

# California Offshore Wind Energy Potential

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## **Abstract**

An initial analysis was performed for areas suitable for offshore wind farm development near the California coast. Based on the analysis, California's offshore wind resource was divided up into three areas; Northern California, San Francisco Bay Area, and Southern California. The siting of an offshore wind farm is limited by water depth, with shallow water being the most preferable economically. Acceptable depths for offshore wind farms were broken up into three categories, based on current and future wind turbine tower support technology;  $\leq 20$  meters depth for monopile towers,  $\leq 50$  meters for water jacket tripods/quadrupods, and  $\leq 200$  meters depth for deep water floating tower technology which is likely to be developed in the next 15 years. Using the Penn State/National Center for Atmospheric Research *Mesoscale Model version 5* (MM5) to predict winds aloft at high resolution (1.67 and 5 km) near the locations of interest, annual 80 meter wind speeds were found for each area. Annual 80 meter wind speeds were based on the average of January, April, July, and Octobers' 2005 MM5 model data. Using the REpower 5M 5.0 MW, 126 meter diameter offshore wind turbine, a preliminary overall resource assessment was made for coastal California. Initial estimates show that 2-10 TWh, 9-27 TWh, and 67-293 TWh of energy could be harnessed annually using monopile, state of the art, and future turbine support technology in Northern California, the Bay Area, and Southern California respectively.

## **Introduction**

Offshore wind resource estimates have been performed for some parts of the US, including the Mid Atlantic Bight [Kempton et al., 2007], Georgia [Elliott and Schwartz, 2006], and Lake Michigan [Owen, Robert H., Jr., 2004]. As far as the authors know, only one California offshore wind resource estimate was performed to date [Musial and Butterfield, 2004]. This estimate, which relied on 50 m height mesoscale weather model predictions that the authors state had not been validated with actual wind data, found that significant resource potential

existed off the coast of California in mostly deep waters. This resource assessment broke up usable areas by depth (0 to 30 m depth and “deep”) and distance from the shore (5-20 nautical miles and 20-50 nautical miles). This methodology excluded significant shallow water areas, with good wind resource, close to the shore. Further, the study was based on a 50 m turbine hub height; a height at which modern wind turbines are no longer built. Several studies have looked at winds off the California coast [Haack, et al., 2005; Archer, et al., 2005a] but not for the purpose of wind energy assessment. An overall global wind energy study that scaled buoy data off the California coast to the 80 m height found good offshore wind resource does exist at some of the buoy sites [Archer, et al., 2005b].

This study analyzed the California offshore wind energy potential at the modern<sup>1</sup> hub height of 80 m. Taller turbine hubs take advantage of higher wind speeds aloft due to reduced surface friction and hence, produce more power given the same wind resource. The format of this resource assessment study, was loosely based on a offshore wind resource assessment methodology from the University of Delaware [Dhanju et al., 2007]. In this study, we calculate the usable surface area of three different depth classes (20, 50, and 200 m max depth) off coastal California, calculate the average wind speeds at these locations, and finally calculate the total power and annual energy outputs. In order to come up with useful energy calculations, it was necessary to pick a specific turbine model. The REpower 5M 5.0 MW turbine [REpower Sytems AG, 2007] with a 126.0 m rotor diameter was chosen for this study. Although the hub height for the offshore REpower 5M, is 90-100 m, this study used the more conservative 80 m height. You could expect to find approximately 7.6% more wind power at the 100 m height, based on traditional coefficients used for the power law<sup>2</sup>.

In order to estimate winds offshore, where little in-situ data exists, the Penn. State/National Center for Atmospheric Research *Mesoscale Model version 5* (MM5) weather model was run at 5 km and 1.67 km resolution over the entire state of California and San Francisco Bay Area respectively. MM5 was run for the months of January, April, July, and November 2005 to approximate seasonal and an annual average for the California offshore wind resource. Using these 80 m wind speeds, in conjunction with the bathymetry suitable for offshore turbine development near the coast, a power and energy total of the California resource was calculated.

## **Modeling the California Offshore Wind Resource**

The Penn State University/NCAR *Mesoscale Model version 5* (MM5) was used to model the winds offshore California at high resolution. One parent domain at 5 km horizontal resolution was created over the entire on and offshore regions of interest in California. A 1.67 km horizontal resolution, 1-way nested-domain was

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1 It should be noted that the some turbines have higher turbine heights than 80 m. The ENERCON E-112 (4.5 – 6.0 MW) has a hub height of 124 m [ENERCON, 2005]. The Vestas V90 3.0 MW has a hub height between 80 - 105 m [Vestas, 2007].

2 For example, using the wind profile power law with  $\alpha=0.11$  , yields a 2.5% increase over the 80 m to 100 m wind speed; a 7.6% increase in power

created over the San Francisco Bay Area. Figure 1 shows the domain configuration for MM5.

In order to more accurately resolve the winds at the 80 m height, two additional horizontal layers (sigma-levels) were added to the MM5 model directly above and below the 80 m offshore height, with a total vertical resolution of 28-levels ( $p_{top}=100$  hPa). A linear interpolation was used post process to calculate the 80 m wind speed. The 10 m wind speed was also calculated, for future validation

