ASSESSMENT OF THE WIND RESOURCE AT THE GRACE PACIFIC QUARRY SITE IN KAPOLEI, OAHU

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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Abstract

The goal of this research project is to determine the feasibility of building a wind farm at Grace Pacific Quarry (GPQ) in Kapolei. This location was chosen because wind maps for Oahu suggest that the location of GPQ has a sufficient wind resource for a wind farm. Meteorological data from Grace Pacific Wind Towers were used to analyze the quality of the wind resource at GPQ. The people who work at First Wind in Hawaii were interviewed, and the wind resource at their wind farms was compared with that at GPQ. Finally, the thesis discusses local and political considerations and environmental impact studies needed to assess the feasibility of constructing a wind farm in Hawaii.

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CHAPTER 1 INTRODUCTION

The topic of energy is becoming of more and more concern to society. The total amount of resources to produce electricity in the world is diminishing as we keep consuming non-renewable resources. About 3/4 of total world commercial energy is provided by coal and oil (The Environmental Literacy Council, 2008); therefore, it is essential to find ways to produce more renewable energy. “Renewable sources for generating electricity are becoming more economically attractive than other sources of energy” (Pitiruek, 2011). The power of the wind has been used for more than three thousand years. Wind power was already used to provide mechanical power to pump water or to grind grain before the early twentieth century. And in 1890s, more than 100 windmills which were used for pumping water were produced in United States (Chiras, 2009). Furthermore, wind energy has been used by the ancient Hawaiians. The ancient Hawaiians not only knew how to use wind to go on to their voyages, but also used wind energy in everyday activities, such as sailing for fishing (wwg/ history.html, 2002).

Wind energy has several advantages when compared to other energy resources, such as biofuels, solar, wave, and geothermal energy. Wind energy costs less, does not directly pollute the atmosphere, and is widely distributed compared to other types of renewable energy. Wind energy is able to provide long-term energy. As technology develops, there is a reasonable expectation that the cost of wind energy will be cheaper than fossil fuels, since once the wind power plants are constructed, a stable and clean energy is provided without the cost of fuel or treatment of energy waste.

Development of renewable energy is essential for Hawaii. Hawaii currently has the highest electricity prices in America. 7.5 percent of Hawaii's $63 billion GDP is spent on fuel, close to the same percentage of GDP spent on food (Fessler, 2011). Kapolei has strong prevailing trade winds from NE to SW (Fig.1). Therefore, Kapolei has the potential to develop a wind farm. By producing more energy, Hawaii can be more independent of oil, lower the price of electricity and protect the environment.

There are several reasons for choosing the Grace Pacific Quarry (hereafter GPQ). A study conducted by U.S Department of Energy, using a numerical model, suggests that the wind power density is favorable at GPQ (Fig. 2). GPQ is a relatively flat open area, secure site, and HECO has a transmission station on the south side of the quarry. The Grace Pacific Quarry is a commercial site which means that once the mining at the site has been finished, the land can be used to build a commercial wind farm. The boundary layer is a part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a timescale of about an hour or less (Stull, 1988). Wind turbines are placed in the boundary layer. The boundary layer is affected by frictional influences due to the topographical factors that slow down the wind flow near the earth's surface (Tewari, 1982). The wind speed increases with increasing elevation in the boundary layer (Fig.3). The magnitude of the drag force varies as a function of land surface roughness.

The reduction in wind speed near the earth's surface is due to friction as a result of the surface roughness; and wind velocity profiles are varied for different terrain types (Brown, 2010). For example, rough, irregular ground, trees, and man-made obstructions on the ground will slow down the movement of the air near the surface, and reduce the wind speed (Oke, 1987). A smooth water surface has low surface roughness. When the wind passes through area with a low surface roughness, the wind speed does not rapidly increase with the elevation as it does on land (Lubosny, 2003). Over a city or a rough terrain, the friction effect can cause a decrease of 40% to 50% of the geostrophic wind speed aloft; while over open water or ice, the reduction may be only 20% to 30% (Thompson, 1998). As indicated in Fig. 4 , when the ground is less rough (the grassy area compared to the forest), the wind flow will be faster at the same elevation (California Office of Appropriate Technology, 1983).

