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Resource and Load Compatibility Assessment of Wind Energy Offshore of Humboldt County, California

Christina Ortega [1], Amin Younes [1,2], Mark Severy [3], Charles Chamberlin [1,2] and Arne Jacobson [1,2,*]

1 Schatz Energy Research Center, 1 Harpst St, Arcata, CA 95521, USA; tina.ortega@humboldt.edu (C.O.); amin.younes@humboldt.edu (A.Y.); charles.chamberlin@humboldt.edu (C.C.)
2 Department of Environmental Resources Engineering, Humboldt State University, 1 Harpst St, Arcata, CA 95521, USA
3 Pacific Northwest National Laboratory, 1100 Dexter Ave. N, Seattle, WA 98109, USA; mark.severy@pnnl.gov
* Correspondence: arne.jacobson@humboldt.edu

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Abstract: Floating offshore wind is being considered in northern California as indicated by the Bureau of Ocean Energy Management's issuance of a lease consideration in the Humboldt Call Area. Humboldt County offers access to this enormous resource, but local electric load and transmission are limited. The potential impacts of offshore wind generators at three different scales were studied using a regional grid model of Humboldt County. Offshore wind generation was calculated using modeled wind speed data and 12-MW turbine specifications and integrated with projected load and historical generation. Offshore wind farms deployed in the Humboldt Call Area achieve annual capacity factors between 45% and 54% after losses and maintenance. Power output is variable between and within seasons, with full power output 30% of the time and no output approximately 20% of the time. Electricity from a 48-MW wind farm provides 22% of regional load with limited exports. A 144-MW wind farm serves 38% of local load, exporting 40% of its electricity with the extant 70-MW transmission capacity. A full build-out of 1836 MW would result in 88% curtailment with existing transmission. Across scenarios, offshore wind variability necessitates reliance on existing power plants to meet local demand in periods of low wind.

Keywords: renewable energy; offshore wind; turbine; floating platform; transmission; losses; generation; load; power; model

1. Introduction

Offshore wind energy can contribute to a clean, affordable, and secure national energy mix [1]. According to the U.S. Department of Energy, the technical generation potential for offshore wind in the United States Outer Continental Shelf is twice our national electrical load [1]. This abundant resource provides opportunities to develop clean and reliable electricity generation to meet growing demands and replace retiring power plants in coastal states. With falling capital costs of offshore wind [2] and advances in the floating platforms suitable for the deep waters along the Pacific Coast, eleven offshore wind developers have expressed interest in installing offshore wind farms along the Humboldt County coast in far northern California [3,4]. However, development of offshore wind in this electrically isolated region requires a comprehensive, integrated assessment of the wind generation potential, local demand profile, and transmission capability to ensure that offshore wind energy can be utilized.

The U.S. Bureau of Ocean Energy Management (BOEM) is considering the Humboldt Call Area for a lease auction [4]. This site, located 20–30 miles offshore from Humboldt Bay, is large enough to accommodate offshore wind farms over 1 gigawatt (GW) nameplate capacity. Developing the resource at this scale would require major transmission infrastructure to connect the wind farm to other demand centers in the state. Alternatively, smaller-scale wind farms could be developed in the Humboldt Call Area ranging from tens to hundreds of megawatts (MW) to serve local and regional loads.

A wide variety of studies have evaluated wind resource potential in regions such as offshore of Ceará, Brazil [5], onshore in the Arabian Peninsula [6] and the entire United States, both onshore and offshore [7]. Further studies have integrated wind speed with turbine power curves to create generation profiles offshore of California (not including the Humboldt Call Area) [8,9], Oregon [10], the east coast of the United States [11], northern Spain [12], the Persian Gulf [13], and the gulf of Thailand [14], and onshore in Rafha, Saudi Arabia [15], South Africa [16], and Algeria [17]. Some of these studies rely on descriptive statistics of measured wind speed [16,17] or modeled wind speed (generally based on relatively sparse measurement data) [9,13], and some use the measured [15] or (most commonly) modeled data directly [5–8,10–12,14,18].

Existing wind resource assessments generally do not integrate power generation with electrical grid demand data to understand how the resource potential would interact with existing local generators and electricity demand. Dvorak et al. [11] go as far as to evaluate generation during the period of local peak demand (08:00–21:00 EST), but they do not model how offshore wind generation would change the profile of other generation sources or impact the electricity transmission system.

The only evaluations of generation potential identified by the authors that include the Humboldt Call Area are country-level evaluations which do not provide sufficient resolution for the offshore wind resource [7,18]. Because of the prospective development of offshore wind in this region, this study evaluates the electricity generation potential and how the resource would interact with existing generators to meet regional demand.

The purpose of the study is to determine the scale of wind farms that are compatible with future load profiles and understand the effects that offshore wind generation would have on the regional energy generation mixture. The study evaluates the compatibility between electricity demand, existing generation sources, and potential offshore wind developments in Humboldt County, California. This report provides a generation and load compatibility assessment for three different scales of potential development: pilot-scale (48 MW), small-commercial (144 MW), and large-commercial (1836 MW). The analysis entails:

1. Assessment of wind resource;
2. Evaluation of offshore wind electricity generation profile;
3. Summarization of existing generation and load in Humboldt County before addition of offshore wind;
4. Analysis of the interaction between offshore wind and local load, generation, and transmission.

This study describes how offshore wind could interact with other regional generation sources, but it does not investigate the transmission upgrades required for interconnection. In parallel with this study, Pacific Gas and Electric Company (PG&E) conducted a power flow analysis to recommend the transmission infrastructure improvements to facilitate interconnection of offshore wind [19,20].

Our model shows that while energy delivered from a pilot-scale development could be almost entirely used locally, electricity from a small-commercial offshore wind generator would rely on exporting almost half of its energy outside this region. Larger offshore wind development in the order of 1–2 GW would require major transmission upgrades in order to avoid severe curtailment. A large-scale development of 1836 MW would deliver an average of 7700 GWh to California annually with a 47% capacity factor, but due to prolonged periods of low wind speeds, the regional grid in Humboldt County would still depend on a natural gas power plant to meet hourly load.

2. Materials and Methods

This section describes the data sources and analysis methods used in this paper. A copy of all input data and analysis code can be found in the Supplementary Materials.

2.1. Load Compatibility Node Model

In order to assess compatibility of generation, load, and transmission, we created an input/output model of generation plus electricity imports (input) and local load plus electricity exports (output). The central node in this model is the Humboldt County electrical system (Figure 1). Electricity generators include all four extant local plants plus three scales of potential offshore wind development. These generation sources are used to meet regional load in the area. Energy cannot be stored in the Humboldt node, so the sum of inputs must equal the sum of outputs at every hour. If local load cannot fully meet this demand, electricity is imported into the area; if there is a surplus of generation, electricity is exported outside of this region. Using information from Zoellick, et al. [21], the transmission system into and out of the area is assumed to have a maximum capacity of 70 MW. If exports exceed the 70 MW capacity, offshore wind (OSW) energy is curtailed to meet this criterion. This analysis does not consider internal limitations or energy losses within Humboldt County.

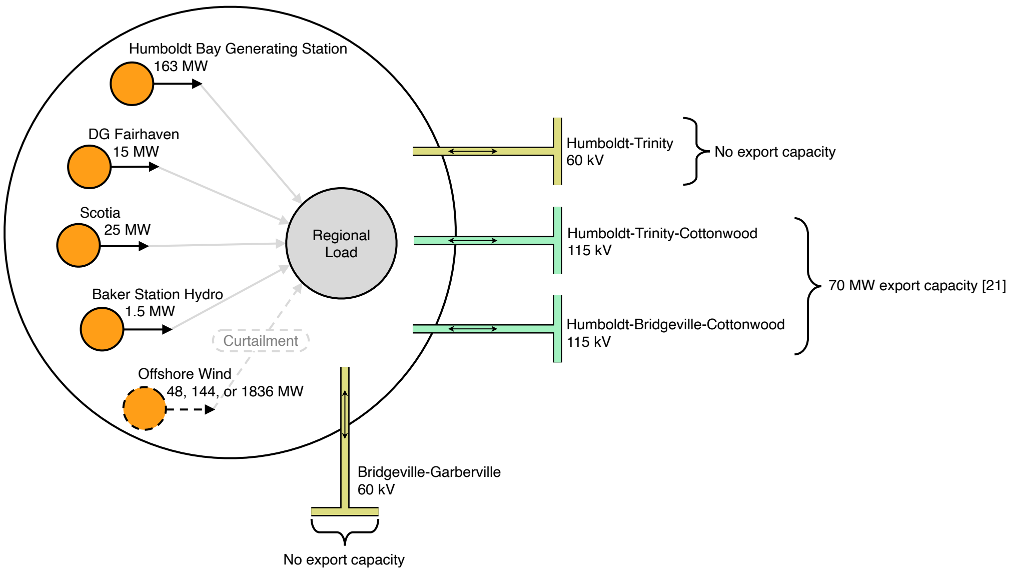


Figure 1. Humboldt County electrical system showing node inputs and outputs.

The analysis was conducted for a future load scenario in 2030, as offshore wind may be deployed by then. Offshore wind generators were modeled at scales of 48 MW, 144 MW, and 1836 MW in the future scenario to determine how these generators could be used to meet electricity demand with existing infrastructure. We quantified the impact of offshore wind generation in terms of (1) a reduction in the energy output of the local natural gas power plant, the Humboldt Bay Generating Station (HBGS), caused by offshore wind, (2) an increase in energy exports from the county, and (3) curtailment of offshore wind electricity output.

This analysis required regional electricity demand data, the generation profile of existing power plants, and the simulated generation profile from offshore wind. The data sources are described in the following sections.

2.1.1. Electricity Demand

Electricity load in Humboldt County has been decreasing according to data provided by PG&E for the period from 2008 to 2018 [22], but future projections predict higher demand, in part due to expected electrification of vehicles and heating. The California Energy Commission's (CEC's) electricity demand forecast for 2030 in PG&E's service territory estimates that electricity demand in this region may decrease by 9.2%, increase by 1.4%, or increase by 13.7% from 2018 to 2030 based on low-, mid-, or high-demand scenarios, respectively [23–25]. However, the aggregated forecast for PG&E service territory shows summer peaking demand with decreased midday net load due to increased solar penetration throughout the 2020s, which does not align with the winter-peaking load in Humboldt County and limited solar insolation in the region. Therefore, we compared the CEC forecast with a forecast of county load in 2030 from the community choice aggregator in Humboldt County, the Redwood Coast Energy Authority (RCEA). RCEA's projected load anticipates the annual average electrical load rising to 102 MW by 2030, 6% higher than the 96.4 MW average in the most recent year of historical data (November 2017–October 2018 (Figure 2) [22]. This load growth falls between the mid and high growth scenarios for PG&E service territory, while matching the hourly and monthly load profiles of Humboldt County. We therefore used the RCEA load projection [26], which forecasts a typical hourly load profile for a day in each month, in the following analysis.

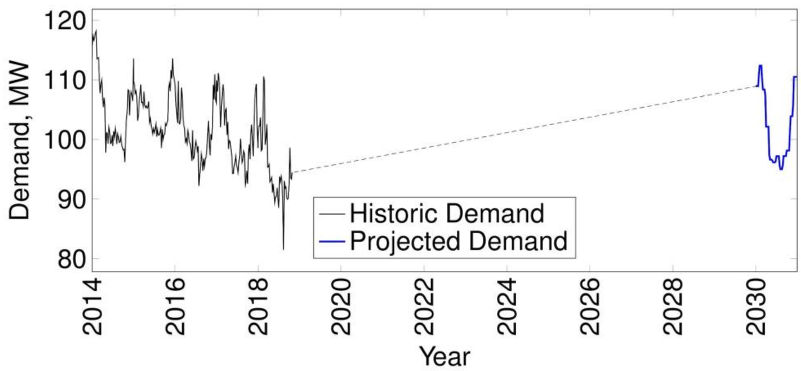


Figure 2. Historical and projected Humboldt County load used in this model.

