Modeling Wind Resources for Harnessing Potential Energy at UC Berkeley

Rachel Walshe Kane

Abstract Energy demand is increasing, greenhouse gas emissions are beginning to have devastating effects, and the feasibility of fossil fuels is uncertain in the long-term. In this context, wind is an attractive alternative renewable energy source. However, before installing a wind turbine to harness energy, the available wind resources and their potential power yields should be determined. The University of California, Berkeley is working to reduce its negative environmental impacts and maximize its use of available renewable resources, such as wind. My research assesses whether the University has sufficient wind resources on campus to make wind a viable energy source. I used archived wind speeds from 2005-2007 and GIS computer algorithms to interpolate a wind distribution of the campus property. I calculated the power density for all locations with sufficient wind speeds and the maximum power yields using Betz's equation. My resource distribution maps indicate that although most areas lack sufficient wind speeds, some locations in the hill area east of campus can support a turbine. These findings refine larger scale studies, thus indicating the importance of site-specific resource assessments.

Introduction

Wind as a renewable energy source may provide a viable alternative to fossil fuels. Beginning with the Industrial Revolution of the 19th century, the increasing energy demand has been largely met by fossil fuels (Demirbas 2008). However, their combustion releases greenhouse gases, which are linked to climate change, air pollution, and the depletion of the ozone layer (UNDP 2000). Furthermore, since fossil fuels are a non-renewable resource, our energy demand will eventually surpass our limited supply (Demirbas 2008). This impending shortage threatens almost all aspects of our modern life (Kammen 2008). Reductions in energy use and the implementation of renewable energy can curb the detrimental effects of fossil fuels while continuing to fulfill the demand for energy services. Sustainable energy sources, which include biomass, wind, solar, geothermal, marine energies, and hydropower, can balance the fulfillment of human needs with the preservation of ecosystem resources for current and future generations (UNDP 2000). According to wind energy studies, worldwide wind resources are abundant and therefore, offer a large energy potential (Ackermann and Soder 2000). Thus, in suitable locations, wind may provide favorable power yields.

California has abundant natural resources, including wind, and a precedent for utilizing them for renewable energy. According to the California Energy Commission, 11.8% of California’s electricity came from renewable resources in 2007. In 2002, California implemented the Renewable Portfolio Standard program with the goal of increasing renewable energy to 20% by 2020. The state has become increasingly ambitious, improving this percentage every couple of years. In 2008, Governor Schwarzenegger issued an Executive Order increasing the requirement to 33%. The California Energy Commission is responsible for meeting these statewide goals.

Wind has a long history of providing power. Humans initially used wind as a source of power for moving ships and pumping water. In 1891, the Danish scientist Poul la Cour developed the first wind turbine to generate electricity (Masters 2004). By the 1930s and 1940s, rural areas throughout the United States had established hundreds of thousands of electricity generating wind systems. These small capacity systems were free standing, or not connected by a grid (Masters 2004). The 1970’s oil crisis spiked interest in wind energy, which grew to focus on large-scale potential (Ackermann and Soder 2000). This led to the development of wind farms comprised of large, grid-connected wind turbines. As these systems require large open spaces, they are found in rural areas where they harness energy and transport it for use. This is somewhat inefficient because energy losses occur during transportation.

Still, medium and large sized wind turbines are the most commonly implemented; they have a power output greater than 100 kilowatts (kW) and are often grid-connected (Ackermann and Soder 2000). The average grid-connected utility scale turbine has a power output of about 1,500 kW with a rotor diameter of 66 meters (m) on top of a 200 m tubular tower (UNDP 2000). The total power produced by a wind farm in North America is typically greater than 50 megawatts (MW) (Ackermann and Soder 2000). While Europe is developing offshore turbines due to limited land space, North America is focusing on land-based turbines due to the large potential found onshore (Ackermann and Soder 2000).