To have a quantitative description for the roughness of GPQ, a numerical analysis is performed to estimate the roughness of the location. Roughness length (z_0) is a parameter in vertical wind profile equations that shows the roughness of the surface. It can be calculated to evaluate the surface conditions at GPQ. Wind speed data were collected at two different elevations for one year for the calculation of the roughness length and to compare with the Z_0 values (see Table 2).

There are several different kinds of anemometers to measure winds: Pressure Plate Anemometer, drag sphere anemometer, cup anemometer, propeller anemometer, hot-wire and hot-flame anemometer, sonic anemometers and so on. The anemometers that were available for this project are sonic anemometers (Figs. 5 and 6). Sonic anemometers have better time resolution and a lower wind threshold than cup and propeller anemometers and greater bandwidth than mechanical anemometers (Table 1). Sonic anemometers have no moving parts and are an ideal choice for this project.

Objective

The goal of this research is to provide a quantitative analysis of the wind power resource at GPQ. Once the wind resource has been established, other factors about building a wind farm are considered. These include environment factors, such as noise, bird and bat fatalities, and Hawaiian burial restrictions. Furthermore, permits that are required for wind farm construction and possible government credits will be discussed at the end of this thesis.

CHAPTER 2 METHODOLOGY AND DATA

Methodology

In this research, there are two steps. The first step is to perform a quantitative analysis to evaluate the wind energy potential at GPQ for a one-year record of wind data. To complete the quantitative analysis, we followed the three steps listed below.

i. Calculated Roughness length (z_0) at GPQ

ii. Estimated the wind shear and turbulence at GPQ.

iii. Calculated the wind power density (WPD) at GPQ

Roughness length

At GPQ, wind speeds are measured at two different heights. The wind speed u_1 is measured at height z_1 (at 10 m) and wind speed u_2 is measured at z_2 (at 2 m), and the roughness length is calculated using the following formula:

$$z_0 = e^{\left[\frac{(u_2 * \ln(z_1) - u_1 * \ln(z_2))}{u_2 - u_1}\right]} \tag{2.1}$$

Wind shear

The wind shear is defined as the change in horizontal wind speed with a change in height.

$$v_2 = v_1 \left(\frac{z_2}{z_1}\right)^{\alpha} \tag{2.2}$$

$$\alpha = \frac{Log_{10}\left(\frac{v_2}{v_1}\right)}{Log_{10}\left(\frac{z_2}{z_1}\right)} \qquad (2.3)$$

Where

v_2 = the known speed at height z_2

v_1 = the known wind speed at the height z_1

α = the wind shear exponent.

This formula shows V_1, V_2, Z_1 and Z_2 are related with the α, which the two wind speeds are located at a height of 2 m and 10 m.

The relationship in Eq. 2.2 allows the wind shear exponent (α) for GPQ to be determined. This is useful because the magnitude of the wind shear exponent (α) is influenced by site-specific characteristics, and therefore, must be determined from the data.

Wind Turbulence

A common indicator of turbulence is the standard deviation (σ) of wind speed. Normalizing this value with the mean wind speed gives the turbulence intensity (TI). This value allows for an overall assessment of a site's turbulence. TI is expressed by

$$TI = \sigma/V \qquad (2.4)$$

Where σ is the standard deviation of wind speed; and V is the mean wind speed. (TSI)

Wind Power Density

Wind power density (WPD) is a good indicator of a site's wind energy potential than wind speed alone. It can directly determine cost efficiency in using wind energy. One can calculate WPD by the following formula:

$$WPD = \frac{1}{2n} \square_{i=1}^{n} \rho v_i^3 \quad W\,\mathrm{m}^{-2} \tag{2.5}$$

Where,

n = the number of records in the averaging interval;

ρ = the air density (kg m^{-3});

v_i = the value of the i^{th} wind speed (m s^{-1}) .

After that, daily averages of WPD can be calculated, and then an annual cycle of WPD is plotted by using the daily average. The results will be plotted through the Matlab software. According to the results, it is possible to see how the wind energy potential of GPQ and the possibility of building the wind farm at GPQ.

In the second steps, some political considerations and environmental impact studies in relation to the feasibility of constructing a wind farm in Hawaii will be discussed. A written interview was given to the first wind company to get information about permits that are required for a wind farm construction, as well as possible government credits.

