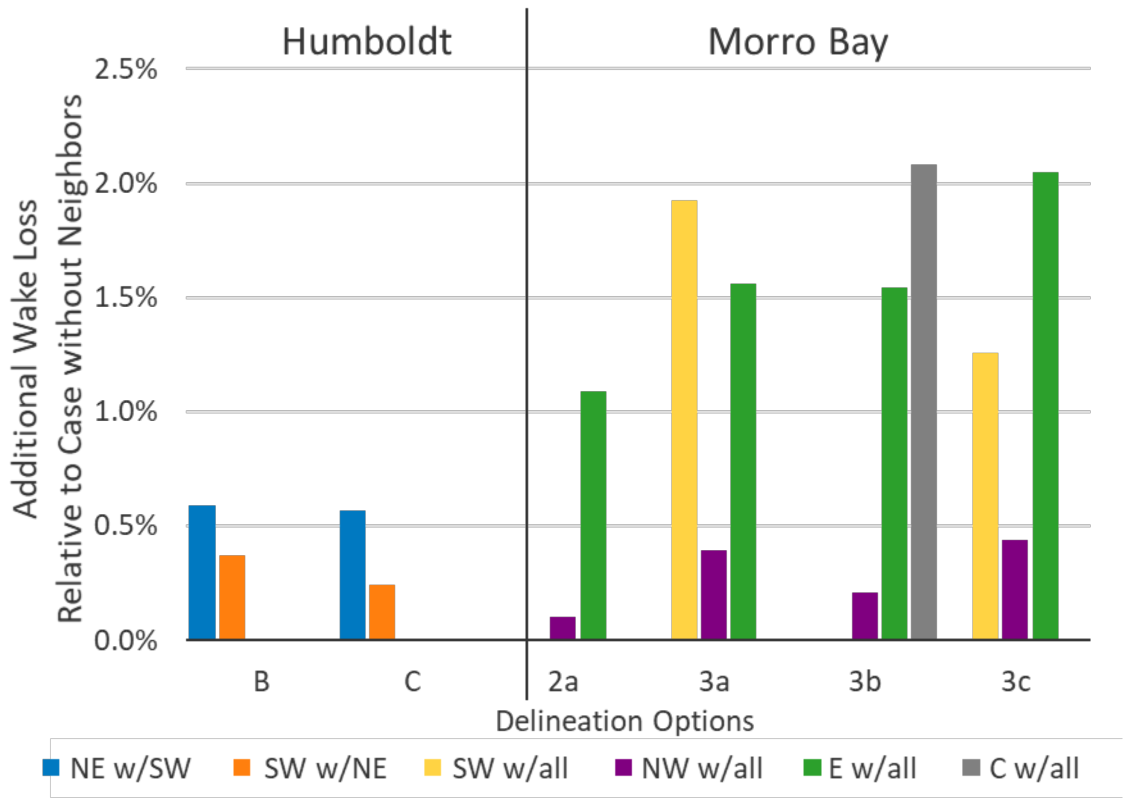


Figure 38. Increase in wake loss due to adjacent wind plants

5.2.3 Sensitivity to Wake Model

This report presents an initial assessment of cluster wake impacts on the generation potential of proposed lease area delineations using the TurbOPark wake model described in Nygaard et al. (2020). Different wake models have been shown to capture the general behavior of measurements but frequently deviate from one another (Moriarty et al. 2014). Some wake model uncertainty estimates for the Jensen (Park) model range from 1.4% to 15% of the predicted wake loss (Nygaard 2015). Murcia (2017) highlights that that one of the biggest challenges for wake model validation is the uncertainties of flow conditions derived from supervisory control and data acquisition. Toward the end of this writing, a new version of FLORIS (v3.0) was released with an updated version of the TurbOPark[4] wake model. The updated model has been validated by Ørsted, an offshore wind energy developer and operator, using data from 19 wind farms.

