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Scenarios for offshore wind power production for Central California Call Areas

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Abstract

In response to the growing interest in offshore wind energy development in California, the U.S. Bureau of Ocean Energy Management delineated three Call Areas for potential leasing. This study provides a comprehensive characterization and comparison of offshore wind power potential within the two Central California Call Areas (Diablo Canyon and Morro Bay) using 12- and 15-MW turbines under different inter-turbine spacing and wind farm size scenarios. Our analysis shows similar daily and seasonal patterns of wind power produced within the Call Areas, which peak in spring and during evening hours. Per-turbine power production is higher in the Morro Bay Call Area due to slightly higher hub-height wind speeds, whereas total power production is higher in the Diablo Canyon Call Area due to its larger size. Turbine type had a negligible impact on average power production per-unit-area because while larger turbines produce more power, they require greater inter-turbine spacing. Combined power production from the two fully built out Call Areas could equal nearly a quarter of California's current annual electrical energy production. A commercial-scale wind farm with a realized power output of 960 MW would require a footprint of at least half of the Morro Bay Call Area or at least a quarter of the Diablo Canyon Call Area. These results provide guidance on offshore wind development over the Central California Coast, and the framework demonstrated here could be applied to other wind data sets in other regions.

KEYWORDS
BOEM, call areas, Central California, ocean energy, offshore wind power, wind farm scenarios

1 | INTRODUCTION

California is taking a leading role in the U.S. to reduce greenhouse gas emissions and address the climate crisis by setting ambitious goals to provide 60% of its electricity from renewables by 2030, and 100% by 2045 (SB-100, California Renewables Portfolio Standard Program). To achieve these goals, the state has incentivized commercial and residential solar energy production, along with commercial onshore wind farms. However, these renewable energy sources alone may not be sufficient to meet California's growing electricity demand. For example, the daily peak in demand occurs in the evening as solar production wanes close to zero. Likewise, the trend toward electric heating (e.g., instead of gas) is expected to increase electricity demand in winter when there is less solar production (e.g., Denholm et al.[1]). To achieve the state's energy targets during all times of the day and throughout the year, California has begun exploring ways to diversify its energy portfolio, including using offshore wind (e.g., Collier et al.[2]).

Offshore wind deployment is increasing in many parts of the world, supplying up to 10%–15% of electricity in locations such as the U.K. and Denmark.[3] Compared to Europe and China, the U.S. has developed offshore wind more slowly (e.g., deCastro et al.[4]), with only a single operating commercial offshore wind farm (Block Island in Rhode Island), several others in the planning stages on the east coast, and none in California or the U.S. West Coast in 2021, in spite of abundant offshore wind resources in both of the east and west coast (e.g., Costoya et al.[5]). However, industry and policymakers are currently exploring the potential for offshore wind development in California, likely using floating wind turbines due to the steep bathymetry and higher potential wind power further offshore in waters too deep for fixed-platform turbines. The California Central Coast—defined here as the area north of Point Conception and south of the Monterey Bay National Marine Sanctuary, and from 3 nautical miles (nm) from the coast (i.e., federal waters) in the east to the 1200 m isobath in the west (i.e., current proposed upper limit for floating turbine technology at this time)—has received considerable interest in the development of offshore wind energy. The California Central Coast has relatively strong offshore winds that align with the peak electricity demand and complement power produced by solar and land-based wind.[4,6] Much of the area is both within a developable depth (<1200 m) and outside National Marine Sanctuary zones that would likely legally preclude development. There are existing grid connections, at the retired Dynegy Power Plant in Morro Bay and at Diablo Canyon Nuclear Power Plant near Point Buchon, that may facilitate transmission and reduce the need for additional infrastructure.[7] The region also sits between major population centers in Southern California and the San Francisco Bay area with high electricity demand. Partly as a result of these reasons, the Bureau of Ocean Energy Management (BOEM), the federal agency responsible for permitting and leasing these types of projects, partnered with the State of California to delineate two “Call Areas,” the areas for commercial wind leases, off of the Central California Coast for potential offshore wind energy development (Figure 1; BOEM[8]).

Recent work explored offshore wind energy resources along the California Central Coast, examining potential power production and the utility and value of that power. Dvorak et al.[9] divided the coast in California into three geographical regions (i.e., Northern, Central, and Southern California) and assessed the annual energy production of each region. Musial et al.[10] estimated the long-term offshore wind power produced by a hypothetical wind farm near the Morro Bay Call Area and in five other reference areas in California. Wang et al.[6] assessed spatial and temporal patterns of wind speeds in the region over daily, seasonal, and annual time scales. Subsequently, Wang et al.[11] quantified temporal variation in the potential power that could be extracted from those winds by offshore wind turbines, and valuation of that power in relation to its alignment with statewide demand for power and wholesale value. Recently, Beiter et al.[7] estimated offshore wind energy production across California's Call