2.1.2. Transmission

The electric transmission system in the Humboldt Planning Area is connected to California's bulk transmission system through four circuits: two at 60 kV and two at 115 kV (Figure 1). Electric load in the region is met through four local generators and electricity imported on the transmission network. The transmission is built to serve local load and not designed to be a large exporter of electricity [19]. The 60-kV transmission line heading south into Mendocino County (labeled Bridgeville-Garberville in Figure 1) serves small communities along its path but is not meant to transfer large amounts of power because of its size and voltage. The two parallel, 115-kV transmission lines running east-west are redundant lines used to import power to Humboldt County as needed and serve the communities along the way. Lastly, a 60-kV transmission line connects to the east in the same right of way as the northern 115-kV circuit. The resulting transmission capability into and out of the county is assumed to be 70 MW following Zoellick et al. [21].

2.1.3. Existing Power Plants

The operating performance of existing power plants in Humboldt County is included in the model as part of the generation portfolio. There are four active power plants located within Humboldt County: a small hydroelectric facility, two biomass power plants, and a large reciprocating engine natural gas power plant (Table 1). Historical electricity generation data were obtained from the CEC's Quarterly Fuel and Energy Report (QFER) [27], which reports production data from all California power plants larger than 1 MW. Recent production levels are used to approximate the output in 2030. Detailed methods for estimating future generation are provided in Appendix A. Solar generation is absent from this analysis for two reasons: front-of-the-meter solar is absent because Humboldt County currently has no such installations, and while some are planned, no operational data are yet available. Behind-the-meter (BTM) solar (also known as rooftop solar or distributed solar) is absent because the electricity demand discussed in Section 2.1.1 represents load visible to the utility, which means that BTM solar was already subtracted from the total load.

Table 1. Humboldt County generation resources.

Plant Name	Nameplate Capacity	Plant Type	Annual Electricity Production [1]
Baker Station Hydro [2]	1.5 MW	Small Hydro	4340 MWh
DG Fairhaven Power Plant [3]	15 MW	Biomass [4]	116,000 MWh
Scotia [3]	25 MW [5]	Biomass [4]	118,000 MWh
Humboldt Bay Generating Station [7]	163 MW [6]	Natural Gas	422,000 MWh

[1] Based on historic averages. See Appendix A. [2] Annual production reported in QFER [27]. Hourly output is assumed to be consistent across the year. Although the hydroelectric plant does not operate like this, the assumption is justified because the capacity of this plant is an order or magnitude smaller than other generators. [3] Monthly generation reported in QFER [27]. Hourly profile is flat by month. [4] Wood/Wood waste solids [28]. [5] Engine #3 is not included in this total because it has not produced power since 2014 [27]. [6] The QFER lists HBGS's capacity as 167 MW, but other sources report it as 163 MW [27]. [7] Operated in the model as a load following plant. Air permits restrict operating level to 12 MW minimum [29].

2.2. *Offshore Wind Resource Model*

The last input to the node model is offshore wind generation. Power output from prospective offshore wind farms were calculated using the wind speed in the Humboldt Call Area. The wind speed data from Draxl et al. [30] were converted into power output values by using a reference 12-MW turbine power curve presented by Musial et al. [10]. Power output was reduced by loss factors including efficiency losses, downtime, and wake effects (Appendix B). Wind farms specifications and design assumptions in this analysis are described below. Geographical specifications and detailed maps of the study locations are provided in Appendix C.

2.2.1. Location

The modeled offshore wind farm is in the Humboldt Call Area, as defined by BOEM's Call for Information and Nominations [4,31]. The Humboldt Call Area is located west of Humboldt Bay between 20 and 30 nautical miles offshore (Figure 3). The area has a footprint of 537 km^2 and ranges in depth from 500 m to 1100 m. The closest electricity grid interconnection point is located at a substation adjacent to HBGS. From the interconnection point, 60 kV and 115 kV transmission lines head east and south to connect into higher voltage transmission lines up to 500 kV that move energy to major load centers.

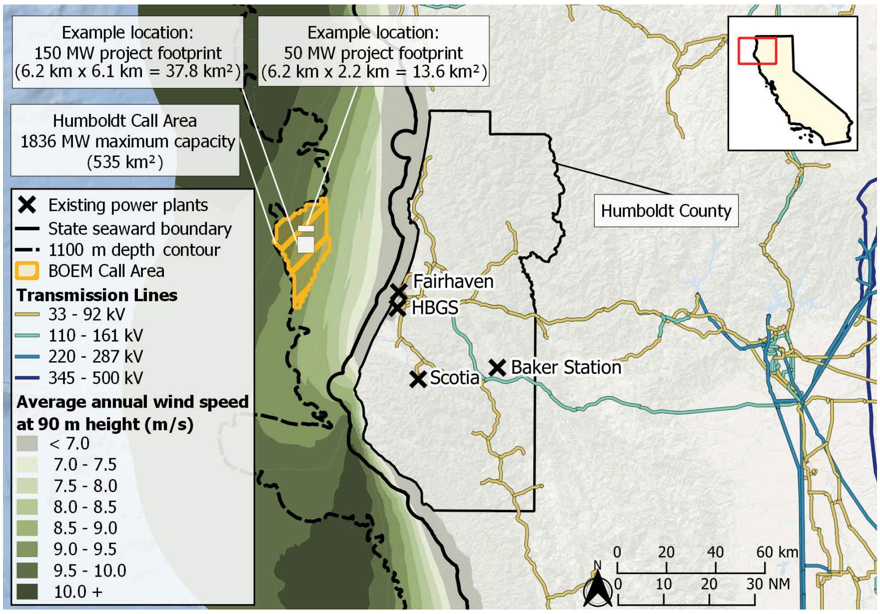


Figure 3. Average offshore wind speeds and extant transmission connections to Humboldt County.

2.2.2. Study Scenarios

Power output was assessed at three scales of offshore wind development plus a baseline scenario. Quantity and power rating of turbines are shown in Table 2 for each scenario:

- Baseline—No offshore wind development. Current generation profile and energy demand are projected to 2030 for comparison.
- Pilot Scale—48 MW nameplate capacity. This scale is assumed to be the smallest wind array that might be installed.
- Small Commercial—144 MW nameplate capacity. This scale was selected because it is the approximate scale of a wind farm proposed in an unsolicited lease request for an overlapping offshore wind area [32].
- Large Commercial—1836 MW nameplate capacity. This scale was selected because it represents a full build out of the Humboldt Call Area, using turbine and mooring line spacing discussed in Section 2.2.4.

Table 2. Study scenarios for offshore wind.

Scenario	Number of Turbines	Turbine Nameplate Power
Baseline	0	-
48 MW	4	12 MW
144 MW	12	12 MW
1836 MW	153	12 MW

2.2.3. Turbines

All wind farms use 12-MW turbines. The specifications for this turbine were derived from the standard reference turbine developed by Musial, et al. [10]. The turbine specifications are outlined in Table 3 and depicted in Figure 4.

Table 3. Turbine specifications [10].

Rated Power	Hub Height	Rotor Diameter	Blade Length
12 MW	136 m	222 m	107 m [1]

[1] Blade length based on GE Haliade-X 12-MW turbine [33].

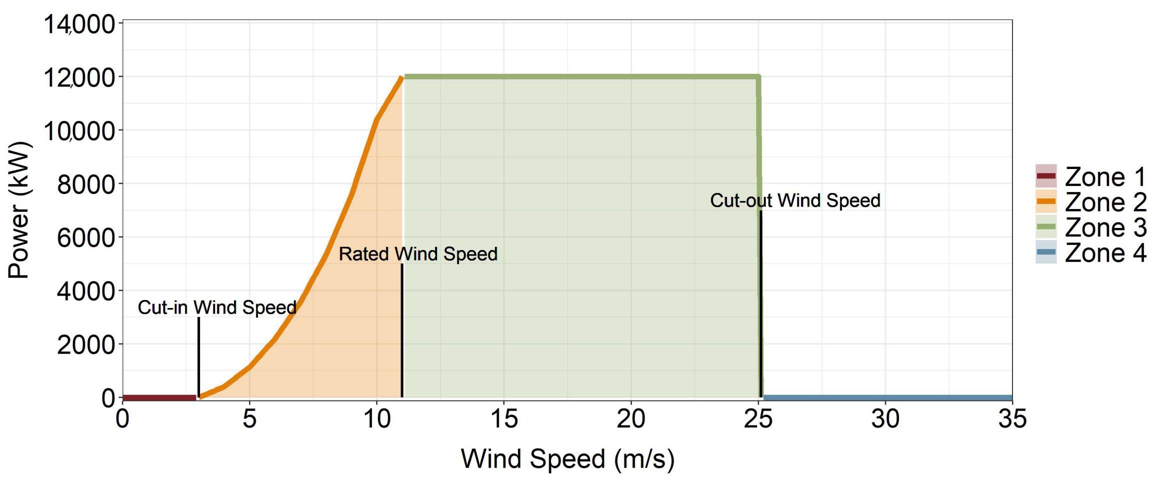


Figure 4. Power curve for a 12-MW turbine, adapted from Musial et al. [10]. The cut-in wind speed is 3 m/s, the rated wind speed is 11 m/s and the cut-out wind speed is 25 m/s.

2.2.4. Turbine Layout

Turbines in the wind farm were spaced with at least seven rotor-diameters (7D) between each tower, following Musial et al. [8]. Based on conversations with offshore wind developers, turbine spacing was increased to 10D in the prevailing north-south wind direction to reduce wake effects. Turbines were offset between rows to increase the packing density while maintaining the 7D × 10D spacing (see Appendix D).

In the 1836-MW (full build out) scenario, some floating turbines were located in waters up to 1100 m depth. With a 45-degree mooring line angle (relative to the sea surface), mooring lines from adjacent turbines would overlap at an ocean depth greater than or equal to 918 m. In waters deeper than 918 m, turbine spacing was increased to avoid overlapping mooring lines (see the turbine layout in Appendix D). The mooring line footprint was determined using bathymetric raster data from the General Bathymetric Chart for the Oceans global ocean terrain model [34]. Lastly, turbines were placed such that the mooring lines would not extend beyond the boundary of the Call Area.

2.2.5. Modeled Wind Speed

The wind speed and direction data used for this analysis were from the National Renewable Energy Laboratory's (NREL) Wind Integration National Dataset (WIND) Toolkit [30]. The WIND Toolkit data is the largest wind integration dataset publicly available and has been validated with observational data from all over the United States [30]. Wang, et al. [35] compared and validated several offshore wind speed datasets and found that the WIND Toolkit was the best available data for California. Measurements of wind speed at turbine hub height on the East Coast suggest that differences in atmospheric stability at offshore locations may change wind shear profiles [36], which are not represented in the model resource available in the WIND Toolkit. Despite this drawback, the WIND Toolkit represents the best available wind speed data offshore California. Data were available at 100 m above mean sea level at hourly resolution for a seven-year period of record. The data set has a spatial resolution of 2 km by 2 km. Within the data set, 122 points fall within the Humboldt Call Area.

Rather than model the average values between each year, the median wind speed year (2009) from the seven-year data set was used to model a typical year of power generation. This allowed for the consideration of the actual variability of the resource which, unlike the average values from all seven years, does not smooth out fluctuations.

2.2.6. Analysis Methods

Spatial Averaging: Instead of averaging wind speed values for every coordinate of data inside the Humboldt Call Area, the coordinate closest to the centroid (40.960258° N, −124.6492° W) of the area was used for the analysis (see Appendix E for validation) to reduce computational intensity and smoothing of variability.

Wind Speed Height Extrapolations: Wind speed data at 100 m were extrapolated to the 136 m hub height of the 12-MW reference turbine using the power law wind shear equation (Equation (1)) assuming a wind shear exponent (α) of 0.1, which is typical for open waters [37].

$$U = U_0 \left(\frac{h}{h_0}\right)^{\alpha} \quad (1)$$

where:

- U, the wind speed at height h = 136 m
- U_0, the wind speed at height h_0 = 100 m
- α, the wind shear exponent of 0.1.

The wind shear exponent depends on atmospheric stability conditions [38]. The assumption of a wind shear exponent of 0.1 may not apply to unstable boundary conditions above the ocean surface, and a sensitivity analysis could be applied in future work to understand how this assumption may influence the results.