With the success of large-scale wind energy, recent developments have returned to small wind turbines for private use. A small wind turbine constitutes a system of 100 kW or less and is also referred to as “distributed wind” or “small distributed wind” (NREL 2009, elect. comm.). Similar to the use of solar panels for single buildings, distributed wind provides power for residential or small industrial applications, thereby reducing intrusions into rural areas and eliminating the transportation of utility wind energy (Mertens 2002). The National Renewable Energy Laboratory (NREL), along with the U.S. Department of Energy (DOE), is working on small wind projects to increase the number of distributed wind turbines. In response to growing consumer demands, research is underway to improve commercially available small wind turbines (NREL 2009, elect. comm.). These systems vary in design; generally, their tower heights range from 18 to 30 m with rotor diameters of 7 to 15 m (NREL 2009, elect. comm.). These are much smaller than utility turbines but still require some open space, complicating their integration with the built environment.

Currently, the scientific community is moving forward with designs for urban environments. Space for a turbine tower is limited in urban areas due to building density. As a solution, building mounted turbines can achieve the necessary height without wasting space. However, placing wind turbines in the vicinity of buildings introduces design complications due to interactions between wind patterns and buildings (Mertens 2002). Wind speeds near the top and sides of a building generally increase by about 20% from that of the undisturbed wind speed further from the building (Mertens 2002). Machines that are mounted directly onto a building can potentially utilize the increased wind speeds next to the building. It is economically beneficial to place the turbine on an already existing structure, thus eliminating the cost to build a tower.

Private wind turbines can be beneficial both economically and environmentally. While start-up is expensive due to installation costs, wind turbines can reduce electricity bills (Entegrity 2008). According to the U.S. Energy Commission, wind energy costs about \$0.04 to \$0.06 per kilowatt hour (kWh) and is the cheapest renewable energy technology (DOE 2008, elect. comm.). In environments where wind is sufficient, turbines potentially provide better economic savings per kWh than solar panels (Mara 2007). Private wind-generated electricity also reduces the demand on utility systems that get their energy primarily from fossil fuel plants (Asmus *et al.* 2003). Thus, the implementation of distributed wind turbines benefits the individual owner as well as society as a whole.

Before installing a wind turbine, it is important to assess its potential costs and benefits by determining the theoretical wind energy potential for the desired location. Turbines harness wind power by converting the kinetic energy from moving air masses, which are driven by solar radiation, into electricity (UNDP 2000). Betz's equation[1] accounts for the maximum theoretical power that can be harnessed from the wind (Ackermann and Soder 2000). From this equation, we can determine the effects of the wind and turbine characteristics. Area, and therefore power, increases exponentially with turbine blade diameter[2]. Thus, larger wind turbines are more efficient in harnessing wind power. There is an obvious advantage to greater wind speeds, but since power increases exponentially with wind speed (Fig. 1), the use of average speeds can be misleading. Often, the potential power found from a wind average is far less than from a wind speed probability distribution (Masters 2004). Air movement is greatly affected by the friction it experiences

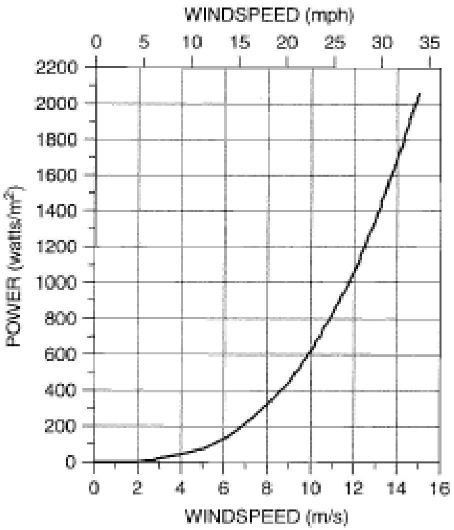

Figure 1. Power in the wind, per m^2 of cross sectional area (Masters 2004).

