Analysis of Factors Affecting Wind Turbine Power Density

Jacob Braslaw, Gabrielle Skow, Jack Holbrook – University of California, Santa Barbara

Introduction

Wind turbines are becoming a larger part of the energy sector. As of 2018, wind power generated more than 7.2% of California's electricity [1]. This percentage is going to increase due to the California passing Senate Bill 100 which states that 100% of electricity in California will come from zero-carbon energy resources by 2045 [2]. To meet this goal wind turbines and other renewable energy resources will have to take the place of current fossil fuel power plants.

Renewable resources require more land than their fossil fuel power generating counterparts because of their lower capacity factors [3]. As California looks to meet their energy demands with a conglomerate of renewable resources, wind turbines included, concerns are starting to arise about how much land will be needed [4]. To help mitigate this issue our project focuses on factors that affect the power density of wind turbines. Power density is a metric for describing how much energy is generated per unit of land and consists of the units watts per square meter of land [5]. From this study we aim to understand what factors lead to a higher power density, thus requiring less land consumed to meet California's energy demands.

Research Questions

- What are the effects of land and turbine attributes on wind turbine power density?
- Given findings from research question 1, where is a suitable region in Kern County to install a wind farm?

Data and Site Location

Data

- Gathered from 4 sources

1)US Wind Turbine Data Base
2) 3 meter DEM
3)Soil
4) County of Kern: Open GIS Data

Study Location

- Southern California, defined by less than 36 degrees latitude.
- Suitable region located within Kern County

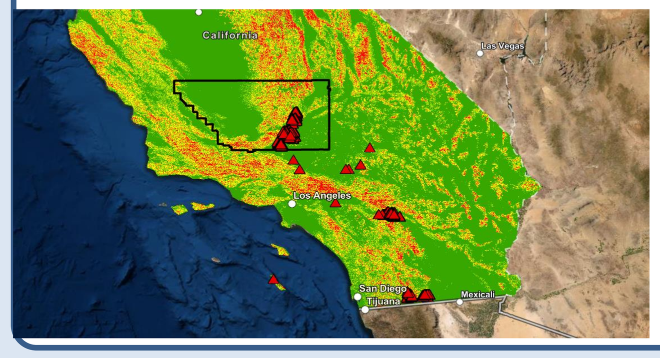
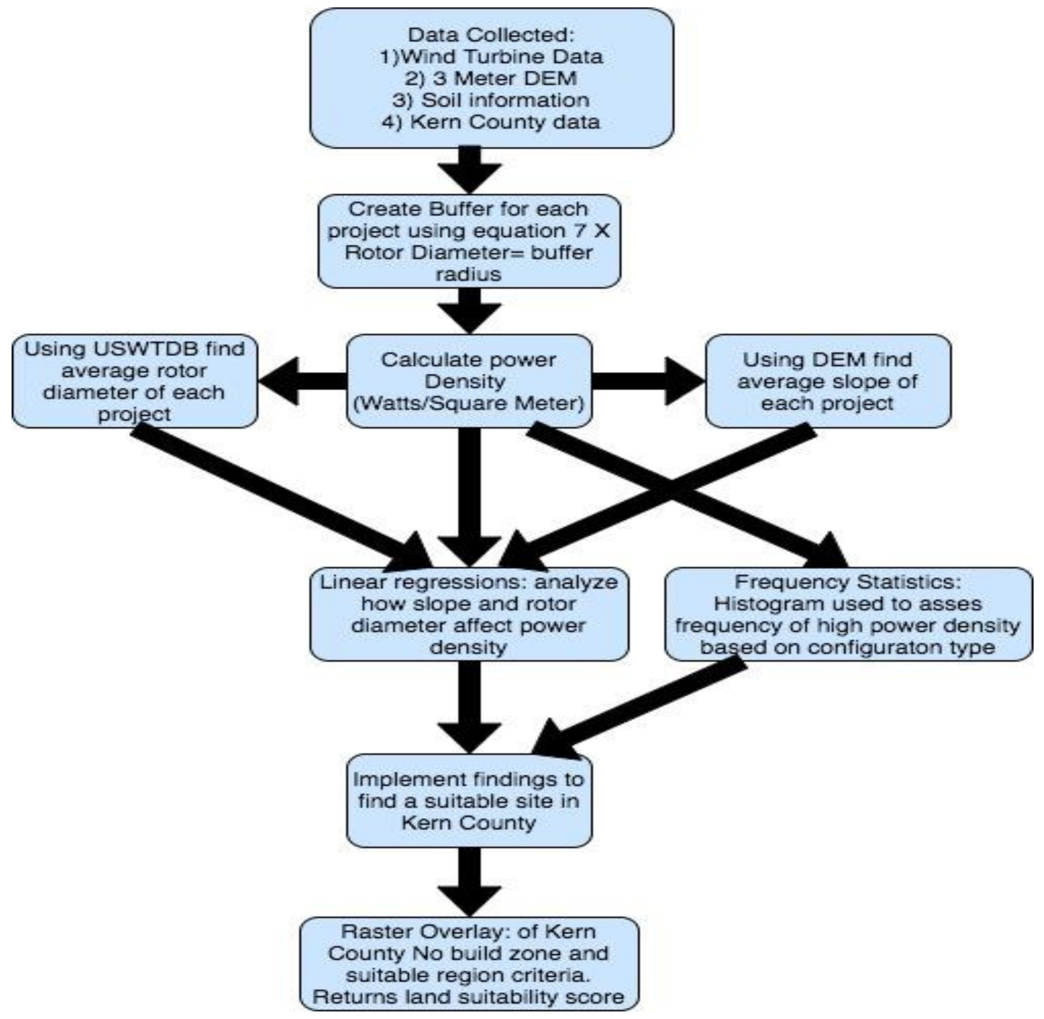