To illustrate the range of expected wake losses obtained with different choices of wake model, a few representative cases were modeled with the updated version of TurbOPark. Detailed results can be found in Appendix A. Figure 39 shows the wake losses for Humboldt delineation B for 1 nm spacing with catenary technology and 4D × 10D spacing with TLP technology. The 1 nm spacing with catenary technology represents the lower bound of wake losses. In this case, the wake loss estimates from the updated version of TurbOPark increase from 4.9%–5.5% to 7.5%–8.6%. This represents an increase of approximately 50% to 60% in wake losses from the earlier

[4] Updated TurbOPark model available on GitHub: https://github.com/OrstedRD/TurbOPark.

version of TurbOPark. The TLP with 4D × 10D spacing case represents the upper bound of wake losses. The updated TurbOPark increases wake losses to 10.7%–12%, representing around a 70% to 75% increase in wake losses over the previous version of the wake model.

Similarly, Figure 40 shows the wake losses for Morro Bay delineation 3b for 1 nm spacing with catenary technology and 4D × 10D spacing with TLP technology. For the 1 nm catenary case, the updated TurbOPark increases the wake losses to 5.8%–9.8%, a 30% to 60% increase in wake losses from the previous version. The 4D × 10D spacing with TLP case shows wakes losses of 10.4%–17.6% with the updated TurbOPark, representing a 60% to 90% increase in wake losses.

This analysis indicates the possible range of expected wake losses for the wind plant configurations investigated in this report. As highlighted by Murcia (2017), wind farm flow model uncertainty quantification is challenging due to the accessibility of quality validation data as well as the complex physics involved. The wake loss estimates obtained with the updated TurbOPark model are higher than those obtained with the earlier model version (by up to 90% in certain conditions). In Humboldt, the interarray wake losses are similar in both the northeast and southwest farm with both wake models, although the wake losses are larger in the updated TurbOPark model. In Morro Bay, the eastern and central farms show a significant increase in wake losses caused by the other farms, while the northwestern farm does not. The updated TurbOPark model predicts larger interarray wake losses for the eastern and central wind farms than the original model.

The data presented here show that initial wake losses are highly dependent on the chosen wake model and configuration of input parameters. Higher fidelity modeling would be needed for a more precise understanding of wake losses in the regions investigated, but these simulations give a good overall sense of how the sites would perform based on very general layout assumptions. As this study only considered buildouts of the two existing WEAs, more analysis investigating regional offshore wind wakes (like Pryor, Barthelmie, and Shepherd [2021]) may be needed to inform future planning efforts.