---

[1] Betz's equation for Power (W): $P = \frac{1}{2}\rho v^3 A C_{Betz}$

[2] Area: $A = \Pi\left(\frac{D}{2}\right)^2$

from the land beneath it; thus, air flowing over built environments, which have a higher friction coefficient, tends to speed up (Masters 2004). These influencing factors should be considered when assessing the potential yields and feasibility of installing a turbine in areas with potentially sufficient wind resources.

The University of California, Berkeley (UCB) is concerned with reducing its negative environmental impacts. In its efforts towards a more sustainable campus, the University is interested in utilizing available renewable energy resources. As it is uncertain whether private wind turbines are a viable energy option on University property, UCB needs to gage the energy potential on its campus. A wind analysis including the average wind speeds for various heights throughout the campus will enable the calculation of the wind power density. I intend to provide the data and conclusions for the campus wind energy potential. My findings will ideally aid the University to progress with the implementation of the alternative energies best suited to its resources and needs.

My research has two objectives: (1) to determine the available wind resources on campus and (2) to assess the potential power output of the available wind resources and, in conclusion, determine whether or not they are sufficient to support a wind turbine. This study modeled the wind distribution over University-owned property and the subsequent estimation of the potential energy yield from Betz’s potential power equation to determine the potential for installing wind turbines. I considered two factors of suitability: ‘Are the wind speeds high enough to warrant the installation of a turbine?’ and ‘Is the physical environment able to support the necessary wind turbine?’ I did not expect the main University campus to be favorable for harnessing wind energy or supporting a large enough wind turbine. I did expect any University property suitable for supporting a wind turbine would be up on the eastern hill above the main campus. I expected to rule out wind energy as an optimal alternative energy for UCB, thereby, encouraging the University to focus its efforts on developing another better suited renewable energy source.

The wind analysis was done through GIS, utilizing ArcGIS to interpolate wind speeds from already existing data and determine the wind distribution. From these resource maps, I calculated the corresponding theoretical potential energy.

Methods

Methods and Objectives To determine the available wind resources, I used archived wind data and computer algorithms to interpolate a wind distribution on the University campus. Subsequently, I created a model for the potential power outputs for the wind speed distribution. Using these findings, I determined the most suitable locations to harness wind energy.

Study Site The study site for this project was the University of California, Berkeley in the east San Francisco Bay of Northern California. I examined the main campus and University owned property east of campus including the Lawrence Berkeley National Laboratory and the hill area. I collected archived wind speed data from Met stations throughout the San Francisco Bay Area. The raw data spanned three years, from January 2005 to December 2007.

Procedure The first step in assessing the potential wind energy is to determine the available wind resources. I collected existing wind speed data, as wnd files spanning three years, from Met stations on and near the campus. Each wnd data file contained the measurement location, air pressure, temperature, direction from which the air blows, and the wind speed. The measurements were taken each hour of every day. I inputted the data for each day into Microsoft Access and calculated the annual wind speed averages at each measurement location. Since wind speed increases with height, and higher speeds contain more energy, the wind speed averages at each station were interpolated to three different heights: 10, 30, and 50 m. To account for the influence of surface friction on wind speed, I used the following equation to calculate wind speeds at different heights (Masters 2004):

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^{\alpha}$$

v = velocity at height H; v_0 = velocity at height H_0; α = friction coefficient;
H = height interpolating to; H_0 = initial height

I estimated a friction coefficient of 0.35 for urban and forest terrain (Masters 2004). The resulting data file containing annual averages at the three heights for each station was added into ArcGIS and projected onto the Universe Transverse Mercator Coordinate System from the 1983 Zone 10 North American Datum. Next, I interpolated a raster dataset for the wind distribution of the study site. Inverse Distance Weighted (IDW) is a widely used interpolation method for wind studies (Martin and Palomino 1994). An IDW is governed by the geographic theory that objects close together tend to be more similar (Luo *et al.* 2007). In a study comparing spatial interpolations of wind speeds, Luo *et al.* (2007) found cokriging to be the most accurate interpolation tool because it accounts for two variables, speed and elevation. However, cokriging did not increase the variability or detail of my findings, so I used IDW algorithms. Using the ArcGIS IDW tool, I interpolated the wind distribution with a 30 m cell resolution for each height.