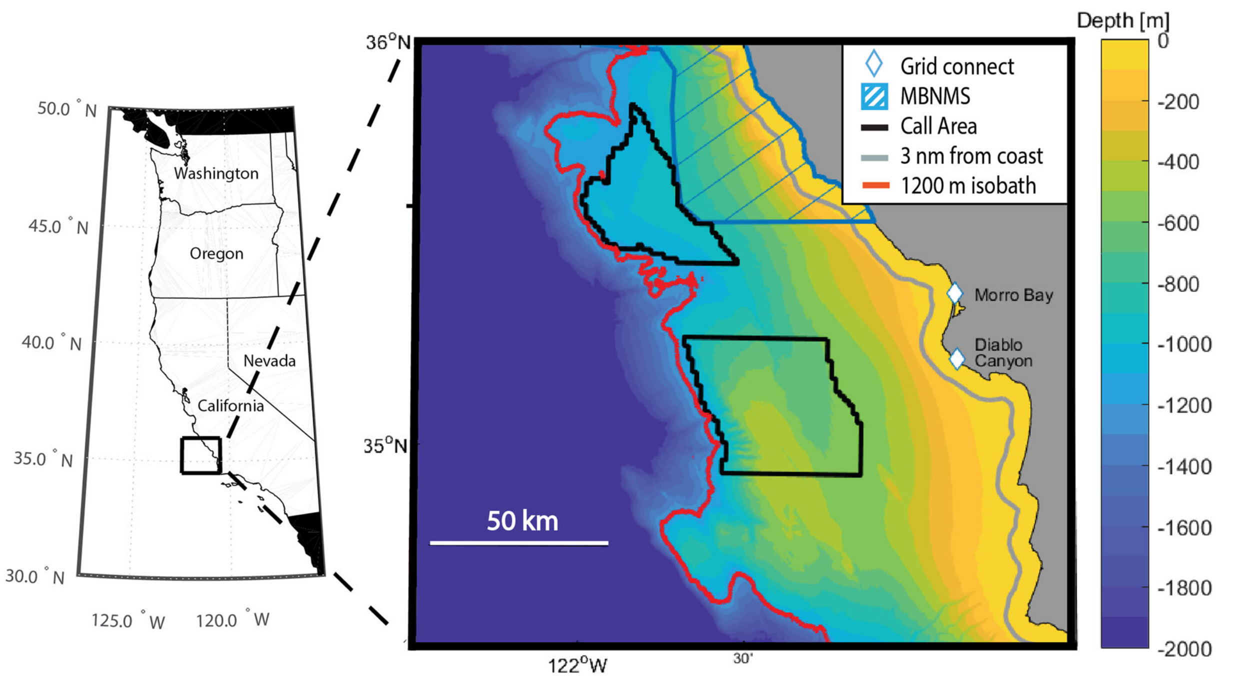

FIGURE 1 Bathymetry of the Central California Coast highlighting the two Call Areas (black lines; Morro Bay Call Area to the north and Diablo Canyon Call Area to the south), the locations of existing state electrical grid connections (white diamonds, the Morro Bay Power Plant to the north and the DCNPP to the south), Monterey Bay National Marine Sanctuaries (MBNMS, dashed blue lines), and the 1200-m isobath (red line) and the 3-nm distance limit from the coast (gray line)

Areas by four turbine types, including the latest projected 15-MW turbine, and computed the cost of a large-scale (1000 MW) wind farm assuming a 7-rotor diameter by 7-rotor diameter (D) spacing. In the California Coast call areas, there have been proposals for pilot-scale, medium-scale, and commercial-scale projects, and thus the need for power production estimates for different wind farm sizes.[12] Additionally, no previous studies in the Central Coast Call Areas have combined detailed assessments of the temporal (daily and seasonal patterns) and spatial characteristics of power production while considering the latest turbine technology (i.e., hub height and power curve characteristics) different turbine spacing scenarios, and different wind farm size scenarios.

As technology and local interest from developers, regulators, and other stakeholders have increased, an updated and more comprehensive assessment of offshore wind resources within the Call Areas of the Central California Coast is needed. To meet this expanding need, this study aims to provide an accurate estimate of power production with reasonable future turbine design and spacing scenarios. We focused on the BOEM California Central Coast Call Areas ("Diablo Canyon" and "Morro Bay"; black polygons of Figure 1) since these are areas where offshore wind energy development is likely to occur. We evaluated a variety of scenarios for offshore renewable energy production and the potential ocean area occupied in the Call Areas using both 12- and 15-MW turbines, considering alternative wind farm sizes, different spacing scenarios, and daily and seasonal variations. These results will help inform potential stakeholders, policymakers, and citizens as to whether, how, and where to pursue offshore wind energy development in California.

2 | DATA AND METHODS

This study used the WIND Toolkit data set, which provides hourly wind data during 2007–2013 from near surface to 160 m above the sea level in intervals of 20 m with a spatial resolution of 2 km between grid points.[13] The WIND Toolkit is among the best datasets for analysis in this region because of its high temporal (1 hr) and spatial (2 km) resolution, as well as its small error in comparison to buoy measurements along the California Central Coast.[6] While preparing this contribution, an updated wind resource data set (CA 20) developed by NREL became available, which shows a 17.4% and 19.7% increase in the mean 100-m wind speed at the centroids of the Morro Bay and Diablo Canyon Call Area, respectively, from the WIND Toolkit.[14] We chose the WIND Toolkit for analysis, because it was previously validated using a variety of statistical metrics against local Central California buoy measurements on different time scales, including daily and seasonal time scales, which have been shown to be critical for meeting grid demand and for the reliability and functioning of the grid system.[6,11] Furthermore, a recently deployed (October 2020) offshore wind buoy in Central California equipped with LIDAR does not contain enough data, particularly over seasonal time scales, to validate hub-height wind speeds against the new data set.