Fig 1. Map of Study region. Kern county boundary lines in black. Points indicate turbine locations.

Methods



Factors Affecting Power Density

Analyzing Slope

Methods:

1. United States Geological Services provided us with a 3-meter DEM layer that we converted to raster
2. Once converted to raster, the slope tool is used to create a slope layer measuring slope on a scale from 0-90 degrees.
3. Zonal Statistics were then used to find the mean, max, and min slope of each project
4. Line of linear regression ran that compared average slope to power density

Slope Results:

The line of linear regression shows that there is a positive correlation between slope and power density. This analysis is statistically significant with p and F-values of less than 0.05. Therefore, we concluded that slope does affect power density. The line of linear regression also shows that there is a drop in power density when slope is greater than 20 degrees so we concluded that the placement of our turbine within Kern County should be on a slope of 20 degrees or less.

Analyzing Rotor Diameter

Methods:

1. US Wind Turbine Data Base provided us with rotor diameter values for 5,000 of the 5,958 turbines we studied.
2. Given strong linear correlation (R^2=0.84) between turbine capacity and rotor diameter we used line of best fit to estimate the values of the 1,000 missing entries.
3. Using select by attributes each project allowed wind turbines to be grouped to the project name they belonged to.
4. We ran a linear regression comparing rotor diameter to project power density

Rotor Diameter Results:

The linear regression yielded a negative correlation between rotor diameter and power density. The analysis of the data set proved to be statistically significant with both p-value and F-value <<0.05. The regression was adjusted removing turbine projects that had two or less total turbines. This was done to increase the buffer model's ability to accurately capture land use. The regression resulted with a R^2 value = 0.149. Our regression analysis showed us that 14.9% of power density can be explained by the average rotor diameter size of the project.

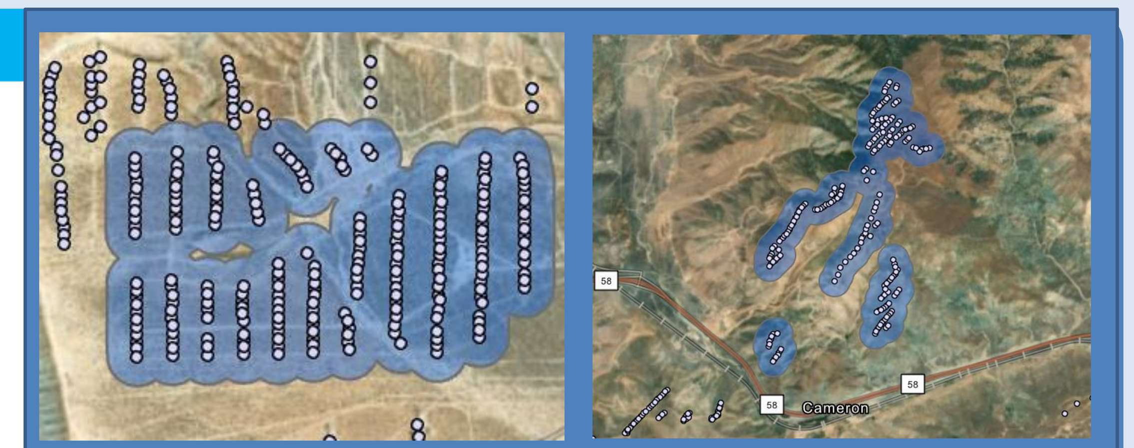


Fig 2. Tehachapi 2 Wind farm (3.1 w/ m^2) , left. Wintec Wind farm (9 w/m^2) , right. We want to find why power density varies so much.