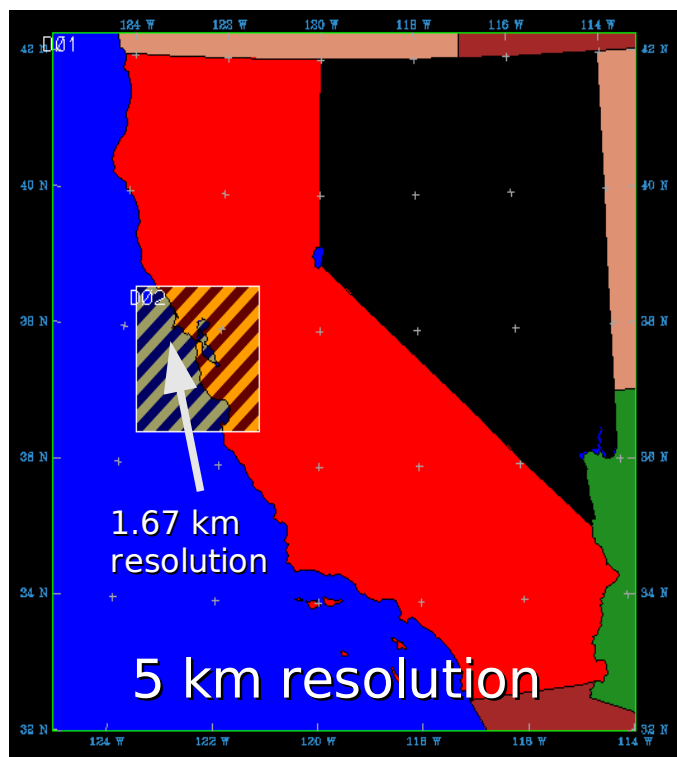


Figure 1: Mother and nested 1-way domain at 5 and 1.67 km respectively used for modeling the 80 m offshore wind resource. The 80 m wind fields were derived by increasing the vertical resolution of MM5 around the 80 m height.

studies that will utilize offshore buoy wind data (typically at the 5-10 m height). All of the wind data was inserted into a large, geospatial database that allows geospatial querying of the wind data overlain with the bathymetry data.

Figure 2 shows the modeled average 80 m wind speed for the months of January, April, July, and October 2005. The MM5 model ran, using 8-processors on a GNU/Linux cluster, using all of the default MM5 physics options. The National Center for Environmental Prediction 1 degree by 1 degree Global Final (FNL) Analyses was used to create initial and boundary conditions for MM5 [National Center for Environmental Prediction, 2007]. Boundary conditions were updated every 6 hours. The model was restarted every 7 days and reinitialized with the FNL data. An additional 6 hours was added to each model run to allow the model to spin-up before wind fields were used. This extra 6 hours was thrown out and not used in the calculation of the wind resource. Using these four months of modeled data with hourly output, a projected annual average wind speed at each offshore location was predicted. A temporal analysis of wind speeds for a specific site (off of Cape Mendocino) using the average hourly output was also performed using this data. Although we have not fully validated this MM5 output against in-situ buoy and radiosonde data, initial comparisons of MM5 winds and buoy wind data have looked promising. Future work will provide a complete validation of the MM5 modeled wind data.

## **Turbine Tower Support Technologies**

An added constraint of offshore wind turbines is the depth at which turbine support towers can be placed, as well as the extra cost associated with each