To estimate power generated by a wind turbine of interest, we interpolated wind speed to the hub height of the wind turbine, then adjusted the interpolated wind speed in relation to variation in air density, following Wang et al.[6] Finally, we converted wind speed to power production based on the respective power curve for turbine type. For more details regarding power generation calculation, see Wang et al.[11]

Since the wind energy industry expects to be deploying turbines with rated power between 12 and 15 MW within the next decade,[15] we assessed power production using both 12- and 15-MW turbines (specifications shown in Table 1). Because engineering technology information of wind turbines for commercial development is proprietary, we used the power curves of 12- and 15-MW turbines estimated by the National Renewable Energy Laboratory (Figure 2).[15] These wind turbines generate no power when wind speed is below their cut-in wind speed, 3 m/s (5.8 kts). Power generation increases with wind speed from this cut-in speed until winds reach rated wind speed at 11 m/s (21 kts). Power generation remains at the rated level between the rated wind speed and cut-out wind speed at around 25 m/s (48.6 kts). When wind speed exceeds the cut-out wind speed, the wind turbines shut down to avoid damage and therefore produce no power. The power coefficient curve as a function of wind speed was plotted in Figure S1.

Following the evaluation of hub-height wind speed characteristics, we investigated temporal and spatial characteristics of potential power production in the BOEM Central Coast Call Areas. First, we explored spatial variation in mean power production and capacity factor across the entire Central Coast region. Capacity factor is defined as the ratio of actual power to the rated power that a turbine could produce in a given time period (e.g. He and Kammen[16]). The capacity factor of new offshore wind projects is expected to be around 50%.[3] In other words, a 12-MW turbine is expected to produce an average of about 6 MW of power over the course of a year. Considering the technological, geographical, and legal constraints to development in the region (see Section 1), we investigated the Central California Coast study domain feasible for development defined by spatial points north of Point Conception (north of 34.5°N), outside National Marine Sanctuaries, 3 nm off of the coast, and a maximum

TABLE 1 Turbine specifications for 12- and 15-MW turbines, adapted from Musial et al.[8]

Turbine rated power (MW)	12	15
Turbine rotor diameter (m)	222	248
Turbine hub height (m)	136	149

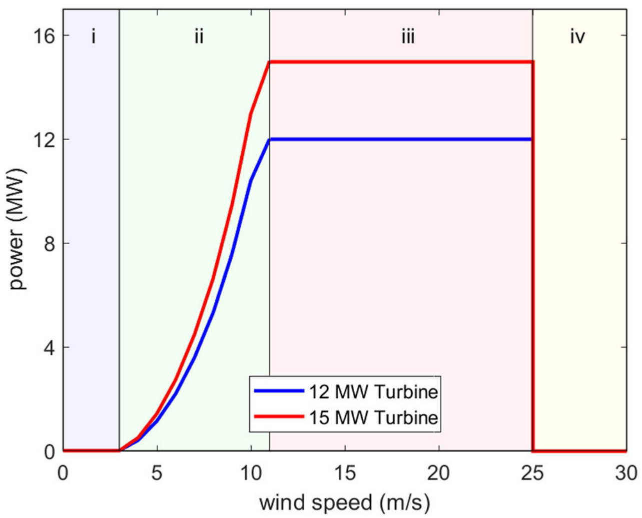

FIGURE 2 Power curves of 12- and 15-MW wind turbines, estimated by NREL.[15] Background colors represent the following categories: (i) the wind speed range below cut-in wind speed (3 m/s), (ii) between cut-in and rated wind speed (11 m/s), (iii) between rated and cut-out wind speed (25 m/s), and (iv) beyond cut-out wind speed, respectively

depth of 1200 m, with a focus on the BOEM Call Areas in this region. We then characterized the temporal variation in spatial-mean power over each Call Area daily and seasonally.

Since a Call Area could be subdivided into multiple leasing sites, we examined the power produced and area covered (i.e., footprint) for turbine types, wind farms of different production levels, and different spacing scenarios. To date, there is still no consensus on the ideal spacing of turbines, but most configurations range from 7 D between turbines to up to 10 or more D.[17] Therefore, the spacing will impact the total area needed for a wind facility of a given production level, and influence the power produced per unit area. We considered 7D x 7D and 8D × 10D spacing scenarios (e.g., Beiter et al.[7], Glenn et al.[18], and Musial et al.[15]), which represent the likely highest and lowest density configurations, and evaluated 60-, 240-, and 960-MW power production levels, to represent the installed capacity of a hypothetical pilot-scale, medium-scale, and -commercial-scale wind farm, respectively. For each wind farm production level and spacing scenario considered, we captured the full range of its footprint by evaluating two extreme patterns of development within a Call Area, one that assumes turbines are placed at locations with the highest power production (creating the smallest possible footprint for that wind farm production level and spacing scenario), and the other that assumes turbines are placed at locations with the lowest power production (creating the largest footprint). Finally, to provide realistic results with practical utility, we focused our analysis on estimates of realized power production, calculated as the mean annual power produced using WIND Toolkit hub-height wind speeds for the years for which data are available (i.e., 2007–2013) and the projected power curves for 12- and 15-MW turbines. We calculated the capacity factor by dividing the mean annual power produced by the rated power. To provide context, we compared our results to the realized power production from the Diablo Canyon Nuclear Power Plant (DCNPP) of 1980 MW (2200-MW rated power with an estimated capacity factor of 0.9).[19] The DCNPP can supply nearly 10% of California's energy portfolio and is scheduled to be decommissioned in 2024–2025.[20]