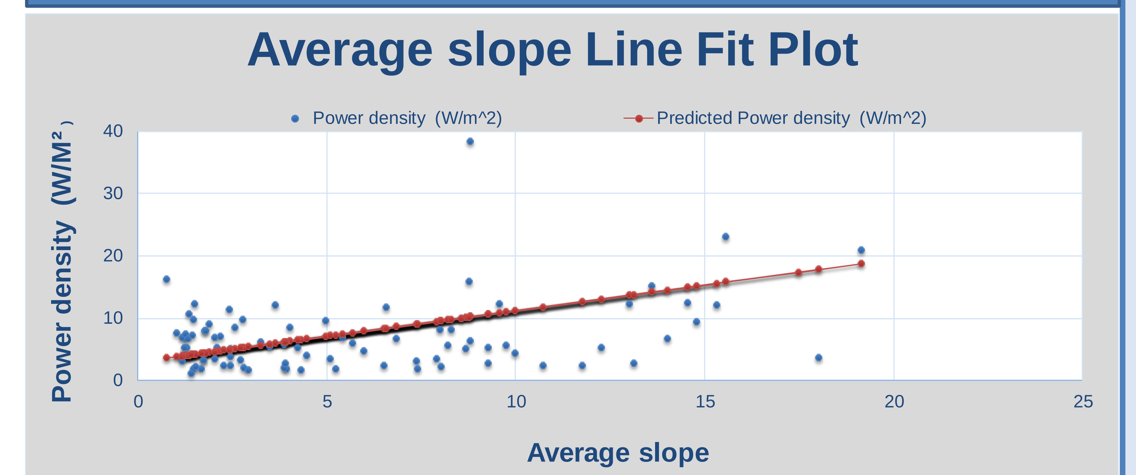


Fig 3. Linear regression showing the trend of slope increasing until 20 degrees, the maximum slope that turbines are built on.

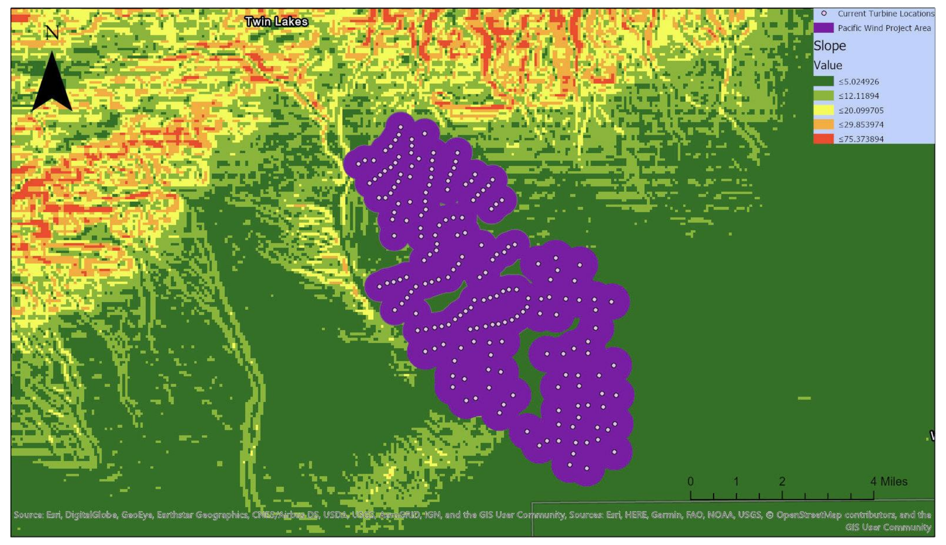


Fig 4. Turbine project Pacific Wind Buffer overlayed on slope data layer to find average slope of the land contained in the buffer.

Locating A Suitable Region in Kern County

Methods:

1. We created a no build raster layer by using union tool of the following layers which represented occupied land

a) Cities and cities unincorporated.
b) Farm Land
c) Critical Habitat Zones
d) Slope greater than 20 degrees
e) Wind less than grid value 3 (6m/s)
f) SSURGO soil Database soil type data

2. We used an overlay of slope and wind data sets then reclassified into values 0-6.

3. Then using clip raster we were able to find suitable regions that are not in the no build zone. The suitable regions are on a scale of 0-6, 6 being most suitable.