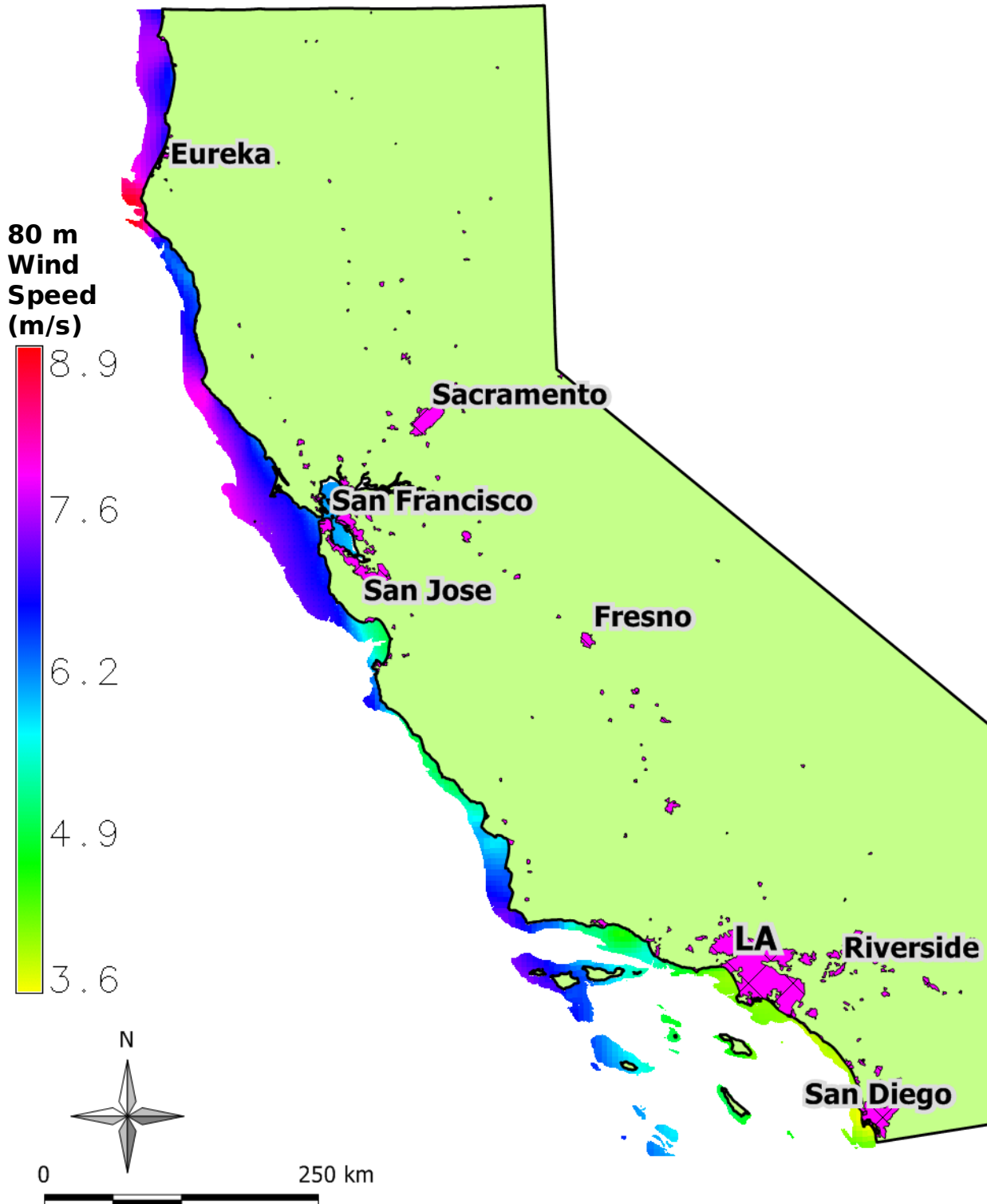


Figure 2: Modeled 80 m wind resource, based on the four month MM5 model runs (January, April, July, and October 2005). Only wind resource from 0-200 m depth is shown on this map and only wind resource greater than 7.0 m/s and 7.5 m/s were included in this study. Pink areas over land are urban centers, where most of the offshore wind energy could be used.

tower technology. The economics of minimizing the amount of underwater transmission cable laid and maintenance requirements of offshore wind turbines lend themselves to much larger turbines than their onshore counterparts. Further, offshore wind turbines are not limited by the maximum shipping sizes of trucks, trains, and roadways like their onshore counterparts.

To estimate the wind resource potential based on depth, the bathymetry data was classified by each type of turbine support technology. California generally has much deeper water offshore than other locations where resource assessments have been performed. In extremely shallow water (up to 5 meters depth), gravity base structures have been used. For this study, we have neglected the gravity base structures, due to their limited utility with California's deeper water. Monopile

structures can be placed in waters up to 20 meters depth (oldest and cheapest technology) [Henderson et al., 2003] and new water jacket tripods/quadrupods can be placed in waters up to 50 m depth [Talisman Energy, 2006]. In the proposed Beatrice offshore wind farm 22 km (12 mi) off the coast of Scotland, support towers will be located at 45 meters depth. Two different water

jacket tripod support designs will use either driven steel piles or suction piles to hold the towers to the sea bed [Henderson et al., 2003]. A water jacket structure was installed in the summer of 2006 in 44 m depth water at the Beatrice wind farm demonstrator project, off the coast of Scotland [REA, 2007]. Lastly, it is likely that floating turbine structures, similar to oil and gas platforms today will be developed in the next 15 years, capable of depths of up to 200 m [MIT, 2006]. These depths are used as technology constraints throughout the study and coincide with the depths used in the offshore wind assessment methodology [Dhanju et al., 2007], with the exception of deep water being considered 50-200 m depth (instead of 50-100 m depth). Figure 3 illustrates three examples of these different classes of turbine support technologies.

### Turbine Tower Support Structures

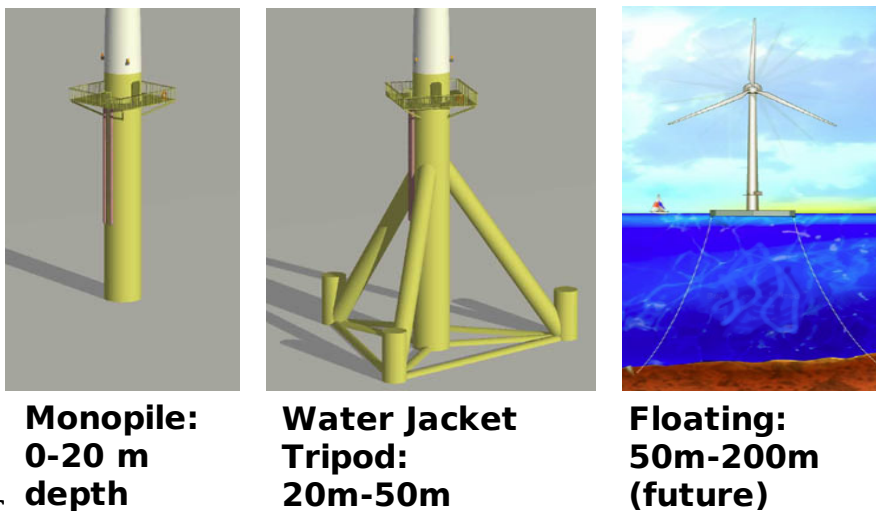


Figure 3: Examples of the three different classes of turbine support structures. Image 1 & 2 source: [OWE, 2007]. Image 3 source: [NREL, 2007]

## Calculation of Offshore Areas Suitable for Turbines

In order to determine the amount of usable area off the California coast suitable for offshore wind turbines, a base layer of bathymetry (underwater depth) was used and divided into tower technology classes (20, 50, and 200 m max depth). The National Geophysical Data Center (NGDC) 3-arc second Coastal Relief Model [NOAA and NGDC, 2000] provided approximately 30 m horizontal resolution<sup>3</sup> over the California domain. This bathymetry data was of significantly higher resolution than used in the previous offshore wind resource assessment of California, which used a 1 km resolution dataset [Musial and Butterfield, 2004].

Where wind speeds had an annual average of 7.0 and 7.5 m/s or higher, they were included as usable water area where offshore wind could be developed. The 7.5 m/s cutoff was chosen to coincide with the NREL *Class 5* resource, with a standard power density of 500 W/m<sup>2</sup> [Elliott et al., 1987]. The 7.0 m/s cutoff was chosen to include the future possibility of an offshore wind turbine that could utilize lower wind speeds. The geospatial intersection of the NGDC bathymetry data and the annual modeled wind resource greater than 7.0 m/s and 7.5 m/s is the basis for the surface areas in Table 1 below.