Data

Meteorological data obtained from Grace Pacific for their site 1 (Fig. 2). Data were recorded every minute, from April, 1 2010 to April 1, 2011. The data includes wind speed (m s^{-1}) at 10 m, mid wind speeds (m s^{-1}) at 2 m, pressure (milibar) and air temperatures (Celsius degrees). By using two wind speeds that are located at different heights (2 meter and 10 meter), we can gain more information about the turbulence associated with upwind profiles at GPQ.

The wind data from Kahuku downloaded from the Pacific Island Ocean Observation system (PAClOOS) are used as an input. The data includes the date and time, air temperature (Celsius degree), wind speed (m s^{-1}) at 10m and pressure (millibars). The date is in the YYYY-MM-DD HH:MM:SS format. The time period is from April, 1 2010 to April 1, 2011.

Chapter 3 RESULT

Roughness Length (z_0)

Based on equation (2.1), the average of z_0 is about 0.084m. Fig.7 shows the daily annual z_0 record. According to Table.1, the roughness length at a barren land should be in the range of 0.01m-0.5m, and the average roughness length at GPQ is fall in this range.

Wind condition of GPQ

Most of the wind speeds at the site are in the range of 4 - 10 m s^{-1} (Fig. 8), which is in the speed range of turbines. The average maximum wind speed was in December 2011, and the lowest was in April 2010 (Table 5). The day time wind speed is stronger than the night time, and it is during the day time that people in Hawaii consume the most electricity. This can be one of the advantages of a suitable location for constructing a wind farm. Figure 9 shows daily average wind data, but for energy resource assessment, the minute-by-minute data were used. GPQ has an average wind speed of 7.64 m s^{-1}. A good wind resource has an average annual wind speed of at least 5.8 m s^{-1} according to the U.S. Department of Interior wind energy final programmatic environmental impact statement[1]. Therefore, the resource assessment suggests that GPQ qualifies as a good site for a wind farm based on the available wind.

The wind shear exponent (α) of GPQ is about 0.40. According to table 3, a barren land should have the wind shear exponent in a range of 0.15-0.2; however, the wind shear value of GPQ exceeded this range. This observation will be discussed in the discussion section.

[1] http://windeis.anl.gov/guide/basics/index.cfm

Wind turbulence (TI) is a relative indicator of turbulence, when TI less than or equal to 0.10 it shows the location has low levels turbulence, moderate levels to 0.25, and high levels greater than 0.25. The wind turbulence at GPQ at 80 m is about 0.19, suggests that the wind turbulence at Kapolei is at moderate level. The consequences of this finding will be discussed in the discussion section.

Wind Power Density (WPD)

The analysis shows that optimal energy production in GPQ is 342.24 w m^{-2} at the height of 10 m. This is a relatively good condition for installing wind turbines (Table 4). Figure 10 shows the result of the daily WPD average throughout the year, and in 2010 one can notice good energy production during summer months and more variable energy production during winter.

Kahuku site

Kahuku Wind Farm, located on the North Shore of Oahu, is Hawai'i is First Wind Company's second project in Hawaii. Kahuku Wind Farm includes 12 wind turbines, with a total generating capacity of 30 MW. The wind farm can produce enough power for up to 7,700 homes on Oahu (First Wind, 2013).

The purpose for obtaining the Kahuku wind farm data is to compare the wind resource at Kahuku with that at GPQ. By analyzing the wind data for Kahuku obtained from the paclOOS site for April 1, 2010 to March 31, 2011, we have calculated wind turbulence and wind power density for the Kahuku site. Wind turbulence at Kahuku wind farm is about 0.24 and the WPD is about 306.67w m^{-2} (Fig.11).

The wind at Grace Pacific Site is more stable and has a higher wind power density than Kahuku wind farm, which suggests that the wind turbine at GPQ could be more reliable than the wind turbines at Kahuku wind farm. Also GPQ site has the potential to produce more electricity than Kahuku wind farm. Moreover, GPQ has wind power density at class 6, which is suitable for most utility-scale wind-turbine applications.