We used the turbine's power curve to calculate the nominal (i.e., zero losses) power output based on the modeled wind speed at 136 m. Since the power curve presented by Musial et al. [10] was discrete, we used linear interpolation between points.

All wind turbines are subject to performance losses from environment, energy management, and system design. As shown in (Equation (2)), the total turbine efficiency is the sequential product of one minus each of these individual loss factors.

$$Total\ Efficiency = \prod_{i=1}^{n} (1 - Loss\ Factor_i) \tag{2}$$

We applied two types of losses to the power estimates: proportional losses, and downtime (shut-off) losses. Proportional losses include effects such as wake, electrical inefficiency, and turbine performance, which affect the entire system and reduce the power output proportionally. Downtime losses cause turbines to shut-off, and are caused by factors such as grid outages, high wind control hysteresis, maintenance events, and site access limitations.

We modeled wake effect losses using the Eddy-Viscosity method [39] calculated using NREL's System Advisor Model (SAM) [40]. We sourced other loss factors from AWS Truepower [41] and Musial et al. [8,18].

We determined the total proportional losses and shut-off losses disregarding wake effects to be 6.4% and 7.3%, respectively. We modeled shut-off losses by setting the power output to zero at 7.3% of times throughout the year, selected randomly. The random application of these losses represents the unexpected nature of failures and grid disconnections. After applying shut-off losses, we removed the remaining 6.4% of proportional losses (such as efficiency losses) from the power output along with the site-specific wake loss factors (Table 4). The individual scenario wake losses were then added to the total losses of 13.2%.

Table 4. Scenario wake losses. Larger wind farms have more internal wake losses because there are more turbines causing obstructions within the array.

Scenario	Wake Loss
48 MW	0.03%
144 MW	1.07%
1836 MW	2.41%

2.3. Power Plant Dispatch Model

In the Humboldt County node model, power plants were dispatched to meet the electricity demand at every hour of each day of the year. The model selected which power plants to dispatch and where to deliver the energy based on the flow diagram shown in Figure 5. First the model dispatched baseload power from the hydroelectric and biomass facilities, then dispatched offshore wind generation. When the production exceeded the demand, offshore wind was exported. When offshore wind energy increased exports above the 70-MW transmission capacity, offshore wind was curtailed to adhere to the capacity restriction. If production was below demand, HBGS was ramped up to meet the local load. HBGS was not allowed to operate below 12-MW to comply with its air quality permit [29]. Additionally, it was not allowed to shut down completely in order to maintain ramping capability [42].

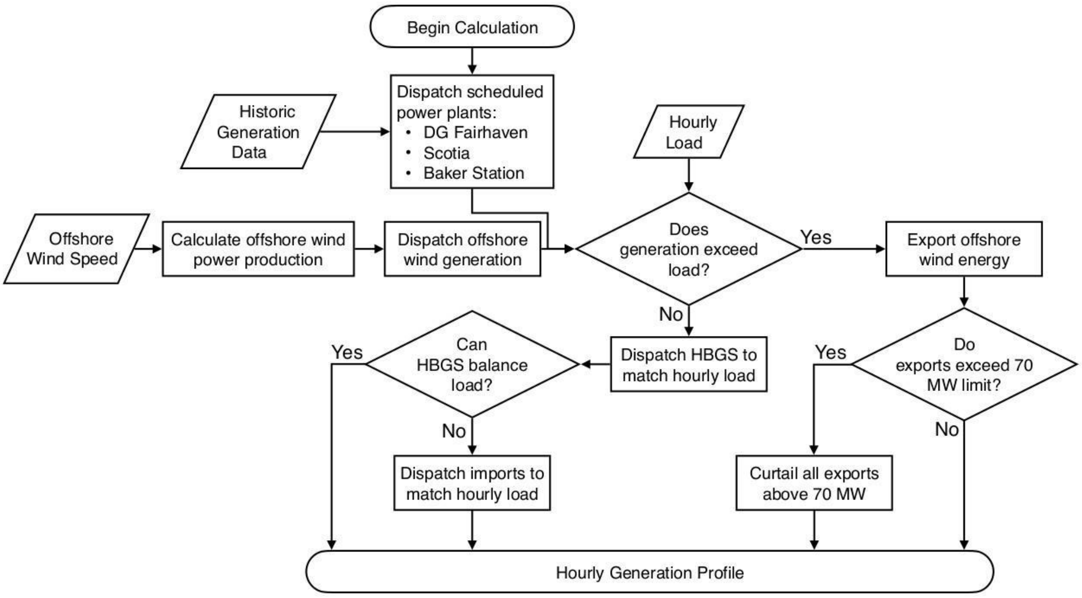


Figure 5. Algorithm for calculating hourly load and generation profile.

3. Results

Energy generation portfolios for the Humboldt region are presented below for four development scenarios. The scenarios consist of a baseline with no offshore wind and three scales of offshore wind development. This section first describes the offshore wind generation profiles, then presents the results for the four scenarios.

3.1. *Offshore Wind Generation*

3.1.1. Wind Speed Distribution

The wind rose (Figure 6) and wind speed distribution (Figure 7) group wind speeds into colored bins defined by the turbine power curve.

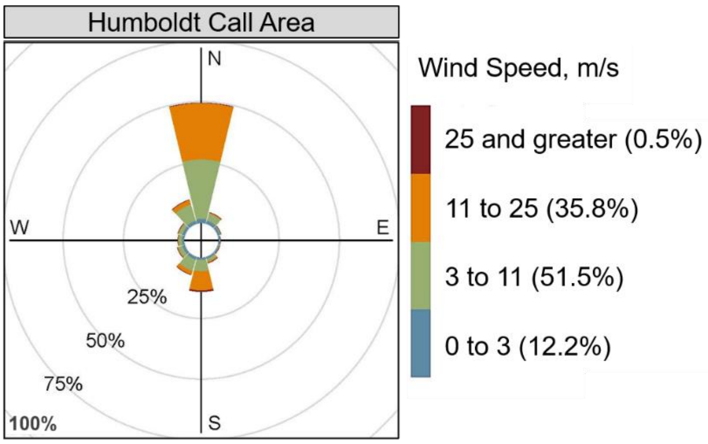


Figure 6. Annual wind rose for the Humboldt Call Area. Percentages on the radial axis represent the percent of time the wind velocity occurred.

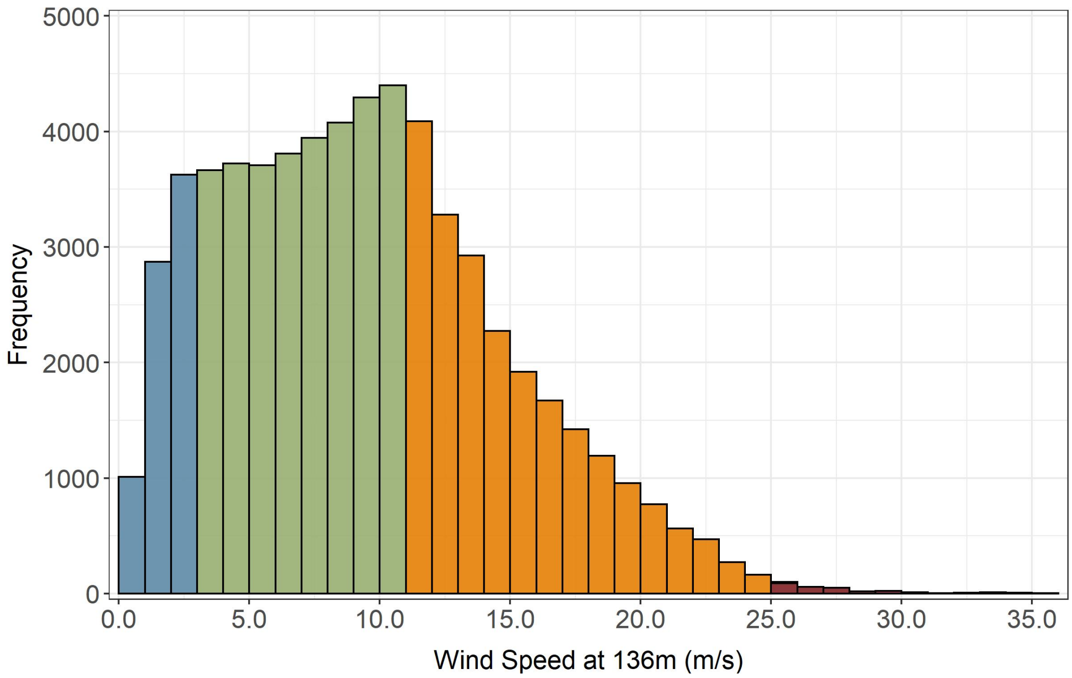


Figure 7. Histogram of wind speed and in the Humboldt Call Area. The *y*-axis is hours of occurrence over the seven-year period of record.

- Below cut in speed: 0 to 3 m/s; no power output because wind turbine is not spinning;
- Increasing power output: 3 to 11 m/s; power output increases with wind speed;
- Rated wind speed: 11 to 25 m/s; power production is constant at rated power output;
- Above cut out speed: 25+ m/s; no power output because wind speed is too high.

Figure 6 shows a bi-directional wind pattern with 50% of the wind from the north and 15% from the south. The area experiences its highest wind speeds in the winter from the south and south-southeast.

Figure 7 presents a histogram of wind speeds. The Humboldt Call Area follows a Weibull distribution, with the most frequent wind speeds at 11 m/s and a long tail of high wind speeds at low probability. The majority of wind speeds occur between 3 and 11 m/s (51.5%), which is the area of increasing power output on the turbine's power curve. The rated power output would be produced 35.8% of the time at wind speeds between 11 and 25 m/s. No power would be produced 12.9% of the time because of low wind speeds (12.2%) and high wind speeds (0.5%).

3.1.2. Wind Speed Variability

Here, we investigate the variability of wind speed between years, seasons, and hour of day. Daily wind speed profiles change with seasonal weather patterns. On average throughout the year, the Humboldt Call Area receives the lowest wind speed between 5 and 8 p.m., and wind speed rises to its maximum at midnight (Figure 8b). Seasonal minimums and maximums follow this trend for winter, spring, and fall, but during the summer, winds are the strongest between 8 a.m. and 12 p.m. and fall to the minimum overnight (Figure 8a). The annual average wind speed from the seven-year period of record show variation in magnitude up to 1.5 m/s, but each year displays a similar daily pattern during each season. We used the annual profile from the median year, 2009, for the energy analysis below.

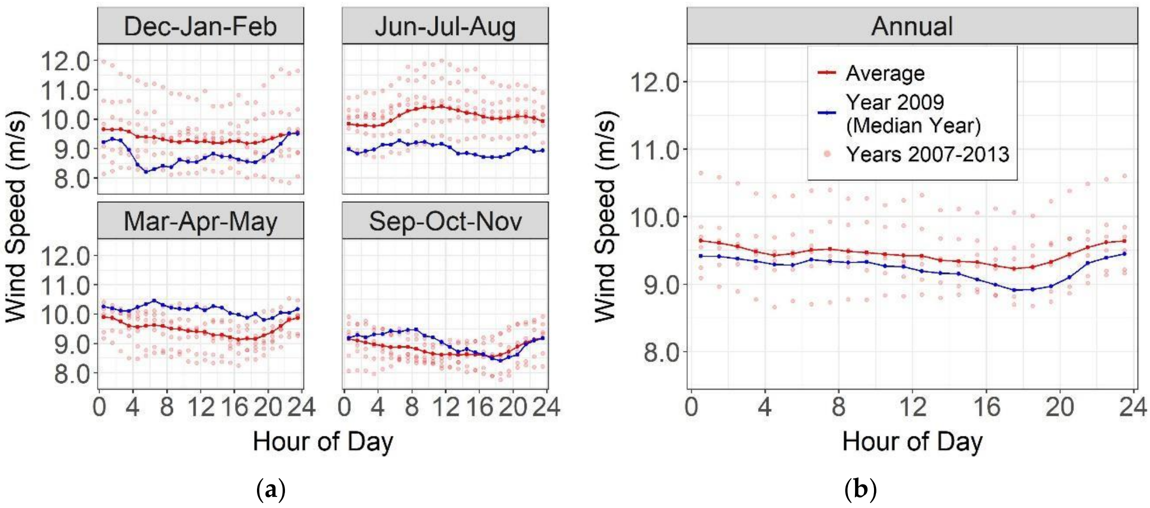


Figure 8. Daily profile of average wind speed by season (**a**) and for the year (**b**) for the Humboldt Call Area. The dots represent data averaged for each of the seven years with the average and median years highlighted in red and blue, respectively.