*Table 1: Usable amount of offshore surface area suitable for wind turbine development contained within each depth region. Only areas that had wind speeds higher than 7.0 m/s and 7.5 m/s were included in this study.*

Summation of Usable Surface Area for Offshore Wind (km <sup>2</sup> )					
Ocean Depth	80 m Avg. Wind Speed	Northern Calif.	SF Bay Area	Southern Calif.	Total
0-20 m	≥7.0 m/s	405	1	41	447
	≥7.5 m/s	99	0	0	99
20 – 50 m	≥7.0 m/s	1080	48	77	1205
	≥7.5 m/s	360	0	0	360
50 – 200 m	≥7.0 m/s	8801	4220	643	13664
	≥7.5 m/s	1960	824	0	2784

In order to simplify the offshore wind resource assessment, the average wind speeds were grouped by ocean depth and cutoff wind speed, shown in Table 2. These average annual 80 m wind speeds were used in the calculation of the turbine capacity factor and nameplate capacity, which in turn will yielded an annual energy output.

<sup>3</sup> The central latitude of California is 37.25°. At this latitude, 3-arc seconds is 8.333E-4 degrees. The earth's circumference is 40,080 m at the equator and 16,600 around the center of California. Leading longitudinal resolution of 14 m and a latitudinal resolution of 33 m for the USGS 3-arc second bathymetry data.

Table 2: Average 80 m wind speeds (m/s) over the usable surface area found in Table 1, based on mesoscale modeling results for January, April, July, and October 2005.

Average 80 m Wind Speed Over Usable Surface Area (m/s)				
Ocean Depth	80 m Avg. Wind Speed	Northern Calif. (m/s)	SF Bay Area (m/s)	Southern Calif. (m/s)
0-20 m	≥7.0 m/s	7.43	7.30	7.12
	≥7.5 m/s	7.96	N/A	N/A
20 – 50 m	≥7.0 m/s	7.52	7.20	7.11
	≥7.5 m/s	8.05	N/A	N/A
50 – 200 m	≥7.0 m/s	7.40	7.29	7.16
	≥7.5 m/s	7.85	7.63	N/A

### Estimate of Wind Power and Energy Offshore

In order to determine how much surface area would be required for each turbine, a 4-diameter by 7-diameter spacing [Masters, 2004] was chosen between turbines, where the turbine diameter is 126 m. Each REpower 5M turbine would require 0.44 km<sup>2</sup> of area per turbine. In order to account for the surface area that would potentially be unusable due to shipping lanes, restricted wildlife preservation areas, viewshed considerations, etc..., a 33% exclusionary factor for all possible turbine areas was included in each nameplate capacity and energy calculation. Future studies should look at the details of each area's exclusion zones, in order to more precisely calculate amount of usable surface area. Table 3 shows the nameplate capacity of each geographical region and depth class.

Table 3: Nameplate capacity of turbines (MW) in each geographical area, depth, and wind speed cutoff, assuming a 33% exclusionary factor for each area.

Turbine Nameplate Capacity (MW)					
Ocean Depth	80 m Avg. Wind Speed	Northern Calif.	SF Bay Area	Southern Calif.	Total
0-20 m	≥7.0 m/s	3,052	8	309	3,369
	≥7.5 m/s	746	0	0	746
20 – 50 m	≥7.0 m/s	8,139	362	580	9,081
	≥7.5 m/s	2,713	0	0	2,713
50 – 200 m	≥7.0 m/s	66,325	31,802	4,846	102,973
	≥7.5 m/s	14,771	6,210	0	20,980

To make an initial estimate of the energy that could be achieved from offshore wind turbines, the REpower 5M, 5 MW wind turbine with a 126 diameter at 80 m height was chosen. The capacity factor for the proposed wind farms was

estimated using Equation 1 which states the relationship between mean wind speed ( $V_{avg}$ ), rated power ( $P_{rated}$ ) and rotor diameter ( $D$ ) [Masters, 2004]. Given this equation, the capacity factor based on the overall average wind speed for each turbine tower technology was calculated.

$$\text{Capacity Factor} = 0.087 * V_{avg} (m/s) - \frac{P_{rated} (kW)}{D^2 (m)} \quad (1)$$

Combining the capacity factor calculation, the average wind speed for each turbine technology, and the usable area (including a 33% exclusionary factor), an annual energy estimate has been made in Table 4.

*Table 4: Annual output energy (TWh) in each geographical region, depth class, and cutoff wind speed. A 33% exclusionary factor was included in these calculations.*

Annual Energy Output (TWh)					
	80 m Avg. Wind Speed	Northern Calif.	SF Bay Area	Southern Calif.	Total (TWh)
0-20 m depth	≥7.0 m/s	8.86	0.02	0.82	10
	≥7.5 m/s	2.47	0.00	0.00	2
20 – 50 m depth	≥7.0 m/s	24.19	0.99	1.54	27
	≥7.5 m/s	9.16	0.00	0.00	9
50 – 200 m depth	≥7.0 m/s	191.07	88.95	13.07	293
	≥7.5 m/s	47.62	18.98	0.00	67

A significant amount of offshore wind energy potential does exist in California, with 78-330 TWh developable annually in all waters. While the vast majority of the California offshore wind resource exists in deep waters (86-98%), a significant amount of energy relative to California's overall electric generation capacity. Each of the three geographical regions are analyzed in more depth, including access to existing transmission lines in the following section.