Interview Results

Carolyn Unser is the Community Outreach Coordinator for First Wind Energy Company. She was interviewed and the following issues regarding current wind farms on Oahu were provided. First Wind Company regards community support as a priority for consideration of the Kahuku's wind farm project, as well as other environmental stewardship factors[2].

The Environmental Impact Statement Preparation Notice report of Kawailoa Wind Farm Project (2010) is an example of dealing with the environment factors. In the report, the numbers of forest birds, both native and non-native, observed are sparse in the area. The report concluded with no seabird or water birds present at the Kawailoa. Furthermore, for wind farms closure issue: "the average cut-out speed for a wind turbine is ~26m s^{-1} (~58mph) and this threshold has not been exceeded."

Ms. Unser stated, "the permits and government processes for the project included a federal Environmental Assessment, Habitat Conservation Plan, state and federal Incidental Take Permits, Environmental Impact Statement, Conditional Use Permit, FAA Determination of No Hazard to Air Navigation, as well as several permits for transportation and buildings. Overall, the project has been thoroughly studied and approved by various government agencies, and most of that information has been available to the public online since July."

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2 For more information please see Chapter 5.

For government support, according to the Corporate Tax Credit, the rate is "2.2¢ per kWh for wind, geothermal, closed-loop biomass; 1.1¢ per kWh for other eligible technologies, and generally applies to first 10 years of operation." For wind powered energy systems the maximum allowable credits for commercial property is eligible for a credit of 20% of the actual cost or $500,000, whichever is less (North Carolina State University, 2012).

(Unser, Community Outreach Coordinator of First Wind Energy Company, March 11,2013)

CHAPTER 4 CONCLUSIONS AND DISCUSSION

The goal of this research was to assess the feasibility of building a wind farm at GPQ site of Kapolei. The result from the analysis of wind data from GPQ were compared with the results obtained from analysis of data from Kahuku wind farm.

Conclusion

- The average roughness length at GPQ is 0.084m, which proved that the site is a barren land
- GPQ is a secure site, and has a geographic advantage since it is relatively close large population centers on Oahu and it is close to a HECO substation.
- The mean wind speed of 7.64m s^{-1} at GPQ is greater than what is defined as a “good” wind resource according to the Wind Energy Development Program EIS.
- Wind turbulence at GPQ is 0.19 which is moderate and is less than found at Kahuku farm.
- Wind power density at GPQ (342.24 w m^{-2}) is greater than at Kahuku wind farm(306.67w m^{-2}), which means GPQ has potential to generate more energy than Kahuku wind farm per turbine.
- The wind speeds at Kapolei did not exceed the wind turbine capacity during the period of study. So there is little concern regarding closure of the wind farm because of high winds.
- Government gives wind farms a tax credit at the rate of 2.2¢ per kWh. The maximum allowable credits that a commercial property is eligible for is 20% of the actual cost or $500,000, whichever is less.

Discussion

Grace Pacific Quarry is surrounded by hills with grass and low bushes. Therefore, according to Table.2, the roughness length at a barren land will be in the range of 0.01m-0.5m. The average roughness length at GPQ computed in this study falls in that range, and proved that GPD is a land with few trees (Fig.12). Having a reasonably low roughness length is important because it results in less turbulence in the air at turbine height. Also, the forecast value of the wind shear exponent at GPQ was between 0.15-0.2 (Table 3), but the actual wind shear exponent at Site 1 is 0.40. There are several possible reasons. It is suggested that the higher wind shear exponent is the result of the hilly terrain upwind of Site 1.

The higher wind shear exponent results in moderate wind turbulence index, which is not ideal. The wind turbulence index for Kahuku wind farm was greater still. Therefore, given that GPQ has good wind power density, it is suitable for a utility-scale wind turbines application.

Several environmental issues need to be considered before building a wind farm, such as noise issue, bird flight patterns, and Hawaiian burial restrictions. There are two kinds of noise for wind farms: construction noise and operation noise. As the example of Kahuku wind farm, for the construction noise, typical sound levels produced by construction equipment (Fig.13). Earth-moving equipment would probably be the loudest equipment used during construction. These noises are louder than the operation noises; however, the noise is short-term noise. Operation noise has a long-term impact on the local people. According to the Final EA report of Kahuku Wind Farm (2010), "Kahuku Wind Power facilities are expected to increase the ambient sound environment in the surrounding communities from 0 to 3 dB. A change in sound level of less than 3 dB is not a perceptible difference to most listeners."