After completing the wind distribution, the available wind resources were assessed for their potential energy yields. I used the Raster Calculator tool in ArcGIS to calculate a power density distribution from my wind speed data. This distribution map is also a raster dataset with a 30 m cell resolution. Since wind speeds should be at least 17 to 20 kilometers per hour (km/h) to justify the installation of a wind turbine (AWS Scientific Inc. 1997), I calculated a power density distribution for all locations with wind averages equal to or greater than 17 km/h. Electricity is measured in power, which is energy per unit time. Power density is energy per unit time per area; calculations were done in Watts per m^2 (W/m^2). Air density and the wind velocity determine power density:

$$\text{Power Density} = \frac{1}{2}\rho v^3$$

ρ = density of air; ν = velocity

For air density, I used a nominal sea level value of 1.2 kilograms per m^2 (kg/m^2) (Casillas 2009, pers. comm.). A power density distribution is useful because the power output for any turbine can easily be calculated from it. Power calculations were done in kilowatts (kW). Along with air density and wind velocity, swept area of the wind turbine determines power. To calculate the maximum potential yield of a turbine, I used Betz's equation, which accounts for inevitable energy loss with Betz's constant:

$$P = \frac{1}{2}\rho v^3 A C_{Betz}$$

$$\mathrm{A} = \Pi\left(\frac{D}{2}\right)^2$$

P = power; ρ = density of air; A = area; ν = velocity;
D = diameter of swept area; $C_{P\ Betz}$= Betz's constant = 0.59

Power is proportional to the swept area of the turbine's rotor. I considered the energy potential for a small horizontal axis turbine with a rotor diameter of 15 m; these are the same specifications as the EW50 turbine, a commercially available small wind turbine system sold by Entegrity (2008). Since the area of such a turbine is equal to the area the blades cover throughout their rotation, the potential wind power is proportional to the square of the blade diameter. The power harnessed at a given wind speed increases exponentially with the diameter of the turbine rotor. To calculate the annual energy output, I multiplied the power output, which is energy per time, by one year. This was measured in kilowatt hours (kWh).

After completing the wind speed and power datasets, I overlaid a map of the buildings within the study site to assess the environment's ability to accommodate a turbine. The final datasets were displayed as distribution maps in ArcGIS.

Techniques of Analysis ArcGIS 9.3 software enabled the wind speed and potential power distributions to be viewed clearly through map overlays. Based on this data, I drew conclusions for the suitability of harnessing wind energy on campus.

Results

At a height of 10 m, the wind speeds ranged from about 5.5 to 11.1 km/h throughout the study site (Fig. 2). The wind speeds increase from west to east, with the highest wind speeds occurring in the hill area east of the main campus. However, the interpolated winds remain below the speed of 17 km/h and thus, are not sufficient to support a turbine.