### **Geographical Context of the Offshore Wind Resource**

Although more expensive to build, offshore wind turbines can often provide clean energy closer to California's coastal population centers, where most of population resides. In order to provide geographical context for the California offshore wind resource, we mapped the water depth [NOAA/NGDC, 2000], urban areas [USGS, 2001], and existing transmission lines [FEMA, 1993] together in Figures 4, 5, and 6 for each California geographical region. Figure 2 can be consulted to find the average modeled 80 m wind resource. We combined the modeled wind resource, annual energy output estimate (Table 4), and the transmission/depth maps to come up with the feasibility of developing offshore wind in each of the three geographical locations.

Northern California (Figure 4) could potentially provide 11 TWh of wind energy annually in relatively shallow water (0-50 m), using existing turbine and tower

support technology.<sup>4</sup> This amount of energy alone could offset 6.3% of California's current carbon emitting electricity sources.<sup>5</sup> Further, if deep water turbine support technology is developed, 27% of California's current carbon electricity sources could be replaced by offshore wind energy in Northern California alone.<sup>4</sup>

The initial assessment for the Bay Area (Figure 5) looked less viable for near term development. The good 80 m wind resource seems to occur far from the City of San Francisco and exists primarily in deep waters (50-200 m), with almost zero good wind resource in the Bay itself (see Table 1 for details). Most of the large transmission lines would need to be accessed through the San Francisco Bay outlet, as little coastal transmission access exists. One potentially interesting location in the Bay Area is the Farallon Islands (managed by the City of San Francisco), which appear to have the necessary wind resource (>7.5 m/s) and are surrounded by fairly shallow water (<50 m depth). However, the length of undersea transmission cable required may be cost prohibitive, as the Islands are about 43 km (27 miles) offshore. Further, the Islands' unique bird nesting, marine mammal, and fish populations would need careful review before turbines could be sited in this location. A positive attribute of the Islands' far distance from shore is that it would make the offshore wind turbines nearly impossible to see from San Francisco and might quell any viewshed concerns from City residents.

Based our initial assessment, Southern California (Figure 6) appears to have little easily developable offshore wind resource. It should be noted that some of the offshore sites analyzed had good wind resource for three of the four 2005 months modeled, but had significantly reduced winds in the July 2005 month. While the Pacific High pressure system located off the Southern California coast during the summer may suppress some of the winds, more modeling and validation needs to be performed. It should be noted that the Southern California coast does however provide several excellent grid interconnection points. Further, existing oil and gas platforms in Southern California may reduce public opposition to the siting of wind farms.

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4 Using the more realistic cutoff of 7.5 m/s, 80 m wind speed.

5 Carbon emitting electric generation (coal, natural gas, and biomass) was a total of 174.746 TWh in 2006 including in and out of state sources [CEC, 2007].