Based on the Final EA report of Kahuku Wind Farm (2010), agricultural areas close to the Kahuku Wind Farm experience the greatest increase in ambient sound, up to 3 dB, but the total sound level would still be well below the required limits. The predicted local noise level near Kahuku Wind Power is similar to ambient urban noise levels (Fig.13). Should development of a wind farm be considered at GPQ, there will be short-term noisy construction phase and a small amount of noise (increase the sound level about 3 dB) during operation that will likely be masked by ambient road noise in the area.

For the bird and bat fatalities, usually people thought the Rotor-swept area related to the amount of fatalities. However in Barclay (2007), the Rotor-swept area was not a significant factor for the bird and bat fatalities. The fatality rate for birds increases proportionally to the wind tower height, and with turbine towers 65 m or taller having the highest fatality rates (Fig.15). Therefore, the height of the turbine will need to be considered as part of the business plan. Other factors can influence the fatality rates and may include differences in the number of species present in the area and their population sizes, the use of migration corridors, and variation in numbers of migrants from year to year. Downwash from the wind turbines has been shown to increase evapotranspiration, which can impact plants downwind of the wind farm.

For the Hawaiian burial site concerns, a study would need to be conducted regarding the human burials at GPQ. The AE report for Kahuku Site (2010) said that "if any archaeological deposits or human burials are encountered, the contractor would halt work and contact the State Historic Preservation Division." A similar approach would be considered if there are any the human burials for old Hawaiian at GPQ.

The project will need to perform archeological, environmental impact, and other studies before permits to build can be issued, Implementation of a potential project would require permits from a variety of Federal, State and local agencies. According to the written interview with representative from Kahuku, there are three kinds of permits: environment study, building and land related. These permits for commercial scale wind projects cost from $1.2 to $2.6 million per MW of nameplate capacity installed. Often a building permit fee is based on total project cost and can amount to $5,000-$10,000 per turbine. The cost to hire consultants and complete the required studies can range from $5,000-$50,000 for a single turbine project (Windustry, 2000-2012).

Future Study

This research is a very general report about the feasibility of building wind farm at GPQ. There are several other studies need to be conducted before planning to build a wind farm at GPQ. Firstly, more research needs to be conducted about the surrounding environment, including the plants, birds, bat and animal's current distribution and migration corridors at GPQ, and the possible effect of the wind farm to the surrounding. Secondly, some survey about the local opposition need to be made, and convey the impact and benefits of the wind farm to the local people.

Summary

This project determined the feasibility of building a wind farm GPQ in Kapolei. GPQ is a location has a sufficient wind resource that is suitable for a wind farm. The one year wind data of from GPQ were used for qualitative analysis. The GPD wind data was compared with the Kahuku wind farm data. Finally, a written interview was conducted to get information about environmental impact studies needed to assess the feasibility of constructing a wind farm in Hawaii.

Appendix

Table 1. Comparison of different anemometers types (Hau, 2006).

Anemometer Type	Definition	Advantage and disadvantage
Pressure plate	Simplest anemometer	-Cannot measure low wind speed -The wind speed data is not very precise and not very accurate.
Drag Sphere	Has sensor that measures the drag force on an object in the flow in order to know the wind velocity. See fig.3	sensitive to the change of the weather
Cup and propeller anemometer	The wind past the cups or propellers in any horizontal direction turned the shaft in a manner that was proportional to the wind speed; by counting the turns of the shaft over a set time period to measure the average wind speed for a wide range of speeds (Omega).	-lack of cosine response -the dynamic effect that increases for anemometer when it has larger distance constants
hot-wire and hot-flame anemometers	- measure the wind speed by measuring the speed of the cooling of a heated wire or flame.	+ highly sensitive to low wind speed - not sensitive to high wind speed - expensive - difficult to resolve the low wind speeds because the static sensitivity is too large at low speed.
sonic anemometers	-Measures difference in travel time of sound between transducers.	+they can measure high speed which lowers than 100m s^{-1} without threshold and it has linear output. -expensive.