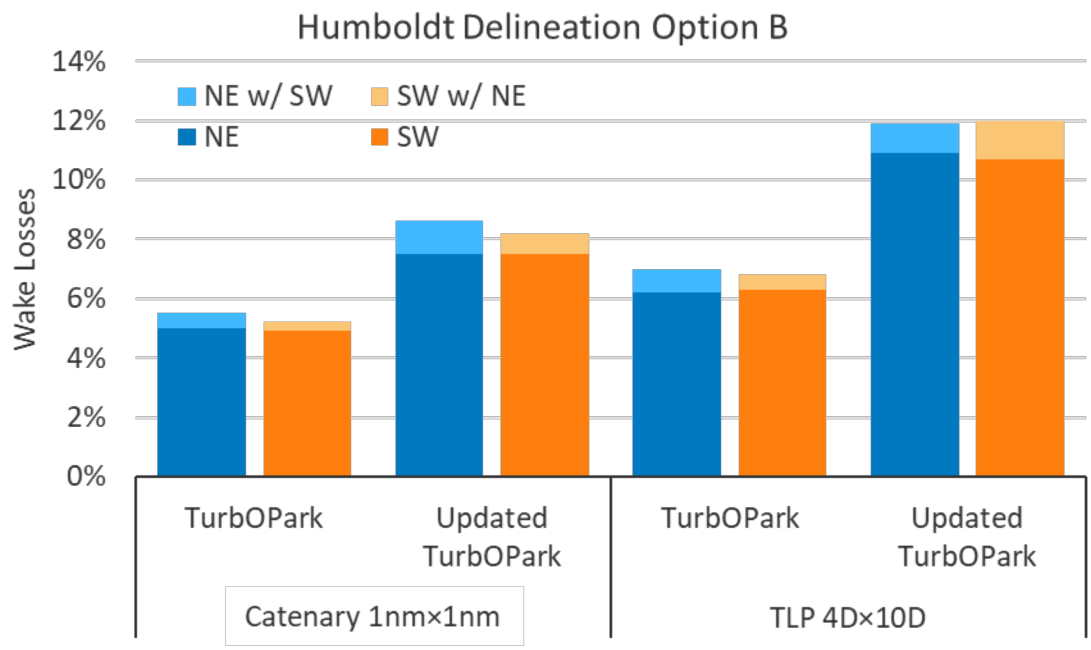


Figure 39. Comparison of Humboldt delineation B wake loss estimates using different versions of the TurbOPark wake model

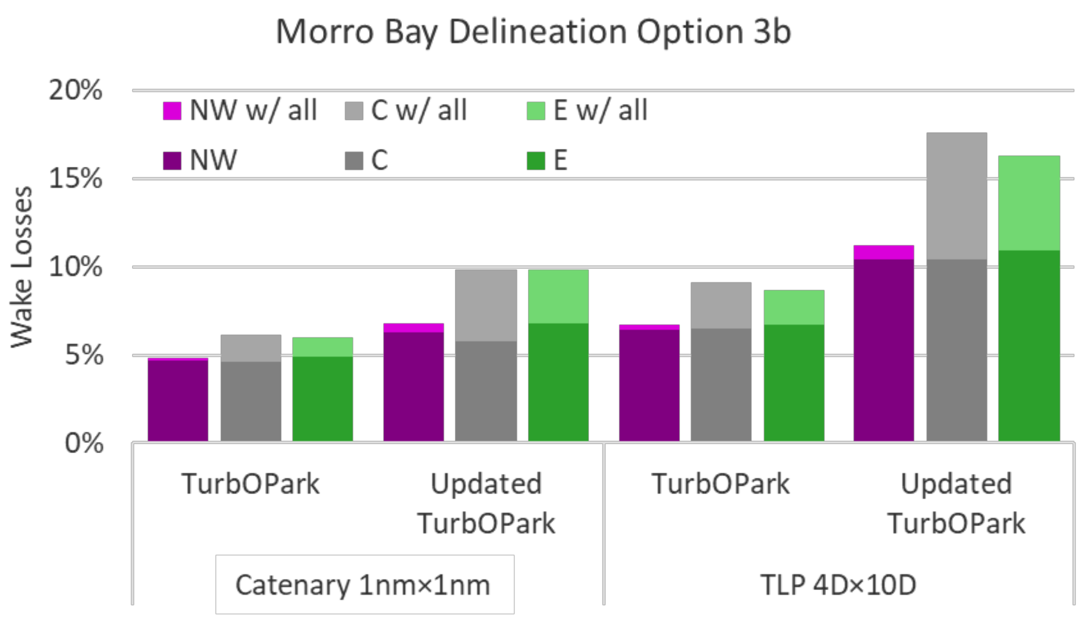


Figure 40. Comparison of Morro Bay delineation 3b wake loss estimates using different versions of the TurbOPark wake model

5.2.4 Additional Considerations

Although our analysis considered example layouts that illustrate possible levels of installed capacity, annual energy production, and wake losses, there are many additional considerations that will need to be incorporated into project planning. One key consideration is the routing of export cables, both within lease areas and from the lease areas to shore. The layouts we modeled do not include assumptions about where substations and export cables would be located within each lease area, nor do they assume that a particular setback would be required from these components. Export cable routes from the Morro Bay WEA will be impacted by the Monterey National Marine Sanctuary, which may disadvantage the northernmost lease areas in delineation options 3a and 3c. Other considerations for plant layouts include navigation lanes, mooring footprints within arrays, and alternatives to rectangular spacing that could increase energy capture. Each of these factors could alter the estimates of generating capacity and energy production that are presented in this study.