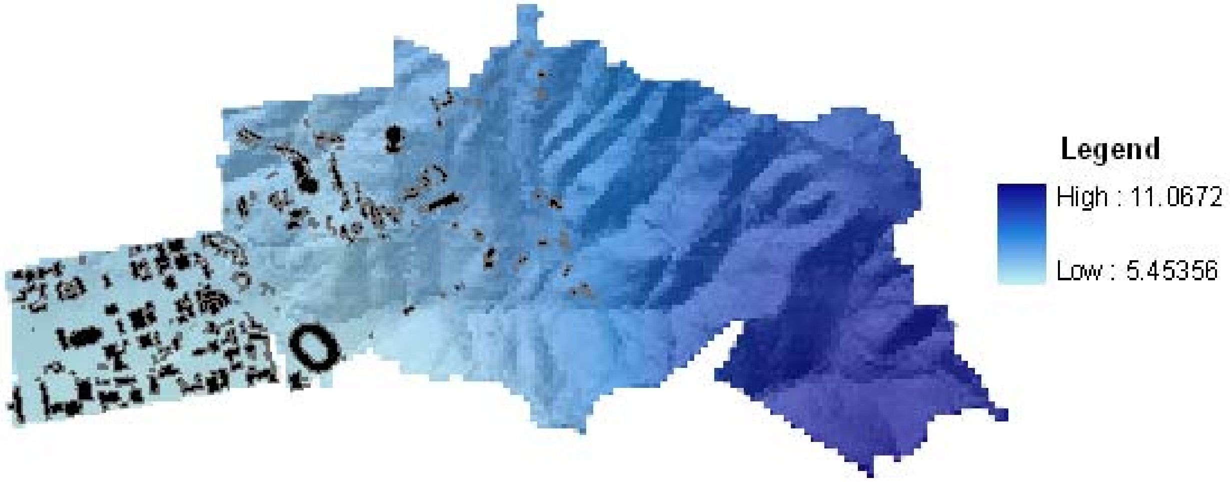

Figure 2. Average Wind Speeds (km/h) at Height of 10 m. No locations with recommended wind speed of 17 km/h.

At a height of 30 m, the wind speeds ranged from about 8.0 to 16.3 km/h (Fig. 3). These speeds increase from west to east and are insufficient for a turbine.

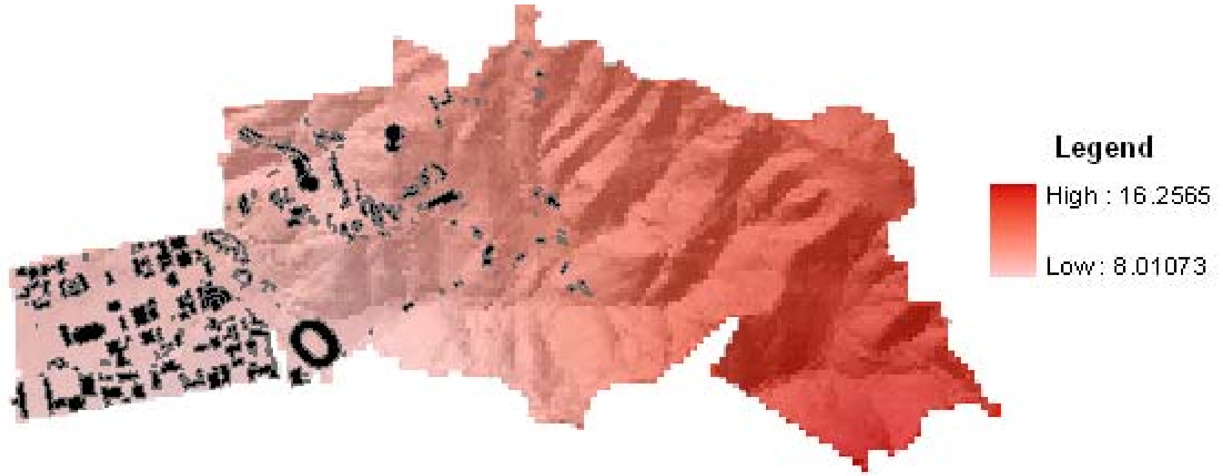

Figure 3. Average Wind Speeds (km/h) at Height of 30 m. No locations with recommended wind speed of 17 km/h.

The wind speeds ranged from about 9.6 to 19.4 km/h at a height of 50 m (Fig. 4). Of a total 4.9 km^2 area, an 0.82 km^2 area has average wind speeds equal to or greater than the recommended 17 km/hr. This area is located in the eastern most hills of University property.