Table 2 Different kinds of roughness length show different landscape feature. (E. Linacre & B. Geerts, 1999)

class		roughness	Landscape features
No.	name	Length:m	
1	sea	0.0002	open water, tidal flat, snow with fetch above 3 km
2	smooth	0.005	featureless land, ice
3	open	0.03	flat terrain with grass or very low vegetation, airport runway
4	roughly open	0.10	cultivated area, low crops, obstacles of height H separated by at least 20 H
5	rough	0.25	open landscape, scattered shelter belts, obstacles separated by 15 H or so
6	very rough	0.5	landscape with bushes, young dense forest etc separated by 10 H or so
7	closed	1.0	open spaces comparable with H, eg mature forest, low-rise built-up area
8	chaotic	over 2.0	irregular distribution of large elements, eg city centre, large forest with clearings

Table 3 The wind shear exponent varies with the terrain.

Terrain	Wind Shear Exponent − α −
Open water	0.1
Smooth, level, grass-covered	0.15
Row crops	0.2
Low bushes with a few trees	0.2
Heavy trees	0.25
Several buildings	0.25
Hilly, mountainous terrain	0.25

Table 4 The site has Wind Power Density (WPD) over 250watt*m^{-2} is consider as a efficient wind farm.

WPD	Level
< 150 Watt m^{-2}	Poor
150 ~ 250 Watt m-2	Fair
250 ~ 350 Watt m^{-2}	Good
> 350 Watt m^{2}	excellent

Table 5 The monthly average wind speed at GPQ.

Month	Average wind speed(m s^{-1})
Apr	6.10
May	7.78
Jun	8.07
Jul	8.03
Aug	7.98
Sep	7.11
Oct	7.36
Nov	8.51
Dec	8.74
Jan	6.28
Feb	7.23
Mar	8.57

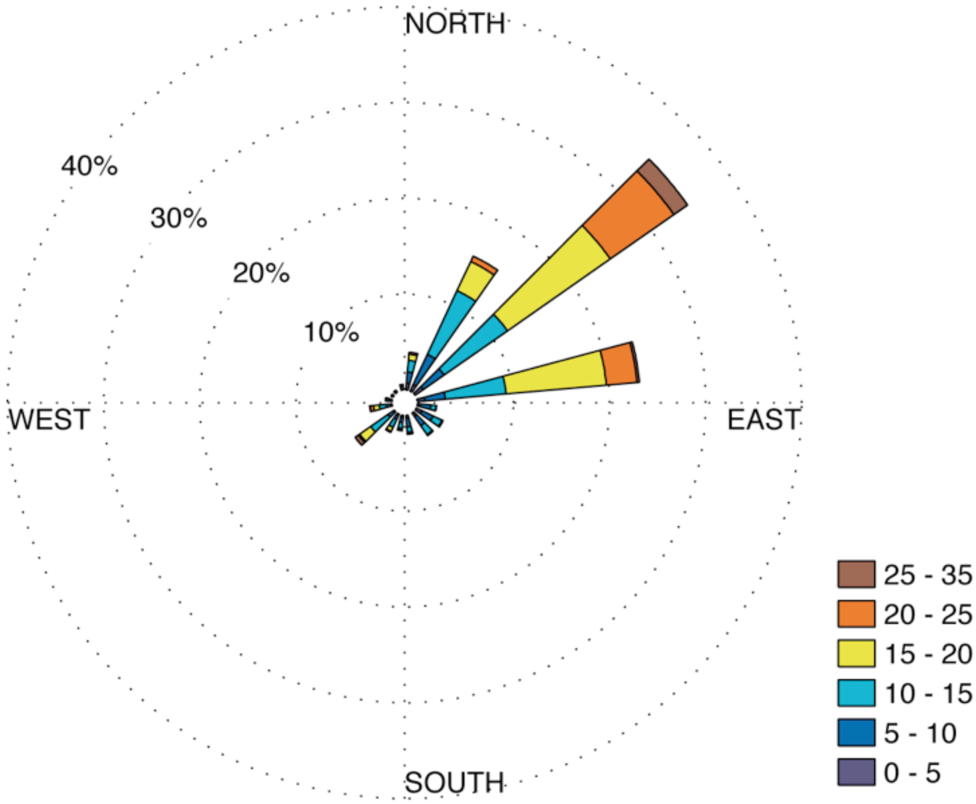

Figure 1 The wind rose diagram provides a sample of the wind speed distribution at GPQ, showing the prevalence of northeast trade winds.