6 Summary and Conclusions

After surveying the available geophysical data and gathering information from wind energy developers to understand the factors that affect their plans for future development, we evaluated several options for delineating the Humboldt and Morro Bay wind energy areas (WEAs) into lease areas of nominally equal value. The power generating capacity of each lease area depends on the wind turbine layout and mooring technology; however, we demonstrated that each lease area can hold a 1-gigawatt (GW) wind plant in most of the modeled scenarios. The likely range of generating capacity is 1.5 to 3 GW in Humboldt and 3 to 5 GW in Morro Bay.

We considered several factors that affect the value of lease areas for wind energy development, including mean wind speeds, water depth, seafloor gradient, seismicity, hard substrate, and access to infrastructure. The largest impact to generating capacity came from the choice of mooring technology and the resulting setback from the lease area boundaries. Based on our setback assumptions, the generating capacity for a wind plant using catenary moorings could be nearly 30% less than with vertical moorings in Humboldt, or approximately 20% less in Morro Bay. This sensitivity to mooring footprints suggests that significant benefits could be realized from further research and development of alternative mooring and anchor designs that optimize the trade-offs among performance, cost, and space requirements in deeper waters.

Interarray wake effects were a key parameter in the delineation of the California WEAs, as they can increase wake losses by up to 30% in some cases. The effect on the various wind farms within a WEA is highly dependent on the wind farm location and the wind speed heading. The interarray effects can cause an energy deficit that is five times higher for downstream farms than upstream farms under some conditions.

One of our objectives was to evaluate whether the delineation options produced lease areas of equal value. There are several possible metrics to assess relative equality or fairness among the lease areas, including area, generating capacity, annual energy production, wake losses and interarray wake effects, and cost factors based on site conditions. Although the lease areas in each delineation option are not completely equal on all of these metrics, none of the lease areas has a substantial advantage or disadvantage overall.

There are additional requirements for infrastructure to support offshore wind that wind energy developers have less control over and may not be detailed in a project’s construction and operations plan. Suitable port access is essential to support offshore wind and, due to the distance between the California WEAs, there will need to be a port in each region. State or local support may be needed for port development.

The availability of bulk transmission access plays a large role in determining the value of the lease areas. This factor will be more important in differentiating between Morro Bay and Humboldt WEAs than among the individual lease areas within these WEAs. Within the Morro Bay WEA, access to the shortest export cable routes may be limited for the northernmost lease area in some delineation options.

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Appendix A. Detailed Results Tables

This appendix provides results from the assessment of generating potential for each lease area in tabular form. The results are organized by mooring type and turbine spacing. The tension-leg platform (TLP) with 4 rotor diameter (D) × 10D spacing cases allow the largest number of wind turbines to be placed in each lease area, whereas the catenary mooring lines with 1 nautical mile (nm) spacing are the most restrictive. Three categories of results are provided in each case:

- Capacity is the product of the turbine capacity (15 megawatts [MW]) and the number of turbines that can fit within the specified mooring setback at the prescribed spacing.
- Net annual energy production (AEP), in gigawatt-hours (GWh), is obtained from the gross AEP for each plant reduced by wake losses and other losses detailed in Table 10.
- Wake losses are expressed as a percentage of gross AEP and were calculated using the Turbulence Optimized Park wake model (TurbOPark).

The following abbreviations are used for the delineation options and lease areas:

2a, 3a, 3b, 3c	Morro Bay delineation options
B, C	Humboldt delineation options
E, C, NE, NW, SW	east, central, northeast, northwest, and southwest lease areas

Tables A-1 through A-2 show the potential generating capacity, AEP, and wake losses for each of the delineation options for Humboldt WEA.