3 | RESULTS

3.1 | Relative frequency of hub-height wind speed

To examine the distribution of wind speeds in the study domain, we plotted the relative frequency of hourly hub-height wind speed at every grid cell within each Call Area over 2007–2013 for a hypothetical 12-MW turbine (Figure 3). We color-coded data into four wind speed categories: (i) below cut-in, (ii) cut-in to rated, (iii) rated to cut-out, and (iv) above cut-out. The relative frequencies in these wind speed categories reveal the percentage of time a turbine has no power production (Category i and iv), increasing power production (Category ii), and rated power production (Category iii).

The two Call Areas shared a similar pattern of relative frequencies in different wind speed ranges. Hub-height wind speed was between the cut-in and rated wind speed (e.g., producing some power, but less than rated power) 57%–63% of the time, between rated and cut-out wind speed (e.g., producing rated power) 25%–29% of the time, and below cut-in wind speed (e.g., producing no power because of insufficient winds) 11%–14% of the time. Extremely strong wind events greater than cut-out wind speed (in which turbines would shut down and produce no power), were very rare in this region: about 0.3% of the time in the Morro Bay Call Area and 0.6% of the time in the Diablo Canyon Call Area.

Although small, there was some spatial variation in the relative frequency of wind speeds between the Call Areas. The Morro Bay Call Area experienced slightly more hours of wind speed below the cut-in (Category i), and the rated and cut-out category (Category iii), and fewer hours of

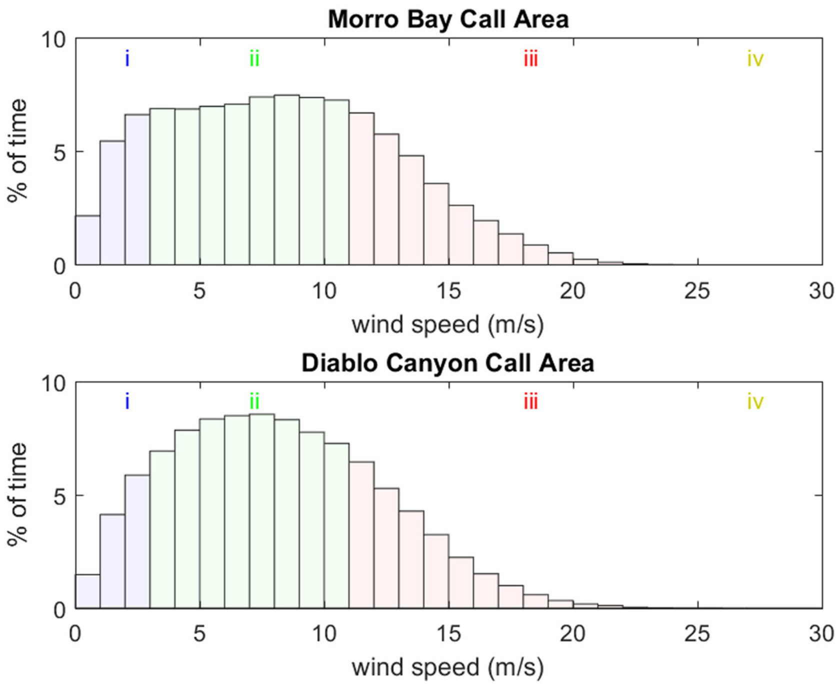

FIGURE 3 Frequency distribution of hourly hub-height wind speed (modeled for a 12-MW turbine) in each 2-km × 2-km grid cell within the Morro Bay call area (top) and the Diablo Canyon Call Area (bottom) over 2007–2013. Roman numerals and bar color corresponds with wind speed categories shown in Figure 2: (i) below cut-in wind speed (≤3 m/s), (ii) between cut-in and rated wind speed (>3 m/s and <11 m/s), (iii) and between rated and cut-out wind speed (≥11 and ≤25 m/s). Because less than 1% of wind speed data is in category (iv) above cut-out wind speed (>25 m/s) regardless of call areas and wind turbines, its frequency is not discernible. Note that frequencies of each wind speed group with 15-MW turbines are almost identical to that with 12-MW turbines. The trivial differences between two types of turbines are due to slightly stronger offshore wind speed at higher hub height. Also note that the frequency of the cut-in wind speed category is equivalent to the frequency of zero power production and the frequency of the between rated and cut-out wind speed category is equivalent to the frequency of rated power production

wind speed in the cut-in and rated category (Category ii) compared to the Diablo Canyon Call Area. Although the 15-MW turbine captured slightly stronger wind speed at its higher hub height than the 12-MW turbine, the frequency distribution of wind speeds was nearly identical between the two hub heights (Figure S2).