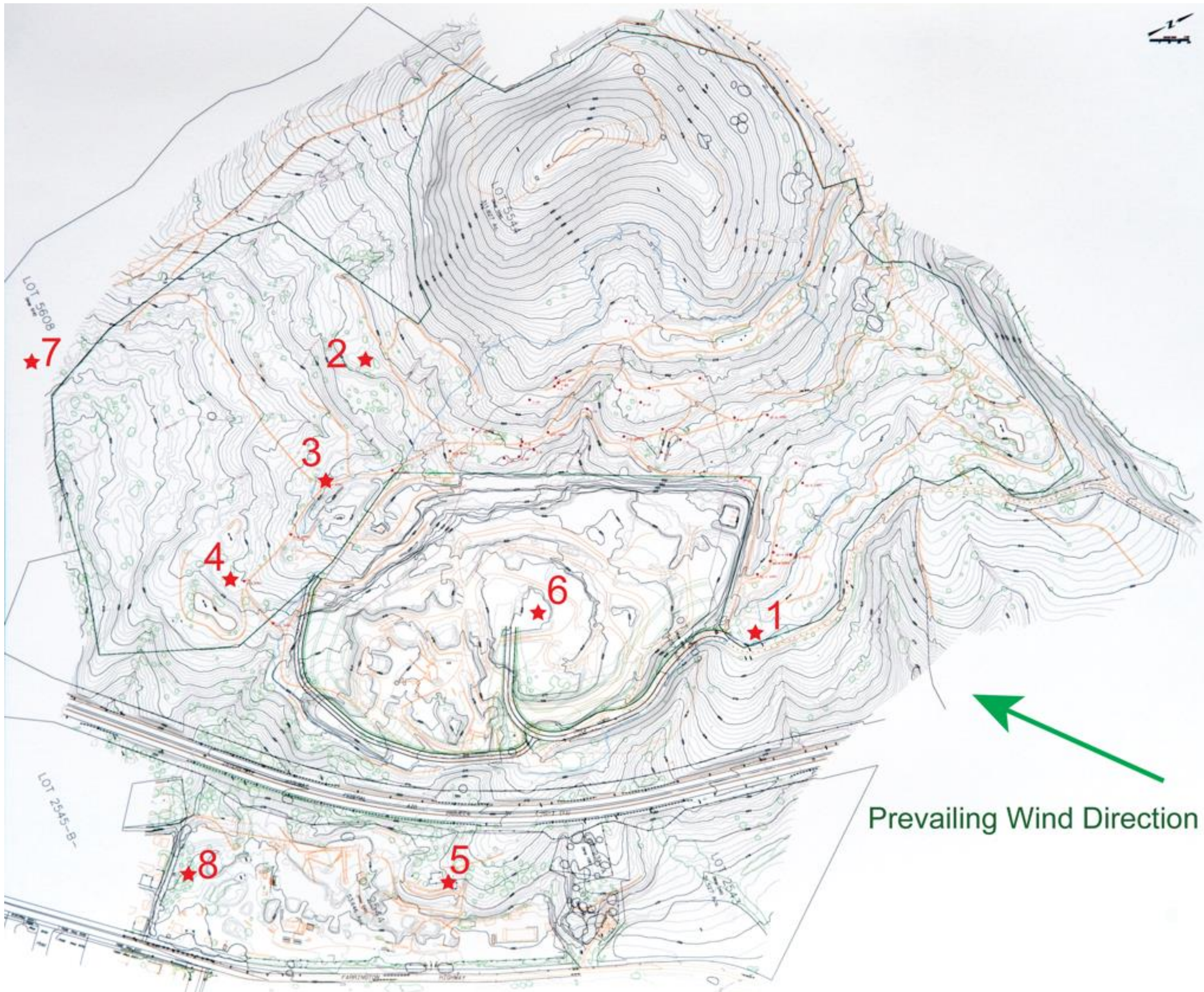

Figure 2 Map of GPQ showing prevailing northeast wind direction and location of instrument sites. In this research, we collected the data from site 1.