3.1.3. Offshore Wind Power Generation

In a typical year, offshore wind farms with a nameplate capacity of 48, 144, and 1836 MW in the Humboldt Call Area produce 202, 599, and 7540 GWh, respectively (Table 5), after taking into account all the loss factors. Annual wind farm capacity factors range between 47% and 48% during the median year of record, and between 45% to 54% over the seven-year wind speed data set. The capacity factor decreases slightly with increased wind farm size due to greater wake effects in larger arrays.

Table 5. Annual energy production for three wind farm scenarios. Median wind speed year bolded.

	Capacity Factor			Annual Energy Production, GWh/year		
Year	**48 MW**	**144 MW**	**1836 MW**	**48 MW**	**144 MW**	**1836 MW**
2007	46%	45%	45%	192	571	7180
2008	48%	48%	47%	203	602	7574
2009	**48%**	**47%**	**47%**	**202**	**599**	**7540**
2010	54%	54%	53%	228	678	8522
2011	51%	51%	50%	216	642	8078
2012	49%	48%	47%	204	605	7601
2013	47%	47%	46%	199	590	7426
Mean				206.3	612.4	7703
Standard deviation				12	36	450
Coefficient of variation				5.80%	5.80%	5.80%

The generation duration curves for the Humboldt Call Area show the power output on the vertical axis and the cumulative number of hours per year when the wind farm would operate at or above that power output on the horizontal axis (Figure 9). The wind farms would operate at full power for an estimated 2850 h, 33% of the year. On the other hand, during 1670 h, or 19% of the year, the wind farm is at zero power output corresponding to times when the wind speed is less than 3 m/s, greater than 25 m/s, or the turbines are at 0 MW output based on downtime. For all scenarios, the generation duration curves show that the wind farms would produce either full power or no power for over 50% of the year; during the remaining time power output for each turbine is between 0 and 12 MW.

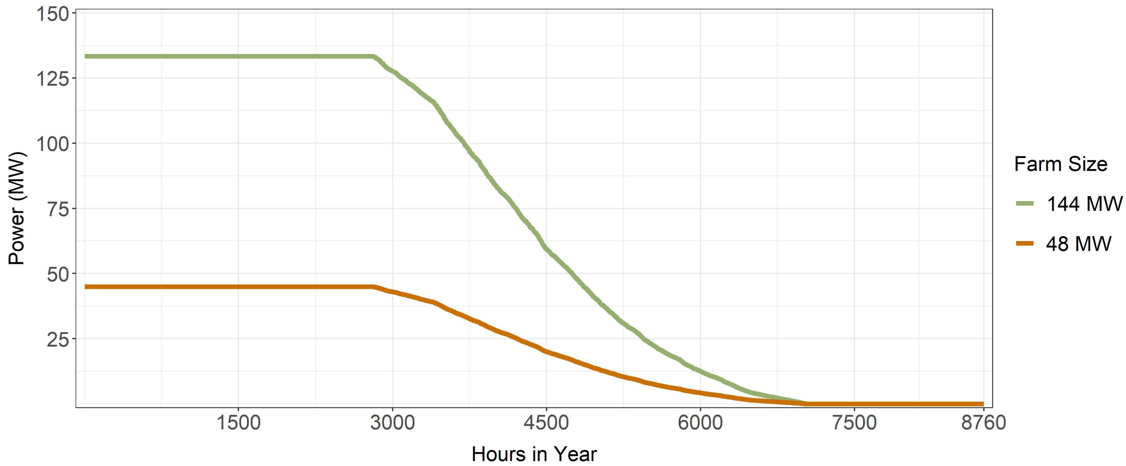


Figure 9. Generation duration curves for 48 MW and 144 MW farms. The 1836 MW development curve has the same shape but is omitted from this chart because it has a much larger power scale.

The hourly distribution of power output from wind farms would be seasonal. Figure 10 shows the frequency of different power output levels for the 144 MW scenario. This highlights the extreme spread between the maximum and minimum power output. In all seasons, the 75th percentile extends to the maximum output, indicating that 25% of the time the wind array is at maximum capacity. On the bottom of each chart, the 10th percentile always rests at 0 MW output, and in many hours, the 25th percentile is also at 0 MW. Power output displays a bipolarly distribution between the maximum and minimum at all hours of the day.

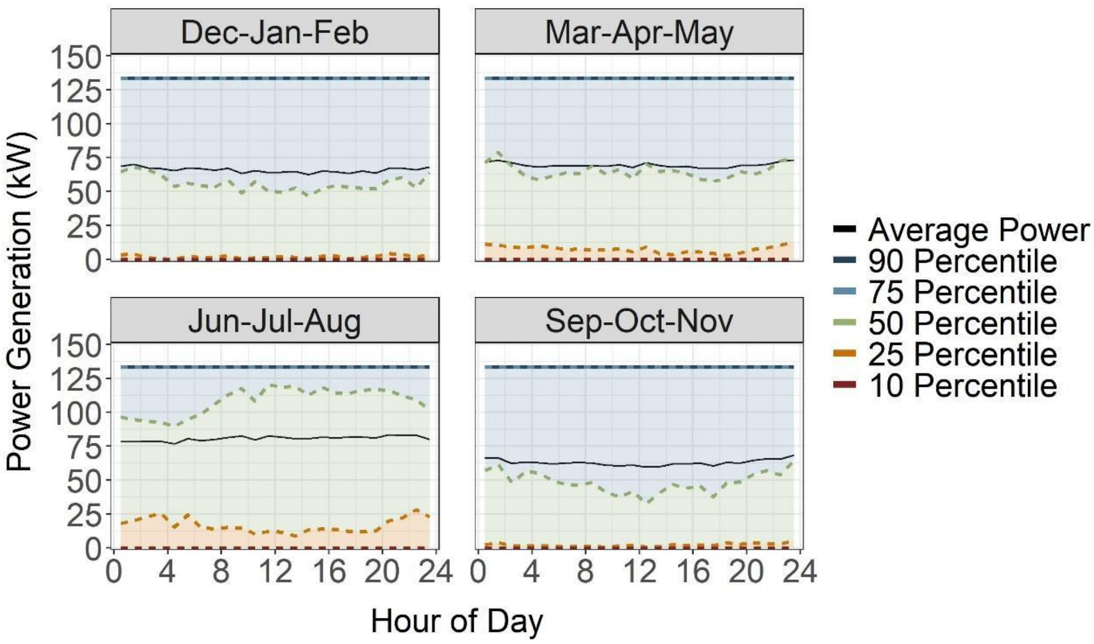


Figure 10. Average hourly power generation of the 144 MW farm in the Humboldt call area by season. Each line represents a different likelihood of occurrence, 10%, 25%, 50% (the median), 75%, or 90%. The green dashed line, at the interface between the blue and green range, shows the median power output or 50th percentile, and the solid line represents the mean.

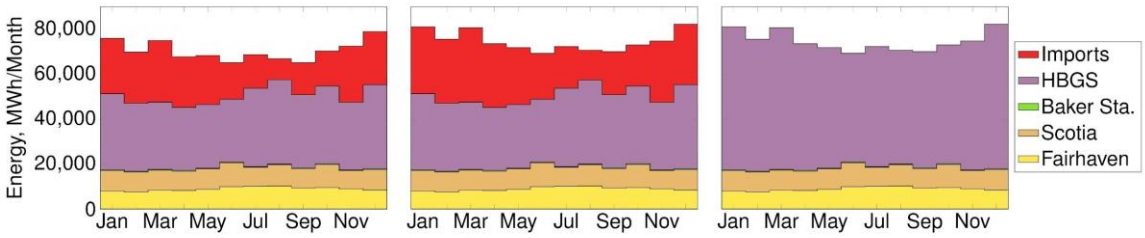
3.2. Offshore Wind Compatibility with Local Generation and Load

Now that the offshore wind power generation profile has been described (Section 3.1), offshore wind was added to the regional model to evaluate the impacts. First, this section describes the baseline generation scenario to understand the 2030 grid conditions without offshore wind. Then offshore wind is added and results are presented for hourly, annual, and monthly generation profiles at three scales.

3.2.1. Baseline Generation in Humboldt

The dispatchable, natural gas-fired Humboldt Bay Generating Station is the primary electricity-generating source for the Humboldt Area. Two biomass-fuel power plants and one small hydro facility are modeled as baseload power. Additional needs were met one of two ways: imports from outside the county, or an increase of HBGS capacity factor beyond the historical averages.

Figure 11 shows the monthly electricity demand and the generation portfolio that we used to meet energy demand for current 2018 load (a) and 2030 projected load (b) and (c). The current profile reflects reported generation data with additional imports to meet the demand (Figure 11a). Using the same historic generation data, imports could be increased to meet the expected load in 2030 (Figure 11b) without overloading the 70 MW transmission capacity.



(**a**) (**b**) (**c**)

Figure 11. Historic generation in Humboldt County coupled with imports required to meet 2030 projected load: (**a**) based on 2017–2018 loads and generation; (**b**) based on 2017–2018 generation and 2030 loads; (**c**) based on 2030 loads with imports replaced by HBGS. Note that Baker Station, a small hydroelectric facility, provides a small amount of energy relative to the other generators.

Instead of relying on imports, the 2030 electricity demand could be met by increasing the output of HBGS to match the hourly demand. Figure 11c depicts HBGS increasing capacity factor to meet the future load. This method of modeling the future generation portfolio provided a preference for power from HBGS over imported electricity. Future generation scenarios that include offshore wind also dispatched HBGS before selecting imports, similar to the model shown in Figure 11c.

3.2.2. Daily Generation Profiles

Adding offshore wind generation to Humboldt County drove a significant change in the local generation mix. Figure 12 shows how the energy generation portfolio changes for different scales of wind farms during three example daily wind patterns. The figure includes the generation profile for low, variable, and high wind speed regimes with 48 MW, 144 MW, and 1836 MW of installed offshore wind capacity.

The example days in Figure 12 provide insight into the effect of offshore wind on the portfolio of regional generation.

- Pilot Scale—A 48-MW wind farm (top row) would operate in tandem with HBGS and other resources to meet electricity demand. Even during windy days, offshore wind generation would not exceed regional load, and no offshore wind energy would be exported out of the region.
- Small Commercial Scale—The 144-MW wind farm would output 133 MW during high wind speed periods. With HBGS at minimum output, the total electricity generation of 169 MW would be balanced with local load by exporting offshore wind energy. During periods of low load and high wind (e.g., midnight to 6 am on the high wind speed day), offshore wind would be curtailed to limit exports to 70 MW.

- Large Commercial Scale—Production from an 1836-MW wind farm would far exceed the region's electricity demand. During periods of moderate to high wind speed, offshore wind energy would be exported at maximum capacity, but the majority of the production would be curtailed because of transmission limitations. Importantly, even with a large offshore wind installed capacity, local generation from HBGS would be needed during low and variable wind speed days to meet the regional energy demand. Given current transmission limitations, this demand could not be met entirely by imports.