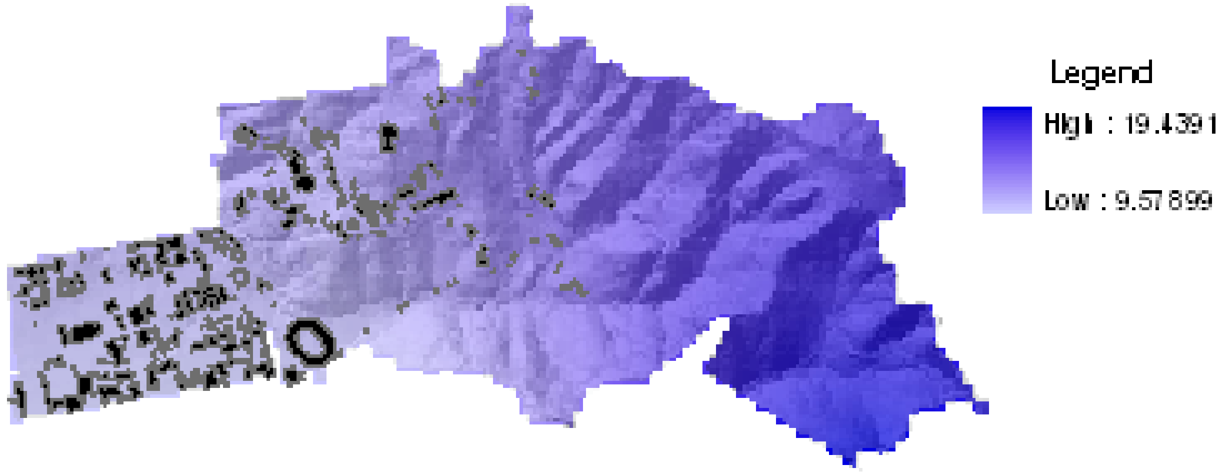

Figure 4. Average Wind Speeds (km/h) at Height of 50 m. Total area is 4.9 km^2. Area with recommended wind speed of 17 km/h is 0.82 km^2.

I calculated the power density distribution for wind speeds at a height of 50 m (Fig. 5). For locations with wind speeds equal to or greater than 17 km/h, the power density ranged from about 63.0 to 94.5 W/m^2. From Betz's equation, the maximum power output of a single small turbine is 9.8 kW. This corresponds to a maximum annual energy output of 86,000 kWh.

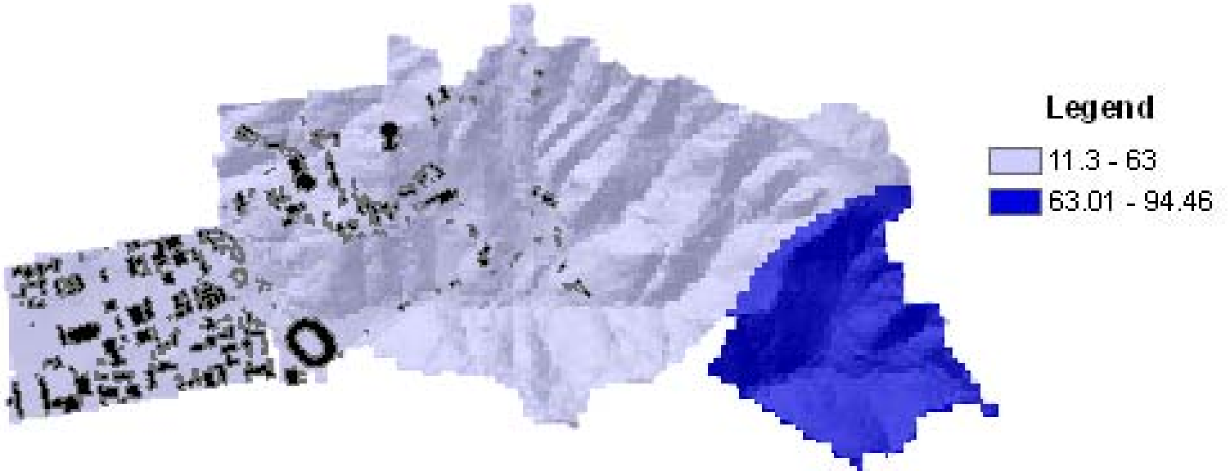

Figure 5. Power Density (W/m^2) Outputs for Small Turbine (Diameter = 15 m) at Height of 50 m. Wind Speeds of 17 km/h and greater are in dark blue. Total area is 4.9 km^2. Area of dark blue region is 0.82 km^2.