3.2 | Spatial and temporal variation in power generation

There was substantial spatial variation in potential power generation across the feasible area for development in the California Central Coast study domain (Figure 4). Potential power production increased with distance from shore due to stronger wind speed offshore (Figure 4). Although per-turbine power production was greater for 15-MW turbines, the spatial pattern of power production across the domain was very similar for both the 12- and 15-MW turbines (Figure 4).

Capacity factor also varied across the domain in a pattern similar to power production: it was higher with increased distance from shore, and it was nearly identical for 12- and 15-MW turbines (Figures 5 and S3). Within each Call Area, the spatial mean capacity factor in the Morro Bay Call Area was 0.51, while that in the Diablo Canyon Call Area was 0.49 (Table 2).

The two Call Areas showed similar daily and seasonal variation in spatially-averaged power production. Offshore wind power production was generally lower in the morning and higher in the evening (Figure 6). Seasonally, power production was greatest in spring, followed by summer, fall, and winter. The daily and seasonal patterns were consistent between the 12- and 15-MW turbines and matched patterns from previous research that considered 10-MW turbines,[11] suggesting that the temporal variation in power production in the Call Areas is likely independent of the specific size or specifications of the turbine(s) used.

The two Call Areas exhibited small but noticeable differences in daily and seasonal variation in terms of magnitude and timing of maximum and minimum power production levels (Figure 6). For example, average per-turbine power production in the Morro Bay Call Area was generally higher than that in the Diablo Canyon Call Area, with a few exceptions between hours 12–18 (i.e., 12:00–6:00 p.m. local time) in the spring and 14–22 (i.e., 2:00–10:00 p.m. local time) in the winter. Power production in the Morro Bay Call Area was about 0.5 MW higher than that in the

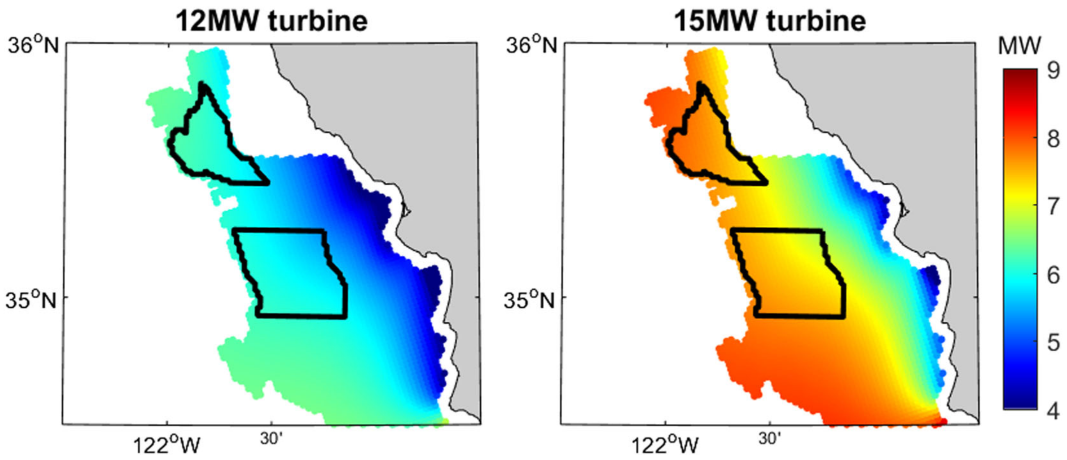

FIGURE 4 Mean power production over 2007–2013 across the areas feasible for development, given one 12-MW turbine (left) and 15-MW turbine (right) per grid cell. Call areas are marked by black polygons. Developable areas are established by spatial grid points north of 34.5°N, outside National Marine Sanctuaries, three nautical miles off of the coast, and a maximum depth of the 1200-m isobath

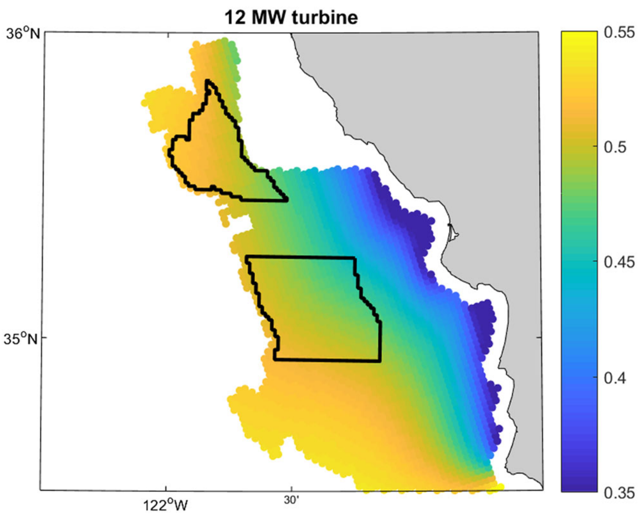

FIGURE 5 Capacity factor over 2007–2013 across the developable areas with one 12-MW turbine per grid cell. Call areas are marked by black polygons

TABLE 2 Summary of capacity factor if each call area is fully built out with one turbine for each 2-km × 2-km grid cell

	Call area	
	Morro Bay	Diablo canyon
No. of turbines	192 turbines	346 turbines
12 MW		
Capacity Factor	0.51	0.49
15 MW		
Capacity Factor	0.51	0.49

Note: Capacity factor = mean of hourly actual power/rated power.