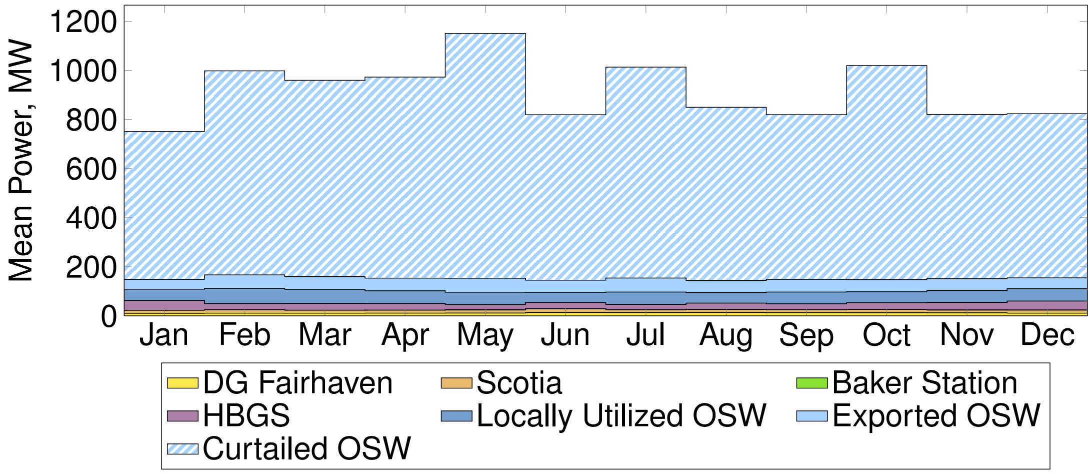


Figure 12. Hourly generation and load during three different wind speed regimes in February 2009 (vertical columns). The generation mix is shown for each day when adding 48 MW, 144 MW, and 1836 MW wind farms (horizontal rows). Note that the *y*-axis scale for the 1836-MW cases covers a much wider range of values than the *y*-axis scales for the 48 and 144-MW cases.

3.2.3. Annual Generation Summary

The annual generation portfolio for the Humboldt region is shown in Figure 13 for historic, baseline, and three different wind farm scales. The historic generation portfolio includes electricity imported to meet current electrical load. The baseline portfolio represents the modeled generation portfolio in 2030 before adding offshore wind. The increase in total energy in the baseline case relative to historic indicates the increase in load between 2018 and 2030. The baseline condition does not include any imports because HBGS is dispatched to meet load in this model before relying on the imports. In the actual energy market, real-time economic decisions based on market prices would dictate whether to dispatch HBGS or rely on imports.

As shown in Figure 13, increasingly large wind developments reduce HBGS's generation. Furthermore, while curtailment would be absent for the 48 MW scenario and a small fraction of potential wind output for the 144 MW scenario, in the 1836 MW scenario nearly all of the output would be curtailed without expanded transmission capacity, with roughly equal remainders utilized locally and exported. Little more usable electricity is extracted from the 1836-MW scenario compared to the 144-MW scenario given the present grid constraints discussed in Section 2.1.2.

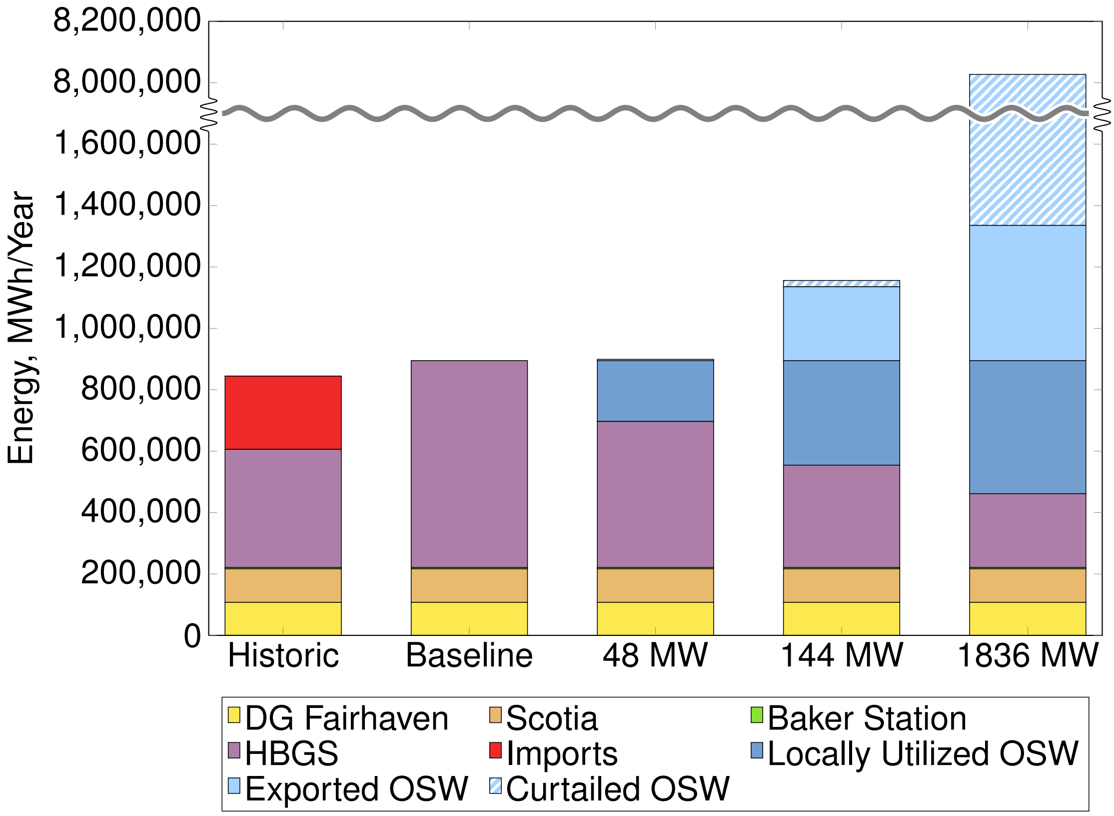


Figure 13. Annual energy generation by source for different levels of offshore wind development. Note the discontinuity in the vertical axis.

Offshore wind development would reduce HBGS output by 29% at 48 MW to 64% at 1836 MW (Table 6). In contrast, exports and curtailment would increase steadily with increased nameplate capacity of offshore wind. For a 48-MW development, nearly all output could be consumed locally, with less than 2% exported and none curtailed. In the 144-MW scenario, exports would increase to 40% of output with 3% curtailment, and in an 1836-MW development exports represent 6% of the total offshore wind output with 88% curtailment.

Table 6. Annual offshore wind electricity generation, end use, and HBGS operating characteristics.

	Scenario			
	Baseline	48 MW	144 MW	1836 MW
Offshore Wind Production, MWh	0	203,000	602,000	7,570,000
Exports, MWh	0	4330	241,000	440,000
Curtailment, MWh	0	0	20,500	6,690,000
HBGS Output, MWh	674,000	476,000	334,000	241,000
HBGS Reduction	-	29%	51%	64%
Emissions Reduction, tons CO_2e [1]	-	44,000–92,000	75,000–158,000	95,000–202,000

[1] See Appendix F for calculation methods.

3.2.4. Monthly Generation Summary

The historic and baseline cases have previously been shown at monthly resolution (Figure 11), while the monthly outputs with the addition of offshore wind generation are depicted in Figures 14–16.

In a 48-MW wind development scenario, offshore wind would provide 22% of regional load (Figure 14). HBGS would remain the dominant electricity source throughout the year, rising in the winter months to meet the increased local demand. Generation would excede demand during the months of May through October, leading to a small amount of exports but no curtailment.

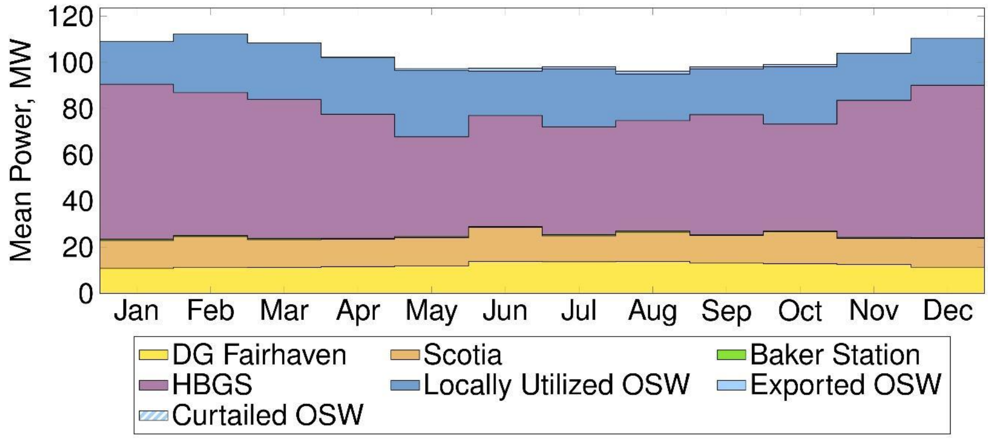


Figure 14. Monthly electricity generation by source to meet Humboldt County's projected 2030 load profile with addition of a 48-MW offshore wind farm.

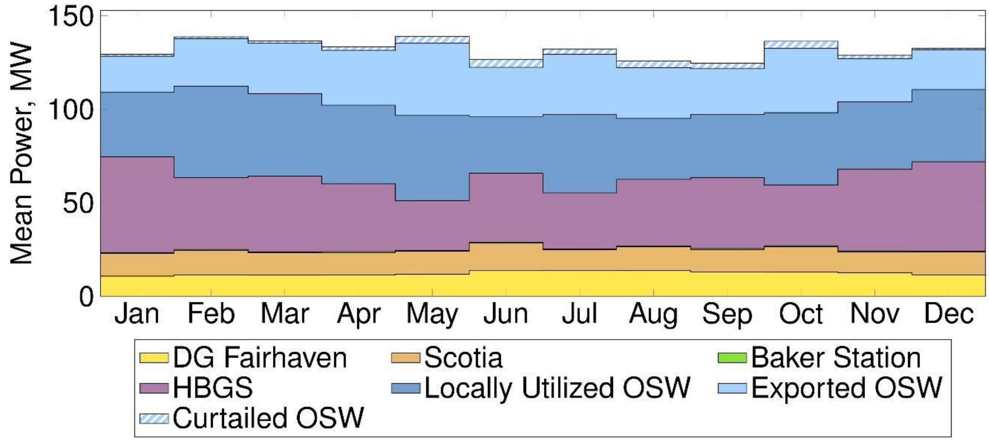


Figure 15. Monthly electricity generation by source to meet Humboldt County's projected 2030 load profile with addition of a 144 MW offshore wind farm.

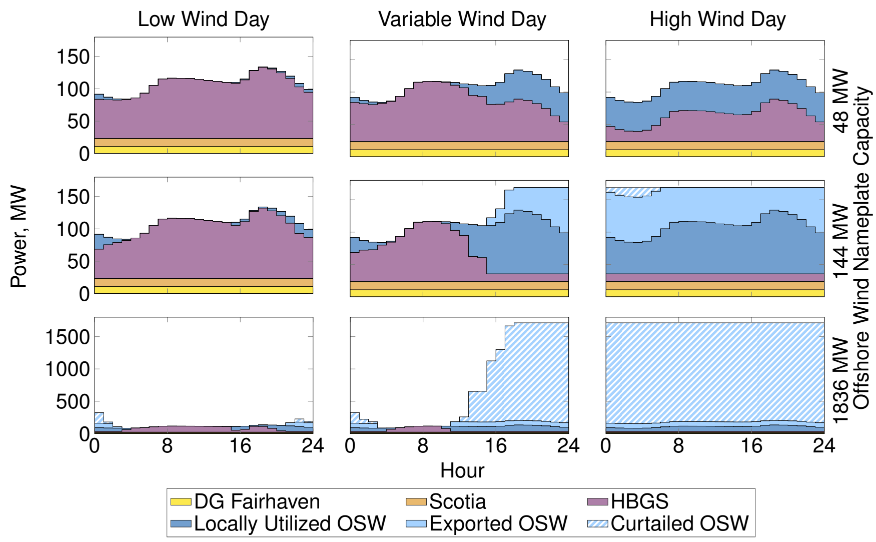


Figure 16. Monthly electricity generation by source to meet Humboldt County's projected 2030 load profile with addition of 1836-MW offshore wind farm.

With a larger, 144-MW offshore wind project, exports would increase to significant levels, and small amounts of curtailment—caused by local generation exceeding local demand by more than 70 MW—would be induced (Figure 15). Offshore wind would displace more HBGS output and grow to become the largest source of local electricity.