Table A-1. Humboldt Delineation Options with TLP

	4D × 10D		**1 nm × 1 nm**	
	B	**C**	**B**	**C**
Capacity (MW)				
NE	1,455	1,470	1,020	1,020
SW	1,590	1,590	1,080	1,110
Total	*3,045*	*3,060*	*2,100*	*2,130*
Net AEP (GWh)				
NE	6,340	6,396	4,483	4,480
NE w/ SW	6,291	6,347	4,454	4,449
SW	6,925	6,916	4,748	4,877
SW w/ NE	6,884	6,892	4,728	4,862
Total w/ both	*13,175*	*13,239*	*9,182*	*9,311*
Wake Losses (%)				
NE	6.2%	6.4%	5.4%	5.5%
NE w/ SW	7.0%	7.1%	6.0%	6.1%
SW	6.3%	6.4%	5.4%	5.4%
SW w/ NE	6.8%	6.7%	5.8%	5.7%

Table A-2. Humboldt Delineation Options with Catenary Mooring

	4D × 10D		1 nm × 1 nm	
	B	**C**	**B**	**C**
Capacity (MW)				
NE	1,155	1,035	735	750
SW	1,140	1,155	765	750
Total	*2,295*	*2,190*	*1,500*	*1,500*
Net AEP (GWh)				
NE	5,046	4,525	3,243	3,306
NE w/ SW	5,019	4,500	3,228	3,290
SW	4,990	5,049	3,379	3,310
SW w/ NE	4,973	5,038	3,370	3,303
Total w/ both	*9,992*	*9,538*	*6,598*	*6,593*
Wake Losses (%)				
NE	6.0%	5.9%	5.0%	5.1%
NE w/ SW	6.5%	6.4%	5.5%	5.6%
SW	5.8%	5.9%	4.9%	5.0%
SW w/ NE	6.1%	6.1%	5.2%	5.2%

Tables A-3 through A-6 show the potential generating capacity, AEP, and wake losses for each of the delineation options for the Morro Bay WEA.

Table A-3. Morro Bay Delineation Options with TLP and 4D × 10D Spacing

	2a	3a	3b	3c
Capacity (MW)				
E	2,790	1,845	1,845	1,830
SW		1,830		1,845
NW	2,835	1,680	1,800	1,695
C			1,905	
Total	*5,625*	*5,355*	*5,550*	*5,370*
Net AEP (GWh)				
E	11,471	7,647	7,647	7,608
E w/ all	11,307	7,491	7,478	7,408
SW		7,580		7,593
SW w/ all		7,401		7,464
NW	11,621	7,019	7,482	7,104
NW w/ all	11,603	6,988	7,461	7,065
C			7,908	
C w/ all			7,689	
Total w/ all	*22,910*	*21,880*	*22,628*	*21,937*
Wake Losses (%)				
E	7.4%	6.7%	6.7%	6.4%
E w/ all	8.7%	8.6%	8.7%	8.8%
SW		6.7%		7.3%
SW w/ all		8.9%		8.9%
NW	7.7%	5.9%	6.4%	5.6%
NW w/ all	7.8%	6.3%	6.7%	6.1%
C			6.5%	
C w/ all			9.1%	

Table A-4. Morro Bay Delineation Options with TLP and 1 nm Spacing

	2a	3a	3b	3c
Capacity (MW)				
E	1,905	1,215	1,215	1,335
SW		1,470		1,260
NW	2,055	1,215	1,410	1,260
C			1,260	
Total	*3,960*	*3,900*	*3,885*	*3,855*
Net AEP (GWh)				
E	7,969	5,117	5,117	5,630
E w/ all	7,870	5,028	5,037	5,504
SW		6,168		5,271
SW w/ all		6,027		5,188
NW	8,555	5,141	5,917	5,345
NW w/ all	8,544	5,118	5,904	5,319
C			5,315	
C w/ all			5,195	
Total w/ all	*16,414*	*16,173*	*16,136*	*16,011*
Wake Losses (%)				
E	5.8%	5.2%	5.2%	5.0%
E w/ all	7.0%	6.8%	6.6%	7.2%
SW		5.5%		5.8%
SW w/ all		7.7%		7.3%
NW	6.3%	4.7%	5.5%	4.5%
NW w/ all	6.4%	5.1%	5.7%	4.9%
C			5.0%	
C w/ all			7.2%	