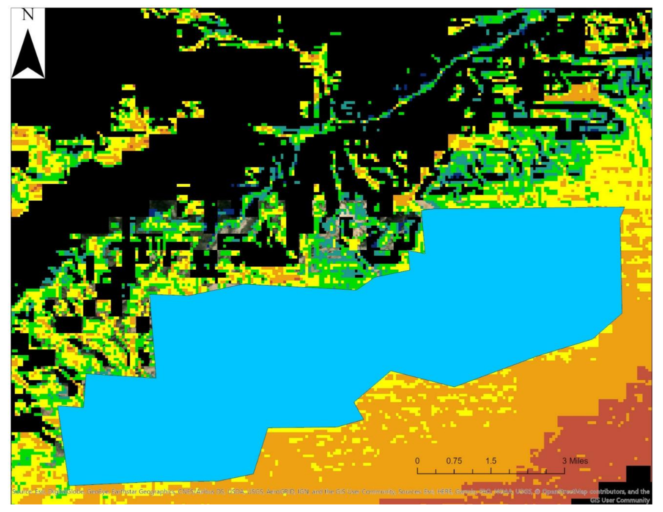


Fig 5. The selected area of land chosen as the most suitable site for our project. Region is larger scale of fig 5.

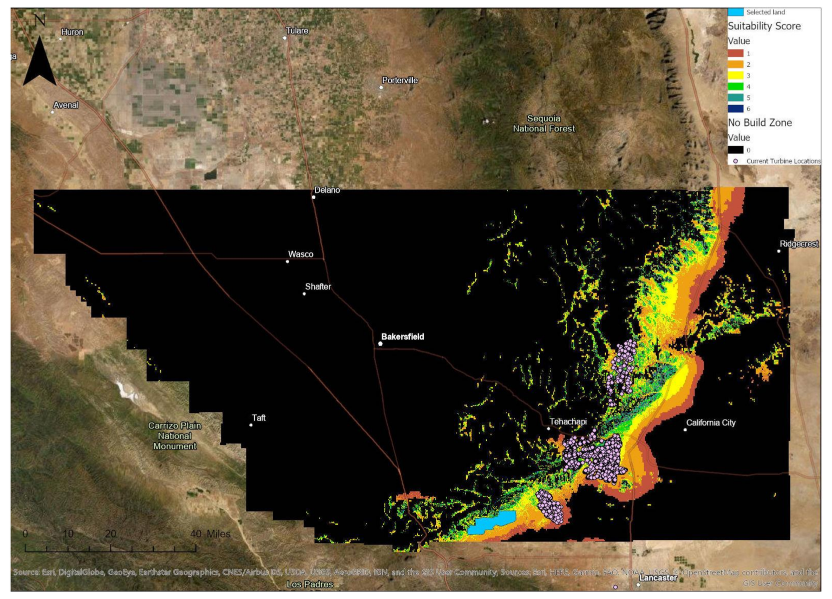


Fig 6. Raster overlay results. Black shows land that is not suitable. Colored pixels show suitable sites

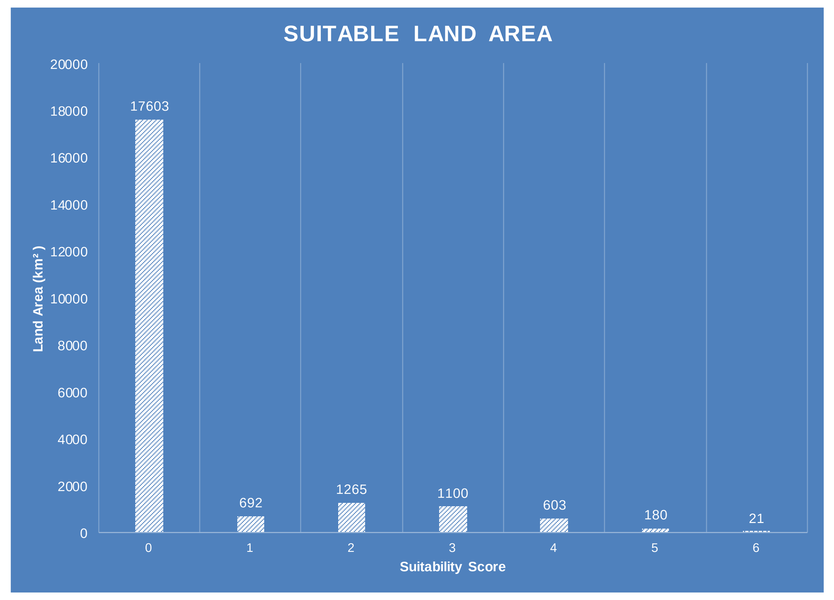


Fig 7. Bar graph showing area of land per suitability score

Results: Our overlay returned 3864 km² total suitable land. This is 18% of Kern County total area. The area we deemed to be the most suitable is 86.25 km². This region consists of land that is valued at a suitability score of 3, 4, and 5.