The result of an 1836 MW offshore wind development would be much more dramatic (Figure 16). Electricity from wind energy would be greater than all other factors by more than an order of magnitude, leading to generation far exceeding demand in all months, and tremendous exports and—without changes to transmission infrastructure—massive curtailment.

4. Discussion

The wind speeds in the Humboldt Call Area are phenomenal. The site can host wind farms with capacity factors near or exceeding 50%. For approximately one-third of the year, wind speeds fall within the rated power output band of a typical turbine (between 11 and 25 m/s), producing the rated power output. However, there would also be extended periods of no power output, summing to approximately 20% of the year, because of low wind speeds or maintenance activities.

Interconnecting offshore wind to the electrical grid in Humboldt County will be challenging because this isolated region of the grid has existing generators sized to meet local load with limited export capacity for surplus generation. This analysis of three wind farm scales shows that wind farms up to 150 MW could contribute toward the local energy profile without severe curtailment.

A pilot-scale offshore wind farm (48 MW nameplate capacity) would integrate well into the local grid, meeting 22% of the local demand while only exporting 2% of its energy outside the region. A small commercial-scale wind farm (144 MW nameplate capacity) would produce three times as much electricity as the pilot scale, but the majority of the additional electricity would need to be sent outside the county. The 144 MW wind farm could meet 38% of the local load compared to 22% for the pilot-scale, but exports would also increase, to 40% of the wind farm's annual output. The disproportional increase in exports is a result of the wind farm capacity exceeding the average regional load: when wind speeds are within turbine's rated power band, electricity must flow to other parts of the state; however, when there are low wind speeds, local generation from the HBGS would still be needed to meet regional demand. These findings highlight how offshore wind, which is a large-scale technology with extended periods of both high and low generation, needs to be interconnected with a large and diverse set of loads that match the capacity of the wind farm. When the wind farm is producing at full capacity (approximately 30% of the year), transmission must support distribution of this power. On the other hand, when the wind is low or the farm is down for maintenance (approximately 20% of the year together) supplemental generation or large-scale energy storage are needed to meet the load. In the Humboldt region, a 144 MW wind farm could integrate with the regional grid without significant curtailment by deploying HBGS to meet regional load in periods of low to moderate wind speeds and assuming the transmission system can support 70 MW of export.

A large commercial development (1836 MW nameplate capacity) would result in a different set of conclusions. Power generation from this larger wind farm meets would meet nearly half of the local load, but despite the large array size, offshore wind couldn't fully displace other existing generators because of periods of no generation. At this large scale, 88% of offshore wind would be curtailed because it exceeds the assumed 70 MW export limitation. In order to facilitate interconnection of this resource, new transmission infrastructure would be needed to connect with larger load centers in the state.

This analysis shows that while the offshore wind resource has potential for over 1 GW of high capacity factor offshore wind farms within the Humboldt Call Area, the existing energy use profile and transmission infrastructure are not compatible with this scale of development. Wind farms on the order of 150 MW could integrate with local energy generation and use patterns to increase renewable energy penetration with limited curtailment of offshore wind farms.

Another key dimension to understanding offshore wind integration into California's north coast is the transmission upgrade requirements. A power flow analysis, conducted by PG&E, provides a preliminary interconnection study that can be used to estimate the infrastructure requirements and interconnection costs of offshore wind generators at the three scales used in this analysis [5].

5. Conclusions

We modeled Humboldt County's electricity generation portfolio with the addition of future offshore wind generation by combining projected regional loads, historical generation profiles, and modeled offshore wind speeds. Offshore wind near Humboldt Bay is a high-potential resource, with a capacity factor much higher than typical land-based wind in the continental U.S. and among the best-studied offshore wind resources in the country. An area offshore Humboldt County has been identified for potential lease to an offshore wind developer and could host up to 1836 MW of nameplate capacity if fully utilized. While most of the output at pilot or small commercial scale (50–150 MW) could be utilized locally, the output of a 1836 MW offshore wind farm would be severely curtailed by the limited extant regional transmission. Offshore wind farms of this large capacity would require new transmission infrastructure to transmit electricity generated off the coast of Humboldt County to other load centers in the state.

To our knowledge, this approach of integrating a wind speed resource assessment with local electricity generation profile excedes the scope of existing wind speed resource assessment studies. This approach allows a wind farm developer to understand the generation potential and the ideal scale of a wind farm which could complement the existing generation portfolio. The methods deployed in this study have the potential to add depth to future wind speed resource assessments, especially in regions which are relatively isolated from the electrical grid.

Supplementary Materials: Analysis code and data are archived at https://doi.org/10.5281/zenodo.3992325.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Method for Calculation of Hourly Generation of Extant Plants

This appendix details the methods used to synthesize future generation profiles for all extant local generation sources from historical data.

DG Fairhaven Power Plant E0037: Monthly generation records between January 2001 and December 2018 were available through QFER [27]. These records showed significant variability, short periods of shutdown, and a long period of shutdown during 2016/2017. All records in which the power plant operated were averaged by month, and then divided by the number of hours in the month to create a flat generation profile (i.e., a constant power output) for each month.

Scotia E0063: Monthly generation records between January 2001 and December 2018 were available through QFER [27]. These records showed significant variability, short periods of shutdown, and a long period of shutdown at the end of 2015. There was also a third generator running prior to 2014, which has not since been operated. Since the data before and after 2016 look distinctly different, only data starting from 2016 were used. All records since 2016 were averaged by month, and then divided by the number of hours in the month to create a flat generation profile for each month.

Baker Station Hydro H0547: Only yearly generation for the years 2017 and 2018 were available for this plant through QFER [27]. The average was taken and assumed to be distributed evenly across the year for every hour.

Humboldt Bay Generating Station G0268: Total monthly generation for HBGS between January 2001 and December 2018 were available by engine through QFER [27]. This plant was retrofitted in 2010 with the replacement hardware (i.e., ten 16.3 MW Diesel cycle engines) brought online during 2011. HBGS was designed to operate in two modes: load following, in which the plant operates at output levels between 11.4 MW and 163 MW; and daily cycling, in which the plant can cycle up to its maximum output and be shut down on nights or weekends [42]. The air quality permit allows for both operational modes, labeled as load following and base load [29].

- Daily cycling: In this mode of operation, "HBGS may be operated at maximum continuous output for as many hours per year as scheduled by load dispatch, and limited by operational constraints of the permit to operate (approximately 75% annual capacity factor)" [29]. The engines may operate for a sum of up to 80 h per calendar day at output levels between 50% and 75% (8–12 MW). Engines are not permitted to continuously operate below 50% capacity [29].
- Load following: As a load-following plant [29,42,43], the engines can be operated at any level from "a single unit operating at 70 percent load to all 10 units operating at full load" to meet variable demand [42].

Because HBGS is a load-following power plant [43], its output was analytically shaped to match county demand. This method resulted in a monthly output 75% higher than historical (QFER) data would suggest. Nevertheless, because it was carried through all analyses, the assumed behavior allows for a consistent comparison. In this model, HBGS was permitted to run between 12 MW and 163 MW, which is slightly conservative with respect to its operating requirements [29,42].

Appendix B. Loss Effects

Table A1 provides additional detail on the loss factors applied to the wind farm's power generation. Most of the loss factor values were taken either from industry values obtained from AWS Truepower [41] or Musial et al. [8,18]. Wake effect losses were modeled using the Eddy-Viscosity method (as recommended in Churchfield [39]) and calculated using NREL's System Advisor Model (SAM), Beta Version 2019.12.2.

Table A1. Geographic specifications of study locations.

Loss Category	Loss Origin	Loss Factor	Depends On	Effect on Model
Wake Effect	Internal Wake Effect of the Project [a]	Varies	Wind farm scale and density, see Table 4	Even reduction
	Wake Effect of Existing or Planned Projects [a]	0.0%		Even reduction
Availability	Contractual Turbine Availability [a]	3.0%	O&M plan; Proven reliability/newness of turbine	Turn to 0 MW
	Non-contractual Turbine Availability [a]	1.3%		
	Availability Correlation with High Wind Events [a]	1.3%	Frequency of high wind events	Turn to 0 MW
	Availability of Collection and Substation [a]	0.2%	Timing of substation downtime	Turn to 0 MW
	Availability of Utility Grid [a]	0.3%	Timing of grid blackouts	Turn to 0 MW
	Plant Re-start after Grid outages [a]	0.2%	Timing of grid blackouts	Turn to 0 MW
	First-Year Plant Availability [a]	0.0%		
Electrical	Electrical Efficiency [a]	2.0%	Distance between turbines and substation	Even reduction
	Power Consumption of Weather Package [a]	0.1%		Even reduction
Turbine Performance	Sub-optimal operation [a]	1.0%		Even reduction
	Power Curve Adjustment [a]	2.4%		Even reduction
	High Wind Control Hysteresis	1.0%	Wind regime at site; turbine model	Turn to 0 MW
	Inclined Flow [a]	0.0%		Even reduction
Environmental	Icing [a]	0.0% [c]	Temperature	Turn to 0 MW
	Blade Degradation [a]	1.0%		Even reduction
	Low/High Temperature Shutdown [b]	0.0% [c]	Temperature, turbine limits	Turn to 0 MW
	Site Access [a]	0.1%	O&M plan, availability of parts, staff, vessels	Turn to 0 MW
	Lightning [b]	0.1%		Turn to 0 MW
Curtailments	Directional Curtailment [a]	0.0%	Layout and spacing	Turn to 0 MW
	Environmental Curtailment [a]	0.0%	Local environmental regulation	Turn to 0 MW
	PPA Curtailment [a]	0.0%	Wind farm scale and density	Turn to 0 MW
	Pre-Wake Total	13.2%		

[a] AWS Truepower [41]. [b] Musial et al. [8,18]. [c] Adjusted to 0 to account for mild northern California temperatures.

Appendix C. Study Locations

This appendix provides additional geographical specifications about the Humboldt Call Area (Table A2). The bathymetric profiles are shown in Figure A1.

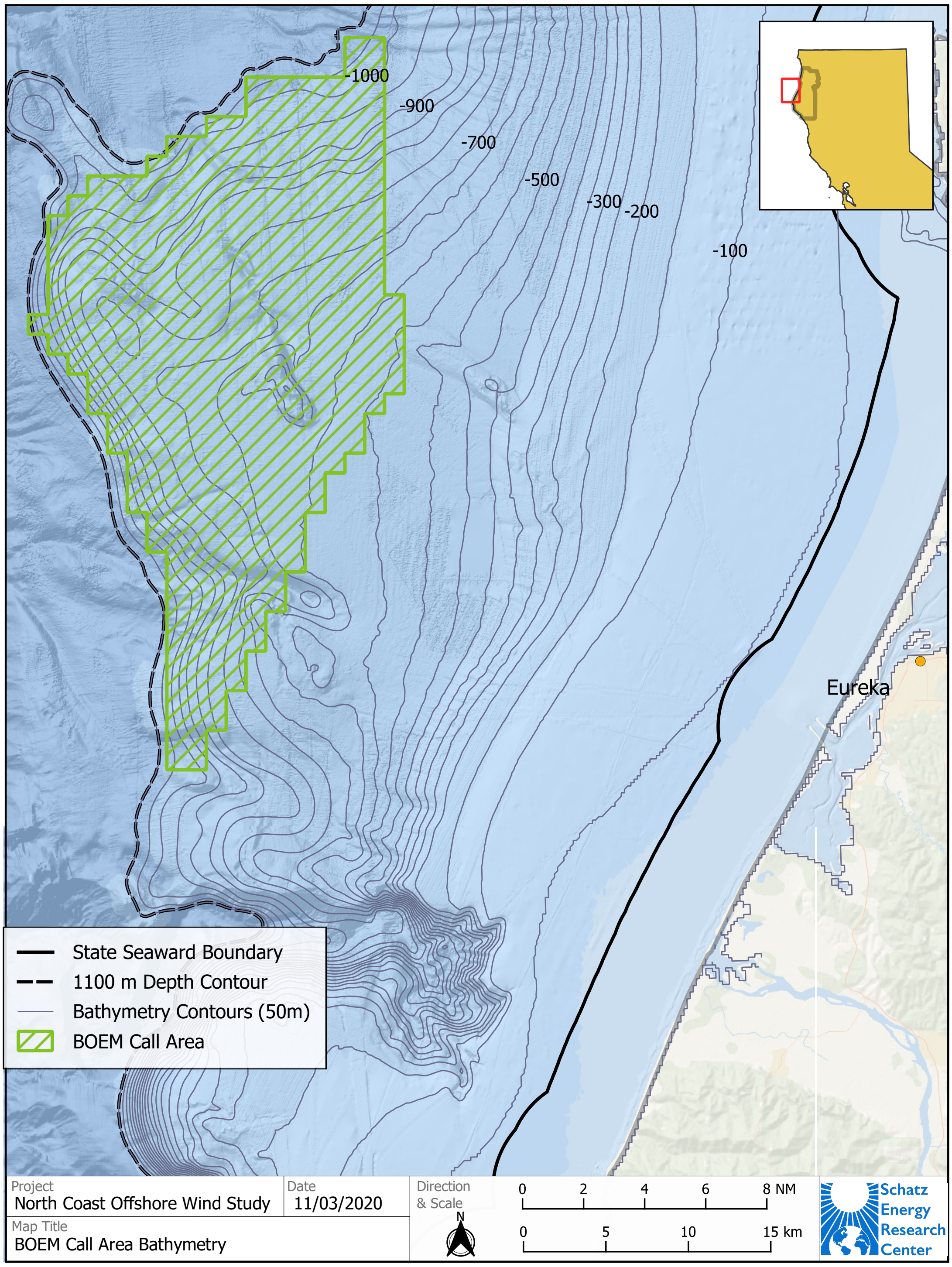

Figure A1. Northern California Call Area with 50 m bathymetric contours.