Diablo Canyon Call Area in summer evenings (Figure 6), Also, the Morro Bay Call Area typically reached its daily minimum and maximum power production levels 1 or 2 hr after that of the Diablo Canyon Call Area.

3.3 | Different spacing scenarios

Turbine spacing influences potential power production per unit area. The 7D × 7D spacing supported greater total potential power production than 8D × 10D spacing, because turbine density was higher (Table 3). A full build out of the Morro Bay Call Area with 12-MW

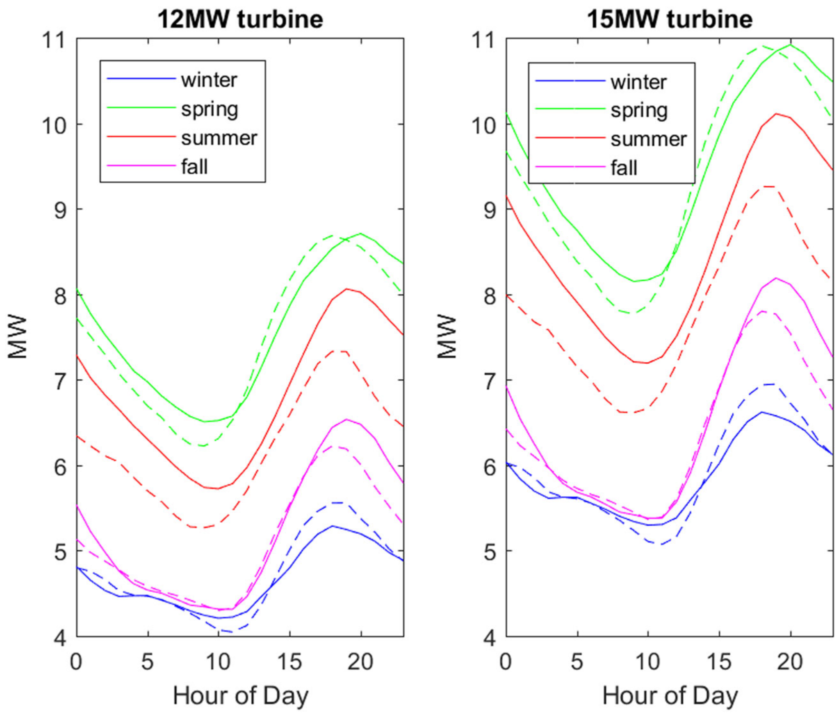

FIGURE 6 Seasonal means of hourly spatial-mean power generation (blue: winter (Dec-Jan-Feb), green: spring (Mar-Apr-May), red: summer (Jun-Jul-Aug), magenta: fall (Sep-Oct-Nov)) over the Morro Bay Call Area (solid line) and the Diablo Canyon Call Area (dashed line) for a 12-MW wind turbine (left) and a 15-MW wind turbine (right)

TABLE 3 Summary of realized power production for different spacing scenarios

Turbine	12 MW	15 MW
7D × 7D		
Spacing (km^2/turbine)	2.42	3.01
Turbines per 4-km^2 grid cell	1.66	1.33
Realized power in MB Call Area if it is fully built out (MW)	1946.30	1949.50
Realized power from a fully built out MB Call Area, relative to realized power produced by DCNPP (1980 MW)	98.30%	98.46%
Realized power in DC Call Area if it is fully built out (MW)	3369.86	3375.39
Realized power from a fully built out DC Call Area relative to realized power produced by DCNPP (1980 MW)	170.19%	170.43%
8D × 10D		
Spacing (km^2/turbine)	3.94	4.92
Turbines per grid cell	1.01	0.81
Realized power in MB Call Area if it is fully built out (MW)	1192.11	1194.07
Realized power from a fully built out MB Call Area, relative to realized power produced by DCNPP (1980 MW)	60.21%	60.31%
Realized power in DC Call Area if it is fully built out (MW)	2064.04	2067.43
Realized power from a fully built out DC Call Area relative to realized power produced by DCNPP (1980 MW)	104.24%	104.42%

turbines and the 7D × 7D spacing would produce about almost 100% of the realized power of the DCNPP (1980 MW). In comparison, the total power production under the 8D x 10D scenario was only about 1.2 GW, or 60% of its 7D x 7D counterpart. With 12-MW turbines, the average combined annual power production from both Call Areas was 5.32 GW under the 7D × 7D scenario and 3.26 GW under the 8D × 10D scenario. Although 15-MW turbines have higher rated power than 12-MW turbines, its larger rotor diameter requires greater spacing, resulting in fewer turbines per unit area. Interestingly, as a consequence of this adjustment in spacing, the per unit area power production was nearly identical between 12- and 15-MW turbines for a given spacing scenario (7D × 7D, or 8D × 10D, Table 3).