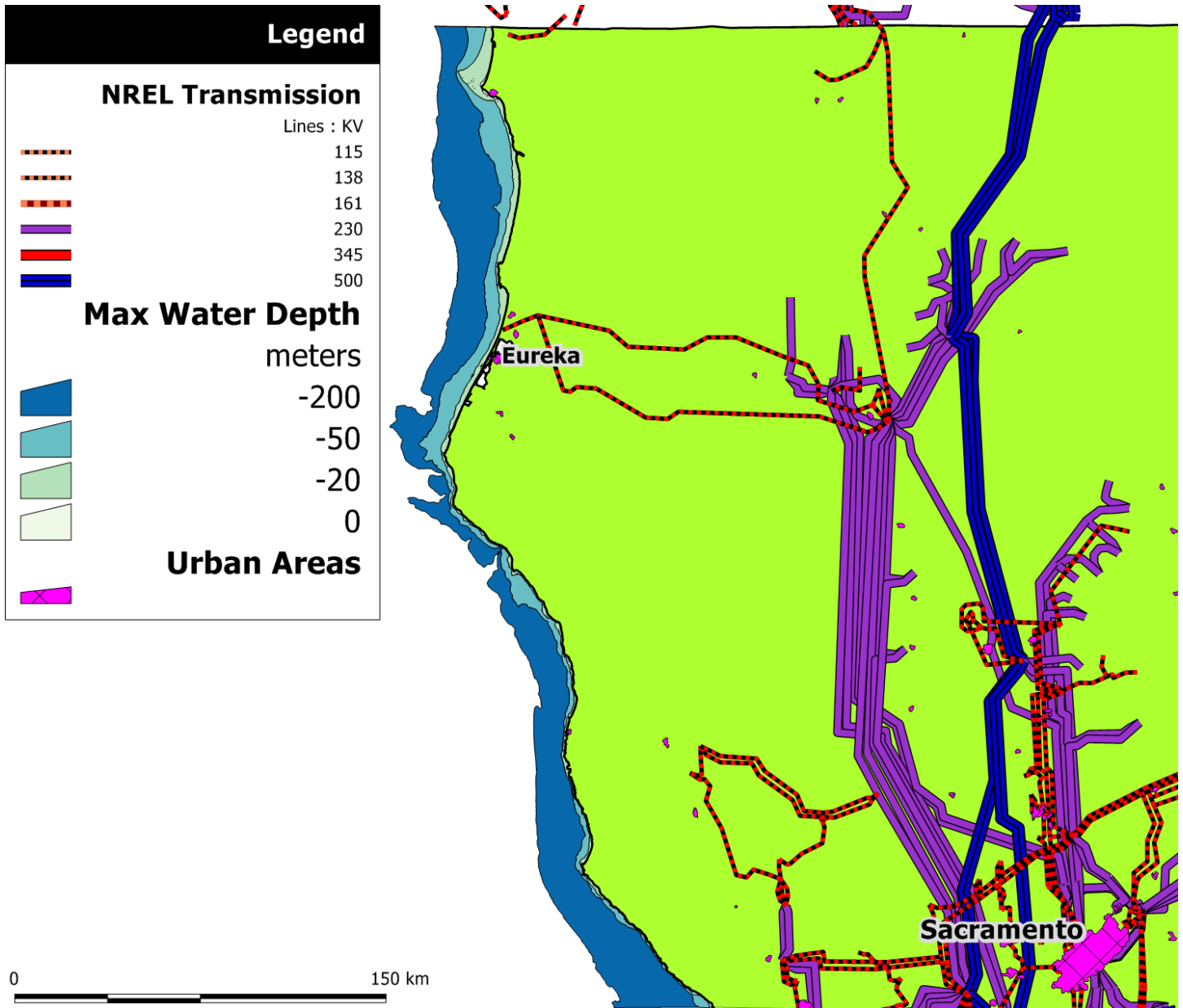
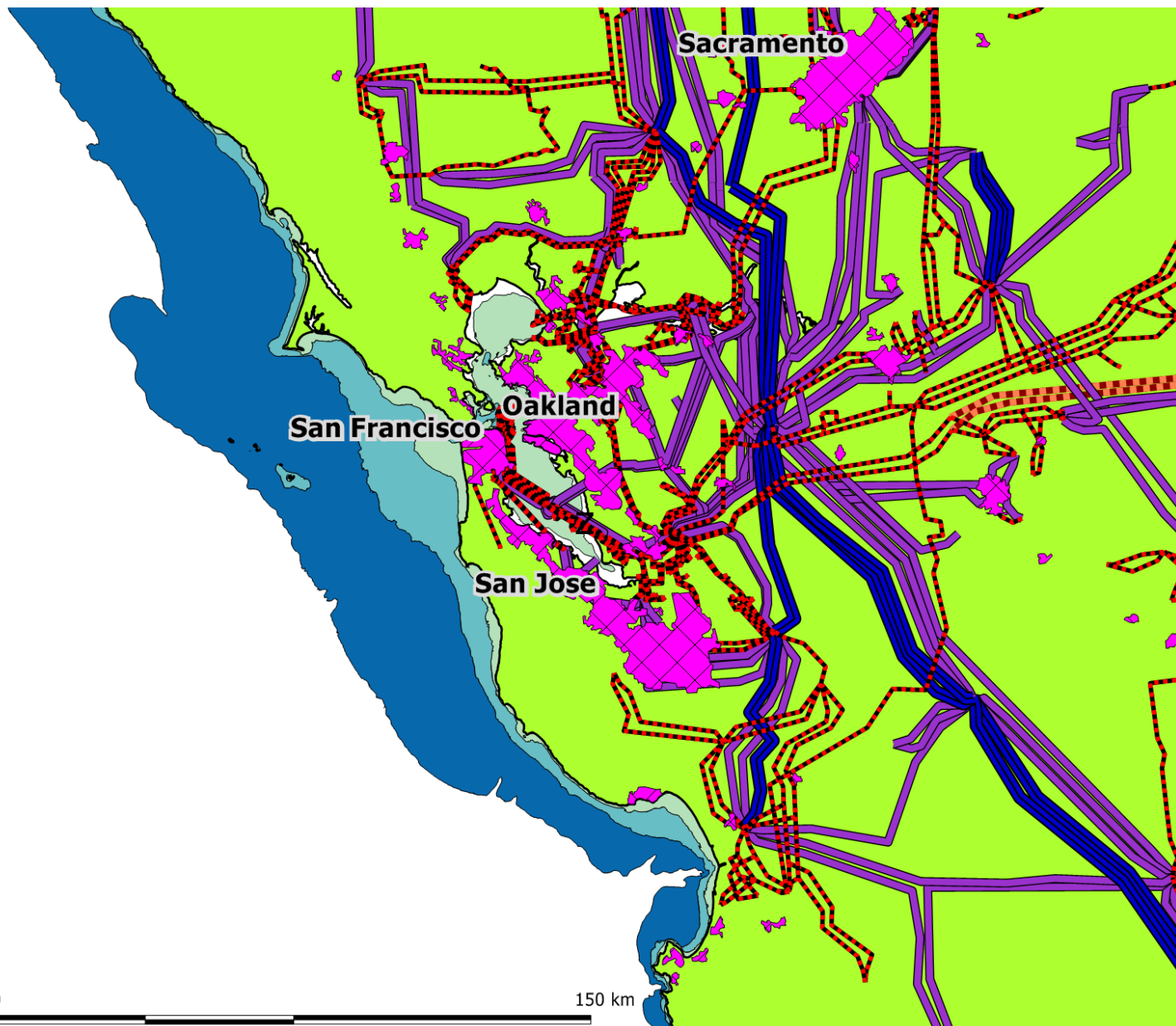


Figure 4: Bathymetry, urban areas, and transmission lines for Northern California. The best California offshore wind resource exists in Northern California but the region lacks any large population centers and any large transmission lines near the coast. Development in this region is still plausible, using the existing 115 kV transmission lines that run through Eureka. See the section titled "Temporal Analysis of Wind" for details.