Table A2. Geographic specifications of study locations.

		BOEM Northern California Call Area
General area		Offshore Humboldt Bay
West-East width		12 NM (22 km)
North-South width		25 NM (46 km)
Total area		207 mi^2 (537 km^2)
Perimeter		81 NM (150 km)
Centroid location	Lat. Lon.	−124.662° 40.965°
Distance to shore	Min. Max.	17.4 NM (32.2 km) 30.4 NM (56.3 km)
Average annual wind speed at 90 m height	Min. Mean Max.	8.875 m/s 9.35 m/s 9.875 m/s
Ocean depth	Min. Mean Max.	1640 ft (500 m) 2673 ft (815 m) 3610 ft (1100 m)
Construction and maintenance port	Name Lat. Lon.	Redwood Marine Terminal 1 40.817° −124.182°
Centroid to port distance, approximate ship route		27 NM (50 km)
Interconnection point	Name Lat. Lon.	Humboldt Bay Generating Station 40.742° −124.211°
Centroid to interconnection point distance, approximate cable route		25 NM (46 km)

Appendix D. Turbine Layouts and Spacing

Turbine placement, spacing, and mooring line footprint for the 1836 MW scenarios are shown in Figure A2 for the Humboldt Call Area.

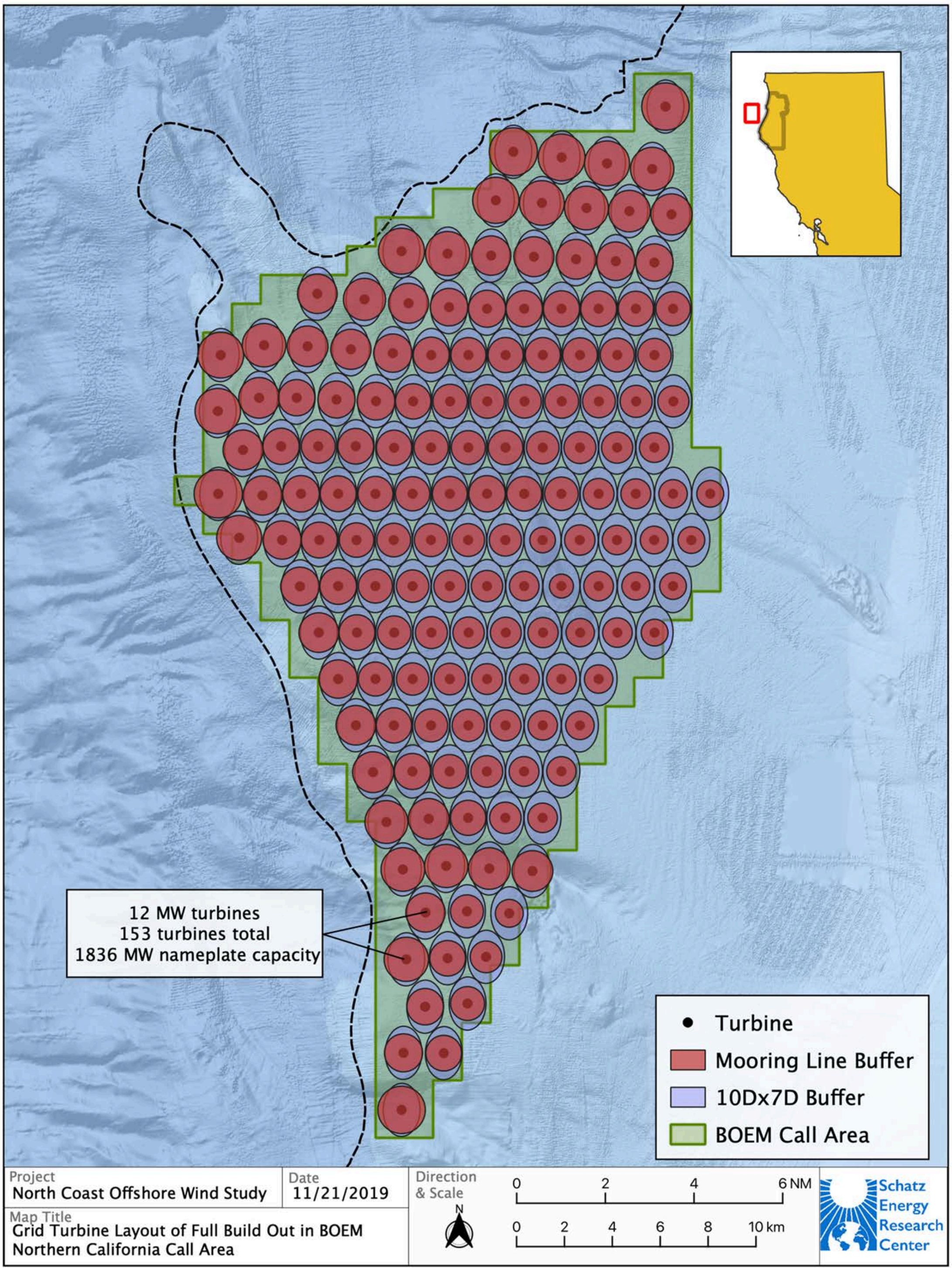

Figure A2. Grid turbine layout of the full-build out scenario in the Humboldt Call Area.

Appendix E. Spatial Averaging: Using the Centroid to Represent an Area

The objective of this analysis is to confirm the assumption made throughout this report that a single site containing wind speed data can be used to represent larger wind farm installations.

Throughout the analysis, we place a single 10-MW wind turbine at select data points on the 2-km grid and scale that 10-MW capacity to meet certain proportions of electric load. This assumes the upscaled capacity will occupy that single data point and the wind resource for that capacity will be the same as at the point. Gigawatt scale power cannot occupy that small of an area. Therefore, we confirmed that using a single point may act as an adequate indicator for a wind farm that would spread into surrounding areas

We examined five different wind farm sizes: 10 MW, 100 MW, 500 MW, 1 GW, and 10 GW offshore Cape Mendocino, where the wind speed is the highest, in order to evaluate the sensitivity of spatial averaging on wind farm output (Figure A3). The wind resource at this site is very good and there are enough data points to place any of these size farms. However, since the data points are on a 2 km by 2 km grid, it was assumed that turbines could be placed between data points and the in-between wind resource would not vary significantly from nearby points. For the wind installations of interest, the number of data points used are given in Table A3.

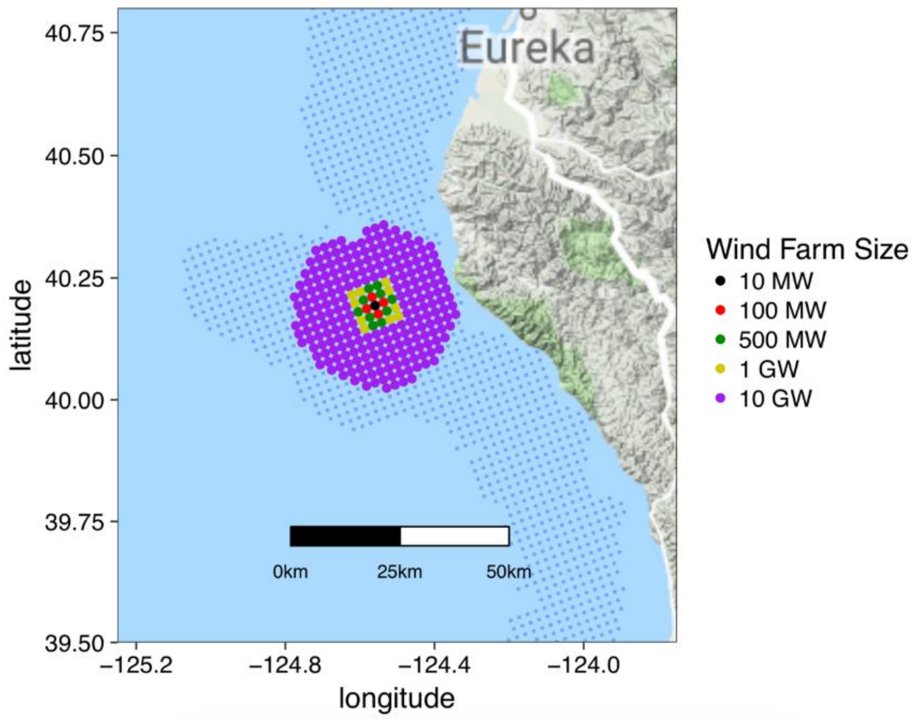

Figure A3. Wind farm sizes in Cape Mendocino ranging from 10 MW to 10 GW. Larger capacities also encompass the points used to display previous capacities in other colors.

Table A3. Number of data points used to represent various wind farm capacities.

Wind Farm Capacity	Number of Data Points
10 MW	1
100 MW	5
500 MW	15
1000 MW	25
10,000 MW	255

We examined wind farms near Cape Mendocino, since that is the location of the highest average annual wind speed on the northern California coast (Figure A3). Seven-year averages of the capacity factor and availability (proportion of time the turbine is producing power) were examined to determine if an expanded wind farm area differs from the capacity at the centroid of the area. Between 10 MW and 1000 MW there was a calculated absolute difference of 0.1% in the capacity factor, which is a negligible difference. Scaling even further to a 10,000 MW wind farm estimated from the wind resource at a single point showed a 0.78% absolute difference in capacity factor. The availability was not noticeably affected by the wind farm size between 10 MW and 10,000 MW.

Table A4. Wind farms at Cape Mendocino ranging from 10 MW to 10 GW. The metrics do not significantly differ between farm capacities.

Wind Farm Capacity	Capacity Factor	Availability
10 MW	66.4%	90.5%
100 MW	66.4%	90.5%
500 MW	66.4%	90.5%
1000 MW	66.3%	90.5%
10,000 MW	65.8%	90.4%

The capacity factors calculated when using wind speed data from the centroid of a 10 MW wind farm through a 10,000 MW wind farm showed a difference of 0.78% in the capacity factor. The maximum range of interest in this study is 1836 MW, where there will be less difference from the extrapolation of the wind speed data area.

Appendix F. Humboldt Bay Generating Station Emissions Intensity Calculation

The EPA's Emissions & Generation Resource Integrated Database lists Humboldt Bay Generating Station (HBGS) 2018 emissions as 179,007 metric tons of CO_2 equivalent, and annual net generation as 383,862 MWh [44]. This leads to an emissions factor of 0.466 metric tons CO_2 equivalent per MWh, or 1030 lb per MWh.