3.4 | Different potential development scenarios

The hypothetical pilot-scale, medium-scale, and commercial-scale wind farms required approximately 10, 40, and 160 turbines to meet their corresponding realized production levels (Tables 4 and 5). Not surprisingly, footprint also increased with farm production level, approximately 23 km^2 (60-MW farm, 12- or 15-MW turbines with 7D × 7D spacing) to approximately 666 km^2 (960-MW farm, 12-MW turbines with 8D × 10D spacing) (Tables 4 and 5). Farms with 15-MW turbines required approximately 20% fewer turbines, but only a slightly smaller footprint, than farms generating the same production levels using 12-MW turbines. Regardless of turbine type, these hypothetical pilot-, medium-, and commercial-scale farms produced realized power levels that were approximately 3%, 12%, and 48% of the realized power production of the DCNPP, respectively (Tables 4-5). Whatever the farm, fewer wind turbines and thus a smaller footprint was required in the Morro Bay Call Area than the Diablo Canyon Call Area because it experienced stronger wind speed on average and has a higher capacity factor. The difference between the two Call Areas in turbine number per farm ranged from less than one (pilot-scale wind farm) to about 10 (commercial-scale wind farm). Compared to realized power production, the number of turbines and footprint based on rated power production were smaller and did not depend on which Call Area the farm was placed (Table S1).

TABLE 4 Summary of realized power production for different wind farm size scenarios in Morro Bay Call Area

12 MW			
Farm size (realized MW)	**60**	**240**	**960**
No. of turbines under 7D × 7D	9.56–10.42	38.39–41.14	155.12–160.71
7D × 7D footprint (km^2)	23.04–25.11	92.52–99.15	373.84–387.31
No. of turbines under 8D × 10D	9.57–10.39	38.48–40.83	156.63–158.84
8D × 10D footprint (km^2)	37.71–40.94	151.61–160.87	617.12–625-83
Realized power relative to realized power produced by DCNPP (1980 MW)	3.03	12.12	48.48
15 MW			
Farm size (realized MW)	**60**	**240**	**960**
No. of turbines under 7D × 7D	7.60–8.33	30.53–32.87	123.52–128.31
7D × 7D footprint (km^2)	22.88–25.07	91.90–98.84	371.80–386.21
No. of turbines under 8D × 10D	7.61–8.31	30.61–32.62	124.81–126.73
8D × 10D footprint (km^2)	37.44–40.89	150.60–160.49	614.07–623.51
Realized power relative to realized power produced by DCNPP (1980 MW)	3.03	12.12	48.48

TABLE 5 Summary of realized power production for different wind farm size scenarios in Diablo Canyon Call Area

12 MW			
Farm size (realized MW)	**60**	**240**	**960**
No. of turbines under 7D × 7D	9.75–11.04	39.23–43.42	158.46–169.23
7D × 7D footprint (km^2)	23.50–26.61	94.54–104.64	381.89–407.84
No. of turbines under 8D × 10D	9.77–10.98	39.35–43.06	159.39–167.13
8D × 10D footprint (km^2)	38.49–43.26	155.04–169.66	628–666.37
Realized power relative to realized power produced by DCNPP (1980 MW)	3.03	12.12	48.48
15 MW			
Farm size (realized MW)	**60**	**240**	**960**
No. of turbines under 7D × 7D	7.76–8.82	31.24–34.70	126.25–135.15
7D × 7D footprint (km^2)	23.36–26.55	94.03–104.45	380.01–406.80
No. of turbines under 8D × 10D	7.78–8.78	31.34–34.41	127.02–133.43
8D × 10D footprint (km^2)	38.28–43.20	154.19–169.30	624.92–656.48
Realized power relative to realized power produced by DCNPP (1980 MW)	3.03	12.12	48.48

4 | DISCUSSION AND CONCLUSIONS

Analysis of potential power production by floating offshore wind energy turbines along the California Central Coast revealed similar frequency distributions of hub-height wind speeds between the Morro Bay and Diablo Canyon Call Areas. The Call Areas also exhibited a similar diurnal pattern of wind speed (lower in the morning, higher in the evening), which is coincidentally complementary to the diurnal pattern of solar energy (peak at mid-day) and demand (peak in evening).[11] These findings suggest that power produced by offshore winds in the Call Areas may be able to meet evening demand for electricity as solar power wanes. In the Call Areas, as well as throughout the study domain representing all feasibly developable areas off Central California, potential power production and capacity factor increased with distance from shore, due to stronger winds further offshore. The frequency distributions of wind speeds, and the diurnal and spatial patterns of wind speed, were all relatively insensitive to turbine type (12 MW vs. 15 MW), despite their different hub heights.

Total potential power production from a fully-built out Call Area was estimated to be greater using smaller inter-turbine spacing (7D $\times$ 7D) scenario because turbine density was higher. Similarly, total power production was estimated to be greater in the Diablo Canyon Call Area compared with in the Morro Bay Call Area due to its larger size. Interestingly, we found that deployment of 15- over 12-MW turbines would not appreciably increase total power production. While a larger turbine generates more power per-turbine, inter-turbine spacing is relative to rotor diameter. The larger rotor of the 15-MW turbine required commensurately larger spacing, such that overall power production was similar to that of a more tightly-packed array of 12-MW turbines.