Discussion

As expected, the only areas with sufficient average wind speeds greater than 17 km/h were found to in the hills east of the main campus. No areas on the main campus were found to have sufficient annual average wind speeds to support a wind turbine. The region with suitable winds is mostly undeveloped, with no buildings, one road, and steep, forest terrain. The region with suitable wind speeds constitutes a 0.82 km^2 area of hills covered in trees, shrubs, and grasses. This area contains the space to support multiple freestanding wind turbines. The lack of buildings in the only suitable region indicates building mounted turbines are not an option for the University. However, since wind speeds can increase next to buildings, further examination of the complex relationship between wind and the built environment may reveal locations suitable for building mounted turbines despite the generally low average wind speeds in the vicinity of University buildings. Overall, my wind resource maps indicate a poor wind regime on University property. While the hills at the east end of the study site provide the best opportunity for supporting a wind turbine, the power yields would be minimal.

Whether or not the opportunities for harnessing wind energy will render economic or emissions savings may be assessed before installing a turbine. Based on the economic analysis performed by Entegrity Wind Systems, Inc. (2008)`` for the University of California, Berkeley at the Richmond Field Station, a 50 kW turbine installed at the site could provide a first year savings of $8,400 and projected savings over 30 years from lower average wind-based energy costs than utility-based energy costs. The estimate was based on the Richmond Field Station's average wind speed of 17.76 km/h. The maximum wind speeds on my study site were similar and so suggest comparable economic energy savings. The estimated cost of installation is $211,500; however, grants are available to reduce the University's direct cost to $121,000 (Entegrity 2008). With these costs and savings, Entegrity (2008) estimated a pre-tax payback period of 12 years. Costs would be increased for my study site because the best-suited location is somewhat isolated. The energy would have to be transported for use, whereas wind energy produced at the Richmond Field Station would be used on-site (Entegrity 2008). At most, a turbine in the hills could produce 86,000 kWh. Based on UCB's current energy costs, the University spends $8,600 for an equivalent amount of energy (Ahmed 2007). Since wind resources are scarce and the power output minimal, the installation of a turbine would have to be highly motivated by the educational value of having one near campus (Casillas 2009, pers. comm.).

Limitations to my findings stem from the raw wind data and interpolation method. The raw wind data points were dispersed throughout the Bay Area and often not local to my study site. Met stations exist closer to the Berkeley campus. Unfortunately, they do not archive their data, so few local records were available to use in this study. Due to the large distance between data points, the distribution becomes more dependent on the interpolation method. The complexity of wind patterns and their interaction with the built environment requires sophisticated models to accurately predict a wind distribution. While IDW interpolation is commonly used for winds, it is a simple interpolation that does not account for changing elevation or details of the environment. As a result, my resource maps provide general trends and expectations but are limited in their detail and accuracy.

Despite these limitations, this site-specific analysis is more detailed than larger scale regional and state estimates. The California wind resource map created by the DOE's Wind Program and the NREL determines the average wind speeds of the San Francisco Bay Area at 50 meters above the ground to be "Poor" (DOE 2008, elect. comm.). In its Wind Resource Assessment Handbook, AWS Scientific, Inc. (1997) recommends these maps as initial indicators of site potential but advises further assessment before implementation. While my findings suggest an overall poor wind regime, they also identify select areas that could support a turbine. The government's coarse wind data gives a broad wind speed range of zero to 20 km/h (DOE 2008, elect. comm.). This range disregards wind speeds of 17 km/h, which can potentially support a turbine. Thus, my site-specific study found opportunities for harnessing wind energy where a broader, more general study overlooked.

As demonstrated by the campus wind resources, wind speeds can vary over short distances, and thus, rough estimates and averages are inadequate for predicting turbine suitability. The contrasting findings between larger scale wind assessments and my study suggest that a wind analysis must be localized. A wind energy study by Bai and Billinton (2004) supported my findings that "wind speed is highly variable and site-specific." Furthermore, since wind speeds and potential power are non-linearly related, slight differences in wind speed can mean large differences in potential power (Masters 2004). Thus, even small differences in wind speed between a rough estimate and a site-specific estimate could have significant effects on potential power calculations.