QFER annual data record for 2018 lists HBGS production as 384,787 MWh, matching the QFER monthly data exactly, and quite close to the EPA's data [27]. The California Air Resources Board [45] lists HBGS 2018 emissions as 179,025 metric tons of CO_2 equivalent. These data lead to a slightly lower emissions factor of 0.465 metric tons CO_2 equivalent per MWh, or 1025 lb per MWh.

These factors are within 0.3% of each other, and the emissions factor of 0.465 metric tons CO_2 equivalent is used because it is more conservative for the purposes of calculating CO_2 reduction.

California's grid average emissions intensity is much lower, 0.22 tons CO_2e per MWh [46], and is also used as a basis for comparison.

References

1. Gilman, P.; Maurer, B.; Luke Feinberg, A.D.; Peterson, L.; Musial, W.; Beiter, P.; Golladay, J.; Stromberg, J.; Johnson, I.; Boren, D.; et al. *National Offshore Wind Strategy*; U.S. Department of Energy & U.S. Department of the Interior: Washington, DC, USA, 2016; p. iv.
2. Mone, C.; Hand, M.; Bolinger, M.; Rand, J.; Heimiller, D.; Ho, J. *2015 Cost of Wind Energy Review*; National Renewable Energy Laboratory & Lawrence Berkeley National Laboratory: Golden, CO, USA; Berkeley, CA, USA, 2017.
3. Principle Power RCEA and Consortium Submit Lease Application for Northern California Offshore Wind Energy Project. Available online: https://web.archive.org/web/20200515162333/http://www.principlepowerinc.com/en/news-press/press-archive/2018/09/13/rcea-and-consortium-submit-lease-application-for-northern-california-offshore-wind-energy-project (accessed on 25 June 2020).
4. Bureau of Ocean Energy Management Commercial Leasing for Wind Power Development on the Outer Continental Shelf (OCS) Offshore California-Call for Information and Nominations (Call). Available online: https://www.govinfo.gov/content/pkg/FR-2018-10-19/pdf/2018-22879.pdf (accessed on 24 June 2020).
5. Lima, D.K.; Leão, R.P.; Dos Santos, A.C.; De Melo, F.D.; Couto, V.M.; De Noronha, A.W.; Oliveira, D.S. Estimating the offshore wind resources of the State of Ceará in Brazil. *Renew. Energy* **2015**, *83*, 203–221. [CrossRef]
6. Yip, C.M.A.; Gunturu, U.B.; Stenchikov, G.L. Wind resource characterization in the Arabian Peninsula. *Appl. Energy* **2016**, *164*, 826–836. [CrossRef]
7. Gunturu, U.B.; Schlosser, C.A. Characterization of wind power resource in the United States. *Atmos. Chem. Phys. Discuss.* **2012**, *12*, 9687–9702. [CrossRef]
8. Musial, W.; Beiter, P.; Tegen, S.; Smith, A. *Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs*; National Renewable Energy Lab.: Golden, CO, USA, 2016. [CrossRef]

9. Dvorak, M.J.; Archer, C.L.; Jacobson, M.Z. California offshore wind energy potential. *Renew. Energy* **2010**, *35*, 1244–1254. [CrossRef]
10. Musial, W.D.; Beiter, P.C.; Nunemaker, J.; Heimiller, D.M.; Ahmann, J.; Busch, J. *Oregon Offshore Wind Site Feasibility and Cost Study*; National Renewable Energy Lab.: Golden, CO, USA, 2019. [CrossRef]
11. Dvorak, M.J.; Corcoran, B.A.; Hoeve, J.E.T.; McIntyre, N.G.; Jacobson, M.Z. US East Coast offshore wind energy resources and their relationship to peak-time electricity demand. *Wind. Energy* **2012**, *16*, 977–997. [CrossRef]
12. Del Jesus, F.; Guanche, R.; Losada, I. The impact of wind resource spatial variability on floating offshore wind farms finance. *Wind. Energy* **2017**, *20*, 1131–1143. [CrossRef]
13. Amirinia, G.; Mafi, S.; Mazaheri, S. Offshore wind resource assessment of Persian Gulf using uncertainty analysis and GIS. *Renew. Energy* **2017**, *113*, 915–929. [CrossRef]
14. Chancham, C.; Waewsak, J.; Gagnon, Y. Offshore wind resource assessment and wind power plant optimization in the Gulf of Thailand. *Energy* **2017**, *139*, 706–731. [CrossRef]
15. Rehman, S.; El-Amin, I.; Ahmad, F.; Shaahid, S.; Al-Shehri, A.; Bakhashwain, J. Wind power resource assessment for Rafha, Saudi Arabia. *Renew. Sustain. Energy Rev.* **2007**, *11*, 937–950. [CrossRef]
16. Ayodele, T.; Jimoh, A.; Munda, J.; Agee, J. Wind distribution and capacity factor estimation for wind turbines in the coastal region of South Africa. *Energy Convers. Manag.* **2012**, *64*, 614–625. [CrossRef]
17. Himri, Y.; Rehman, S.; Draoui, B.; Himri, S. Wind power potential assessment for three locations in Algeria. *Renew. Sustain. Energy Rev.* **2008**, *12*, 2495–2504. [CrossRef]
18. Musial, W.; Heimiller, D.; Beiter, P.; Scott, G.; Draxl, C. *2016 Offshore Wind Energy Resource Assessment for the United States*; National Renewable Energy Laboratory: Golden, CO, USA, 2016.
19. Severy, M.; Alva, Z.; Chapman, G.; Cheli, M.; Garcia, T.; Ortega, C.; Salas, N.; Younes, A.; Zoellick, J.; Jacobson, A. (Eds.) *Pacific Gas and Electric Company Interconnection Feasibility Study Report*; Schatz Energy Research Center: Humboldt, CA, USA, 2020.
20. Severy, M.; Alva, Z.; Chapman, G.; Cheli, M.; Garcia, T.; Ortega, C.; Salas, N.; Younes, A.; Zoellick, J.; Jacobson, A. (Eds.) *Interconnection Constraints and Pathways*; Schatz Energy Research Center: Humboldt, CA, USA, 2020.
21. Zoellick, J.; Sheppard, C.; Alstone, P.; Alstone, A.; Chamberlin, C.; Garcia, R.; Hackett, S.; Lehman, P.; Martin, E.; Schiedler, L. *Humboldt County as a Renewable Energy Secure Community*; Schatz Energy Research Center: Arcata, CA, USA, 2011; p. 18. Available online: https://redwoodenergy.org/wp-content/uploads/2017/08/HumCo_RESCO_Task2_Final_Sep_2012.pdf (accessed on 6 July 2020).
22. *PG&E Refined Load Data 2012–2018*; 2019; Unpublished.
23. California Energy Commission California Energy Demand 2019–2030 Baseline Forecast—Low Demand Case. Available online: https://efiling.energy.ca.gov/GetDocument.aspx?tn=232310&DocumentContentId=64300 (accessed on 6 July 2020).
24. California Energy Commission California Energy Demand 2019–2030 Baseline Forecast—Mid Demand Case. Available online: https://efiling.energy.ca.gov/GetDocument.aspx?tn=232307&DocumentContentId=64301 (accessed on 6 July 2020).
25. California Energy Commission California Energy Demand 2019–2030 Baseline Forecast—High Demand Case. Available online: https://efiling.energy.ca.gov/GetDocument.aspx?tn=232311&DocumentContentId=64299 (accessed on 6 July 2020).
26. *Redwood Coast Energy Authority RCEA RePower Strategic Plan Load Analysis*; 2019; Unpublished.
27. California Energy Commission Source Text Files for Qfer_Web Database. Available online: https://www.energy.ca.gov/almanac/electricity_data/web_qfer/source_files/ (accessed on 25 June 2020).
28. California Energy Commission Annual Generation—Plant Unit. Available online: https://www.energy.ca.gov/almanac/electricity_data/web_qfer/Annual_Generation-Plant_Unit_cms.php (accessed on 25 June 2020).
29. Royall, M.S.; Holm, M.C. Title V Federal Operating Permit & District Permit to Operate: Title V Permit No: NCU 059-12. Available online: http://www.ncuaqmd.org/files/permits/PG&E%20HBGS%20Title%20V,%20Permit%20Renewal%20FINAL%207-19-2018.pdf (accessed on 25 June 2020).
30. Draxl, C.; Clifton, A.; Hodge, B.-M.; McCaa, J. The Wind Integration National Dataset (WIND) Toolkit. *Appl. Energy* **2015**, *151*, 355–366. [CrossRef]

31. Bureau of Ocean Energy Management Northern California Call Area. Available online: https://www.boem.gov/sites/default/files/renewable-energy-program/State-Activities/CA/Humboldt-Call-Area-Map-NOAA-Chart.pdf (accessed on 24 June 2020).
32. Redwood Coast Energy Authority. *Unsolicited Application for an Outer Continental Shelf Renewable Energy Commercial Lease under 30 CFR 585.230*; Redwood Coast Energy Authority: Eureka, CA, USA, 2018.
33. Ctric World's Most Powerful Offshore Wind Turbine: Haliade-X 12 MW | GE Renewable Energy. Available online: https://web.archive.org/web/20200603010921/https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine (accessed on 25 June 2020).
34. Gridded Bathymetry Data (General Bathymetric Chart of the Oceans). Available online: https://www.gebco.net/data_and_products/gridded_bathymetry_data/ (accessed on 25 June 2020).
35. Wang, Y.-H.; Walter, R.K.; White, C.; Farr, H.; Ruttenberg, B.I. Assessment of surface wind datasets for estimating offshore wind energy along the Central California Coast. *Renew. Energy* **2019**, *133*, 343–353. [CrossRef]
36. Shaw, W.J.; Draher, J.; Garcia Medina, G.; Gorton, A.M.; Krishnamurthy, R.; Newsom, R.K.; Pekour, M.S.; Sheridan, L.M.; Yang, Z. *General Analysis of Data Collected from DOE Lidar Buoy Deployments Off Virginia and New Jersey*; Pacific Northwest National Lab.: Richland, WA, USA, 2020.
37. Masters, G.M. *Renewable and Efficient Electric Power Systems*; Wiley Publishing: Hoboken, NJ, USA, 2004.
38. Newman, J.F.; Klein, P.M. The impacts of atmospheric stability on the accuracy of wind speed extrapolation methods. *Resources* **2014**, *3*, 81–105. [CrossRef]
39. Churchfield, M.J. *A Review of Wind Turbine Wake Models and Future Directions*; National Renewable Energy Laboratory: Golden, CO, USA, 2013.
40. *System Advisor Model Version2019.12.2*; National Renewable Energy Laboratory: Golden, CO, USA, 2019.
41. AWS Truepower AWS Truepower Loss and Uncertainty Methods. Available online: https://aws-dewi.ul.com/assets/AWS-Truepower-Loss-and-Uncertainty-Memorandum-5-Jun-2014.pdf (accessed on 24 June 2020).
42. California Energy Commission Final Commission Decision. Available online: https://efiling.energy.ca.gov/GetDocument.aspx?tn=48255&DocumentContentId=44511%20 (accessed on 25 June 2020).
43. California Energy Commission Humboldt Bay Generating Station Repowering, Licensing Case—Docket # 2006-AFC-07. Available online: https://ww2.energy.ca.gov/sitingcases/humboldt/index.html (accessed on 25 June 2020).
44. US EPA Emissions & Generation Resource Integrated Database (eGRID). Available online: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid (accessed on 25 June 2020).
45. California Air Resources Board Annual Summary of GHG Mandatory Reporting Non-Confidential Data for Calendar Year. 2018. Available online: https://www.arb.ca.gov/cc/reporting/ghg-rep/reported-data/2018-ghg-emissions-2019-11-04.xlsx?_ga=2.185991337.1002410208.1588529406-1181294205.1588270068 (accessed on 25 June 2020).
46. California Air Resources Board California Greenhouse Gas Emissions for 2000 to 2017. Available online: https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2016/ghg_inventory_trends_00-16.pdf (accessed on 25 June 2020).