Using findings from rotor diameter analysis and configuration type we recommend that the rotor diameter be 20m and configuration of the turbines be polylines. Using linear regression from fig 3., this will yield a power density 11.01 W/M².

A project on this land is expected to have a rated capacity of 949.62 MW, when accounting for capacity factor that is generally 30% the realistic capacity is 284.88MW. Total energy created per day is 6837.26 MWh.

Given that California's average energy home usage 30 kWh per day, the energy produced by our recommended turbine facility could power up to 224,172 households.

Discussion

Two separate datasets were used to compute the regressions used in the determination of power density. One dataset included records for each individual wind turbine while the other dataset included only a single record as a summary for each wind project. Because of the large difference between the correlation of turbine capacity to turbine rotor diameter and the correlation of project's mean rotor diameter across turbines to its power density It was concluded that spatial analysis could better predict the amount of energy generated from a single turbine based off its spatial footprint rather than a group of turbines. This is due to the lesser value of correlation found when rotor diameter and power density were regressed. The assumption behind the regression being that rotor diameter affects power density since wind turbines tend to affect the airflow around them by about seven times the distance of their rotor diameter. Since disrupted air yields less power to surrounding turbines, power density most likely decreases as a function of the proximity of wind turbines to one another.

The configuration of wind turbines was also analyzed. No single configuration showed a net optimal power density. Further research could be done that breaks down the groups of different configurations by binning turbine capacities, rotor diameters, and the area of each wind project. A problem anticipated with this approach is that the amount of data sub-setting wouldn't allow for enough records in each subset to confidently determine which configuration achieves the greatest power density. Since some configurations, such as a single line of turbines are also asymmetric in nature, the direction of the wind may also affect the power density possible for the turbine arrangement. Independent of the turbine's arrangement, it had been hypothesized that a greater land footprint would lead to a lesser power density, it was discovered during this project that attributes specific to individual turbines and their location such as slope play an important role in determining a project's overall power density. A limitation that the group experienced while Evaluating wind project power density is that records used for project level regressions were aggregated on a per project basis. Projects that consisted of a few turbines were assigned the same weight as projects with a few hundred turbines. The end effect of this was the increased amplification of noise in the dataset that was examined. Because of the nature of how the area for each wind project was determined, there were only records for project area which was used to calculate project power density on a per project level and not a per turbine level. It could be possible to calculate power density on a turbine level, but this would result in hundreds of duplicate values that would not improve the project's summary statistics.

Despite this shortcoming, the data was usable for planning a future project near to existing projects in one of California's best wind resource areas. Data laid over the wind turbine feature class identified areas where wind resources had not yet been utilized. Statistics from the regressions run over existing wind turbine plants indicated optimal turbine size for a future wind project. This will yield a wind project with higher than average power density while also being the largest capacity wind project made in the area to date.

Acknowledgements:

We would like to thank Professor Krzysztof Janowicz for his guidance throughout the UCSB Geography 176 series. We would also like to thank Meilin Shi for her help during office hours allowing us to complete the project. Finally we would like to thank Professor Robert Heilmayr for providing past labs that exemplified statistical analysis used in GIS.

Literature Cited:

1. "Fast Facts about California Wind Energy." CalWEA, California Wind Energy Association, 2020, www.calwea.org/fast-facts.
2. "Bill Text." Bill Text - SB-100 California Renewables Portfolio Standard Program: Emissions of Greenhouse Gases., leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100.
3. OKULOV, V., & SØRENSEN, J. (2010). Maximum efficiency of wind turbine rotors using Joukowsky and Betz approaches. Journal of Fluid Mechanics, 649, 497-508. doi:10.1017/S0022112010000509
4. Zalk, John van, and Paul Behrens. "The Spatial Extent of Renewable and Non-Renewable Power Generation: A Review and Meta-Analysis of Power Densities and Their Application in the U.S." Energy Policy, Elsevier, 25 Aug. 2018, www.sciencedirect.com/science/article/pii/S0301421518305512?via=ihub.
5. J.T., Kramer, L.A., Garrity, C.P. et al. A continuously updated, geospatially rectified database of utility-scale wind turbines in the United States. Sci Data 7, 15 (2020). doi:10.1038/s41597-020-0353-6