In conclusion, institutions or individuals looking to utilize wind power cannot rely on a region's averages but rather, should conduct an analysis for their specific site. Areas assumed to be inappropriate for turbines might actually contain specific locations capable of supporting individual turbines. After establishing turbine suitability, the group or individual involved can then determine the potential benefits, financial and environmental, and make an informed decision whether or not to pursue wind energy. As we attempt to reduce our dependence on fossil fuels, it is critical to know the energy resources readily available in a given location. Accurate assessments will hopefully encourage the employment of alternative energies.

Acknowledgments

Thank you to Christian Casillas for bringing this project to my attention and providing continuous support and encouragement, as well as John Radke for giving me the tools and guidance to complete the interpolation and create my wind resource maps. Also, thank you to the instructors of ES 196, especially Robin Turner and Tim De Chant for their patience and review of my work.

References

Ackermann, T. and L. Soder. 2000. Wind energy technology and current status: a review. Renewable and Sustainable Energy Reviews, **4**:315-347.

Ahmed, F. 2007. Feasibility study 2006-2007 final report. Unpublished report for UC Berkeley Climate Action Partnership. 138 pp.

Asmus, P., K. Fullerton, S. Peterson, H. Rhoads-Weaver, A. Shutak, and S. Schwartz. 2003. Permitting small wind turbines: a handbook. CBE homepage. http://www.awea.org/smallwind/documents/permitting.pdf, accessed April 19, 2008.

AWS Scientific, Inc. 1997. Wind resource assessment handbook: fundamentals for conducting a successful monitoring program. Unpublished report for National Renewable Energy Laboratory. 68 pp.

Bai, G. and R. Billinton. 2004. Generating capacity adequacy associated with wind energy. IEEE Transactions on Energy Conversion, **19:** 641-646.

Casillas, Christian. Ph.D. Candidate, Energy and Resources Group, University of California. 2009, personal communication.

Demirbas, A. 2008. Energy issues and energy priorities. Energy Sources, Part B: Economics, Planning, and Policy, **3:**41-49.

Entegrity Wind Systems, Inc. 2008. Wind turbine project analysis for the Richmond field station. Unpublished report for University of California, Richmond Field Station. 3 pp.

Kammen, D. 2008. Investing in the future: R&D needs to meet America’s energy and climate challenges. United States House of Representative: Select Committee on Energy Independence and Global Warming. Testimony for 10 September 2008 hearing.

Luo, W., S. R. Parker, and M. C. Taylor. 2007. A comparison of spatial interpolation methods to estimate continuous wind speed surfaces using irregularly distributed data from England and Wales. International Journal of Climatology, **28:** 947-959.

Mara, J. 2007. A windmill will lower your bills but might not win over the neighbors; city planners, community associations loom as foes of single-home turbines. Contra Costa Times, p. F14.

Martin, F. and I. Palomino. 1994. A simple methods for spatial interpolation of the wind in complex terrain. Journal of Applied Meteorology, **34:** 1678-1693.

Masters, G. 2004. Renewable and efficient power systems. John Wiley & Sons, Inc, New York. 680 pp.

Mertens, S. 2002. Wind energy in urban areas. REFOCUS, 22-24.

National Renewable Energy Laboratory (NREL). 2009. NREL World Wide Web site, Small wind turbine research. http://www.nrel.gov/wind, accessed May 4, 2009.

UNDP (Goldemberg, J. Ed.) 2000. United Nations Development Program (UNDP). World Energy Assessment. Energy and the challenge of sustainability. UNDP/UN-DESA/World Energy Council, New York.

U.S Department of Energy (DOE), Energy Efficiency and Renewable Energy. 2008. Wind powering America World Wide Web site, California wind resource map. http://www.windpoweringamerica.gov, accessed March 14, 2009.