*Figure 5: Bathymetry, urban areas, and transmission lines for the San Francisco Bay Area. (See Figure 4 for legend.) Although a reasonable amount of shallow water exists near the Bay, wind speeds look to be marginal until the deeper water is reached.*

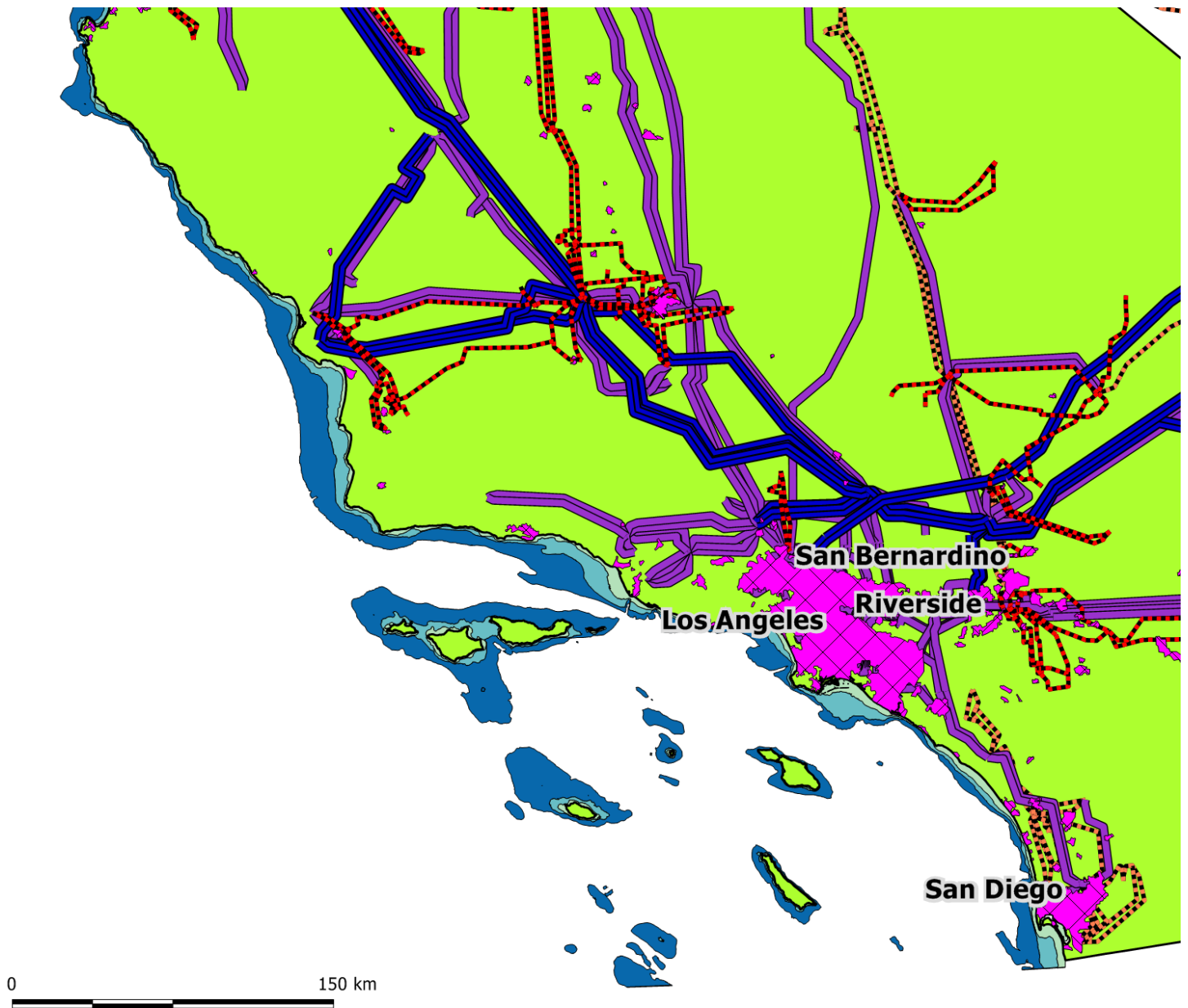


Figure 6: Bathymetry, urban areas, and transmission lines for Southern California. (See Figure 4 for legend.) This study found good wind resource for three of the four months modeled (January, April, and October 2005), but reduced wind resource throughout much of Southern California during the summer month modeled (July 2005). The reduced summer wind is likely due to the position of the large high pressure system (Pacific High) that sits over the region in the summer months.

## ***Comparison of Results to Other Estimates***

Musial and Butterfield of the National Renewable Energy Laboratory (NREL) in their 2004 estimate found that for shallow depths (<30 m) and deep water (>30 m), 2,650 MW and 295,550 MW of developable wind power existed off the coast of California respectively, between 5 and 50 nautical miles (9.3 km to 93 km) from shore. The study was based on the NREL 50 m wind resource data, which they state has not been validated for offshore conditions. The NREL study also used different exclusionary percentages; a conservative 67% for the 5-20 nm (9 km – 37 km) zone and 33% for the 20 – 50 nm (37 km – 93 km) zone. The study also excluded 100% of the 0-5 nm (0-9 km) zone near shore. The NREL study also did not use a cutoff wind speed, as this study did.

For comparative purposes, this study found (Table 3) 3,369 MW of capacity (with a 7.0 m/s cutoff) in the 0-20 m depth range (approximately the 0-30 m range used in the NREL study) and 115,423 MW of capacity in the 20 m-200 m depth range (approximately the “deep” range for the NREL study). The NREL study did not include an energy output approximation, so it's not possible to compare the overall energy output of the offshore wind potential unfortunately. Further, the NREL study was done at the 50 m turbine height, compared to the 80 m turbine height of this study. Though the methodology and assumptions differed significantly, both this study and the NREL study concluded similar orders of approximation for the capacity (within 27% for the shallow water and within 156% for the deep water).