Table A-5. Morro Bay Delineation Options with Catenary Mooring and 4D × 10D Spacing

	2a	3a	3b	3c
Capacity (MW)				
E	2,325	1,440	1,440	1,575
SW		1,710		1,470
NW	2,325	1,275	1,350	1,320
C			1,500	
Total	*4,650*	*4,425*	*4,290*	*4,365*
Net AEP (GWh)				
E	9,588	5,997	5,997	6,559
E w/ all	9,482	5,901	5,896	6,414
SW		7,089		6,074
SW w/ all		6,955		6,007
NW	9,574	5,361	5,642	5,570
NW w/ all	9,563	5,337	5,629	5,543
C			6,270	
C w/ all			6,135	
Total w/ all	*19,045*	*18,193*	*17,660*	*17,964*
Wake Losses (%)				
E	7.1%	6.2%	6.2%	6.2%
E w/ all	8.2%	7.7%	7.8%	8.3%
SW		6.6%		7.0%
SW w/ all		8.4%		8.0%
NW	7.3%	5.3%	5.9%	5.0%
NW w/ all	7.4%	5.7%	6.1%	5.4%
C			5.9%	
C w/ all			7.9%	

Table A-6. Morro Bay Delineation Options with Catenary and 1 nm Spacing

	2a	3a	3b	3c
Capacity (MW)				
E	1,545	930	930	1,035
SW		1,155		945
NW	1,500	825	900	855
C			975	
Total	*3,045*	*2,910*	*2,805*	*2,835*
Net AEP (GWh)				
E	6,481	3,928	3,928	4,384
E w/ all	6,428	3,880	3,884	4,312
SW		4,863		3,966
SW w/ all		4,784		3,926
NW	6,279	3,517	3,810	3,653
NW w/ all	6,273	3,504	3,803	3,639
C			4,132	
C w/ all			4,066	
Total w/ all	*12,701*	*12,168*	*11,753*	*11,877*
Wake Losses (%)				
E	5.5%	4.9%	4.9%	4.6%
E w/ all	6.3%	6.1%	6.0%	6.2%
SW		5.2%		5.5%
SW w/ all		6.7%		6.4%
NW	5.7%	4.0%	4.7%	3.8%
NW w/ all	5.8%	4.4%	4.8%	4.2%
C			4.6%	
C w/ all			6.1%	

Tables A-7 and A-8 compare wake loss estimates for a single delineation option in Humboldt and Morro Bay, respectively, for two versions of the TurbOPark wake model.

Table A-7. Comparison of Humboldt Delineation B Wake Loss Estimates Using Different Versions of the TurbOPark Wake Model

	Wake Losses (%)			
Layout	Catenary 1 nm × 1 nm		TLP 4D × 10D	
Lease Area	TurbOPark	Updated TurbOPark	TurbOPark	Updated TurbOPark
NE	5.0%	7.5%	6.2%	10.9%
NE w/ SW	5.5%	8.6%	7.0%	11.9%
SW	4.9%	7.5%	6.3%	10.7%
SW w/ NE	5.2%	8.2%	6.8%	12.0%

Table A-8. Comparison of Morro Bay Delineation 3b Wake Loss Estimates Using Different Versions of the TurbOPark Wake Model

	Wake Losses (%)			
Layout	Catenary 1 nm × 1 nm		TLP 4D × 10D	
Lease Area	TurbOPark	Updated TurbOPark	TurbOPark	Updated TurbOPark
E	4.9%	6.8%	6.7%	10.9%
E w/ all	6.0%	9.8%	8.7%	16.3%
NW	4.7%	6.3%	6.4%	10.4%
NW w/ all	4.8%	6.8%	6.7%	11.2%
C	4.6%	5.8%	6.5%	10.4%
C w/ all	6.1%	9.8%	9.1%	17.6%