A commercial scale wind farm with a realized power output of 960 MW would occupy at least half of the Morro Bay Call Area or at least a quarter of the Diablo Canyon Call Area. In other words, the two Call Areas can collectively contain a maximum of around six commercial-scale wind farms of this size. If fully built out using the higher density 7D $\times$ 7D spacing and 12-MW turbines, the Morro Bay and Diablo Canyon Call Areas would produce a combined annually-averaged energy production of 46,596 GWh, which is about 23% of the state's electric energy generation of 200,475 GWh.[21] The combined energy production from both Call Areas would equate to 17% of the state's total electric energy mix of 277,704 GWh, which includes both in-state generation and imports.[21]

The framework demonstrated here could be applied to other wind data sets such as NREL's new wind resource data set (CA 20) developed to replace the WIND Toolkit.[14] If NREL's new data set is used, which shows stronger hub-height winds and thus higher gross capacity factor up to 58% for the Call Areas in the Central California Coast (assuming 15-MW turbines and the 7D $\times$ 7D spacing, cf. Beiter et al.[7]), the fully built out and realized power production could reach 2773 and 4997 MW for the Morro Bay and Diablo Canyon Call Areas, respectively, which is 42% and 48% higher than the estimate using the WIND Toolkit. However, we note that the WIND Toolkit dataset has been extensively validated against surface buoys along the Central Coast using a variety of statistical metrics across seasonal and daily time scales[6] and neither dataset (WIND Toolkit or CA 20) has been validated at hub height. The framework could also be used to assess potential power production in other regions. More generally, analyses of domains being pursued for offshore wind energy development in the U.S. (e.g., Oregon and Hawaii) and internationally (e.g., UK) could provide guidance to the industry, permitting agencies and regulators, project developers, the public, and other stakeholders about the suitability and value of these locations for wind farms.

In this study we focused on “gross” power production, which is the power a wind farm would produce without any losses, as opposed to “net” power production, which accounts for losses from several sources. For example, we did not quantify wake loss, which reduces wind speeds and potential power production downstream of a turbine. Wake loss is likely to be greater under the narrower spacing scenario (e.g., 7D $\times$ 7D vs. 8D $\times$ 10D; Musial et al.[17]). We also did not consider energy loss during transmission from a wind farm to shore, which scales with distance to the shore-based grid connection. Transmission loss is likely to be greater for a wind farm in the Morro Bay Call Area than one in the Diablo Canyon Call Area because the former is farther from the nearest grid connection facility on shore. Energy loss due to wake effects, transmission loss, and other factors can be as high as 20% of gross power production, though this estimate varies with site characteristics and is declining with technological advancements.[10] According to Beiter et al.[7], the total losses in the Central California Coast Call Areas were around 15% of gross power production. Valuation of the energy from offshore wind farms will further require estimates of the cost of these losses,[7,22] and socio-economic analysis of the interactions among energy development, production, and demand across energy sectors (offshore wind, terrestrial and marine renewables, non-renewables, and non-electricity energy generators such as gas), across the state of California, and over time in relation to policy changes (e.g., regulating greenhouse gas emissions and broader renewable energy portfolios, as in SB-100 in California).

This study addresses important information gaps related to temporal and spatial characteristics of offshore wind power within the Central Coast Call Areas in California. We evaluated wind resources and areas covered by development by considering alternative scenarios in turbine type, spacing, and wind farm sizes, which were not explored or only partly explored by earlier studies (e.g., Beiter et al.[7] and Musial et al.[17]). Importantly, this study was not intended to mimic how a real wind farm would be deployed or where turbines should be placed within a Call Area. Rather, we provide an approximation of power production and the footprint such power production would occupy across a variety of scenarios to inform the conversation for stakeholders and policymakers with an interest in offshore wind energy development along the Central Coast of California.

We emphasize that the BOEM Call Areas we analyzed in this study had been already identified in partnership with the State of California. However, our approach to estimate energy production and its value (e.g., Wang et al.[11]) could be integrated with analyses of relevant economic, cultural, and environmental factors to inform future offshore wind farm siting—and the development of future Call Areas—in relation to industry, regulatory, and societal objectives. For example, many areas with developable wind energy resources are important for commercial fisheries and marine wildlife (e.g., marine mammals and seabirds), all of which may be impacted by offshore wind energy development.[23] Previous spatial planning research indicates that accounting for these potential economic and conservation impacts (loss of fisheries revenue, displacement of marine mammals, seabird collisions, loss of ecosystem services, etc.) alongside the potential available gains in energy production and value could help identify profitable, productive, and acceptable locations for wind farm development that are both high value and low impact.[24] Combining analyses similar to those we presented here with analyses of impacts of wind energy development in a marine spatial planning framework will allow stakeholders to better understand the benefits and costs of offshore wind energy development in locations where planning has not yet begun. Such information will help other regions that may be suitable for offshore wind energy determine whether, how, and where to implement offshore wind energy to achieve sustainable and productive use of marine resources for meeting its renewable energy targets.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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