## ***Temporal Analysis of Offshore Wind***

The time of day when wind power peaks is important because the summer peak electric demand occurs late in the afternoon, around 5:00 pm [Price, H. and Cable, R., 2001]. In order to analyze how offshore wind energy might fit into California's electric grid, a sample wind park in Northern CA was created. Figure 7 shows one example park, located in some of the best offshore wind in California. The 80 m wind resource we modeled for this proposed wind park is extremely steady throughout most hours of the day and only slows from about 9 m/s to 7 m/s late in the afternoon during the July 2005 modeled month; still an excellent wind resource overall. Using Equation 1, with the modeled annual average 80 m wind speed of 8.1 m/s, we find a 39% capacity factor for this wind park. Using the same methodology to calculate turbine nameplate capacity and annual energy output, this project alone could produce 9.7 TWh annually, with a 2,385 MW nameplate capacity. This wind park alone could replace 5.6% of California's current carbon emitting electric generation.<sup>5</sup>

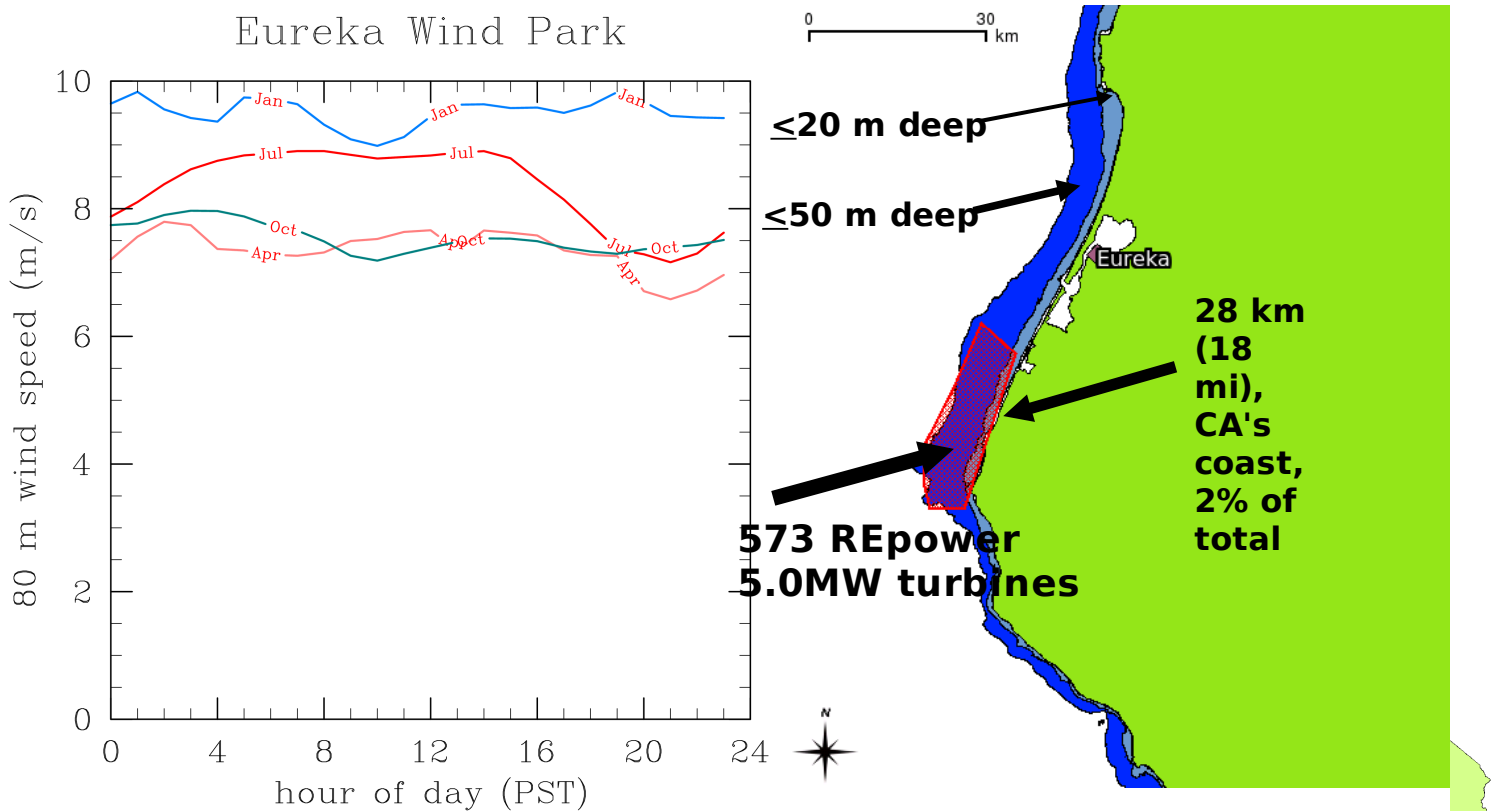


Figure 7: An example wind park off the Northern California coast with average hourly (PST) wind speeds shown on the graph. The winds at 80 m blow continuously throughout the day, most importantly at peak electricity demand times.

## Conclusions

Despite the steep bathymetry off the California coast, significant development potential exists for offshore wind. By looking at the depth of the water more closely, with a higher resolution bathymetry dataset, it was possible to find some areas that were overlooked for offshore wind power development in a previous study. This study also qualitatively looked at transmission capacity and population centers to build a context for the offshore wind resource in California. We found that Northern California had the best 80 m wind resource but has the least transmission capacity. Some of Northern California's resource could be developed today, using existing turbine support technology.

The San Francisco Bay Area however, will more than likely require the development of floating turbine support structures for large scale offshore turbine development. Southern California's wind resource is significantly reduced during the summer months, due to the location of the Pacific High. More in-depth modeling and validation needs to be undertaken to learn exactly what times of the year and in what locations the wind resource subsides in Southern California.

In sum total, based on the 80 m wind speed cutoffs of 7.0 m/s and 7.5 m/s, between 26% and 112% respectively of California's electricity needs could be

provided with offshore wind energy alone [CEC, 2007].

## **Acknowledgments**

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