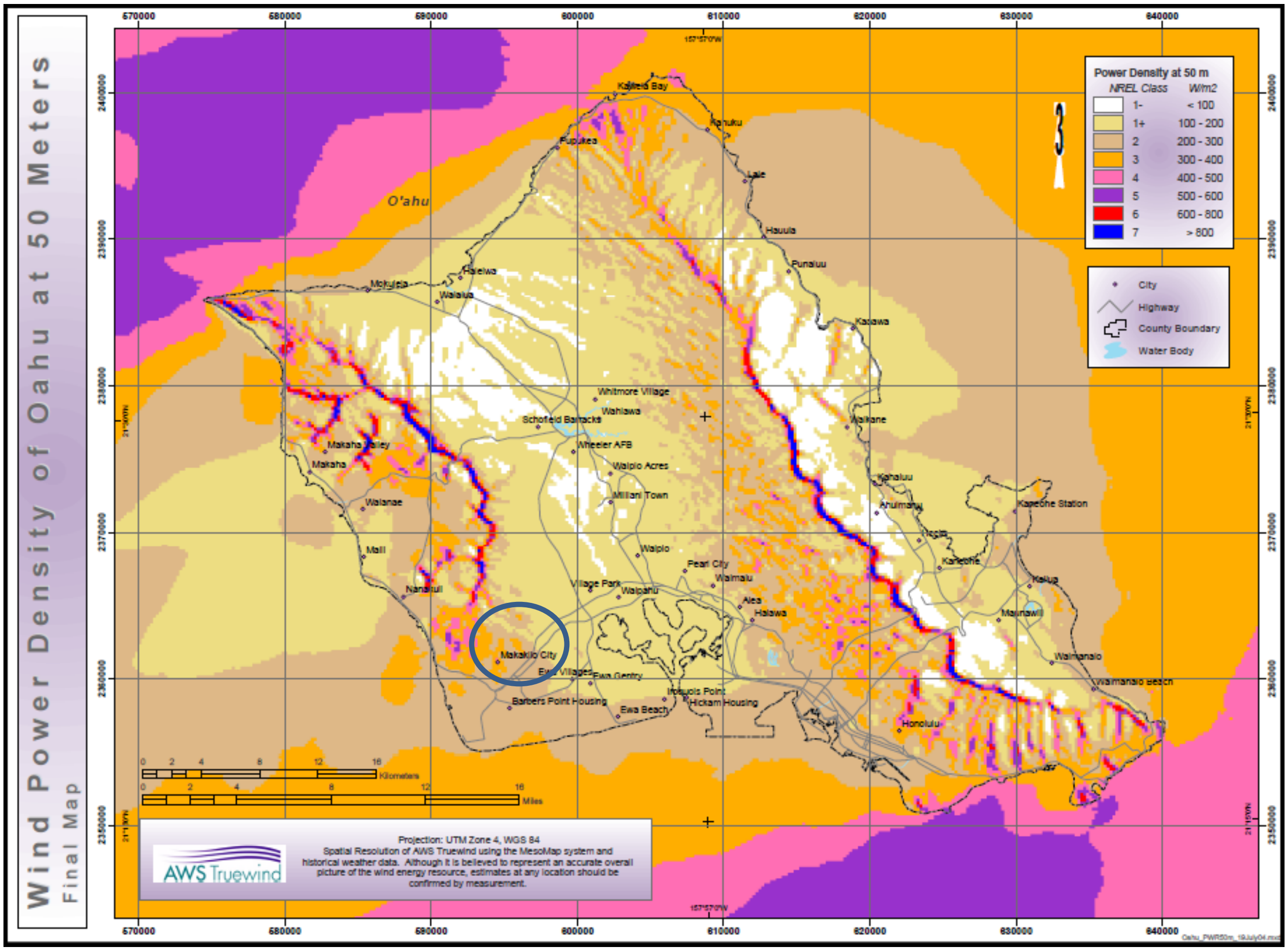

Figure 3 The wind power density at 50m at Oahu. The blue circle shows the location of GPQ. You can see it has wind power density between classes 2 to class 3, which means the GPD has fair WPD.

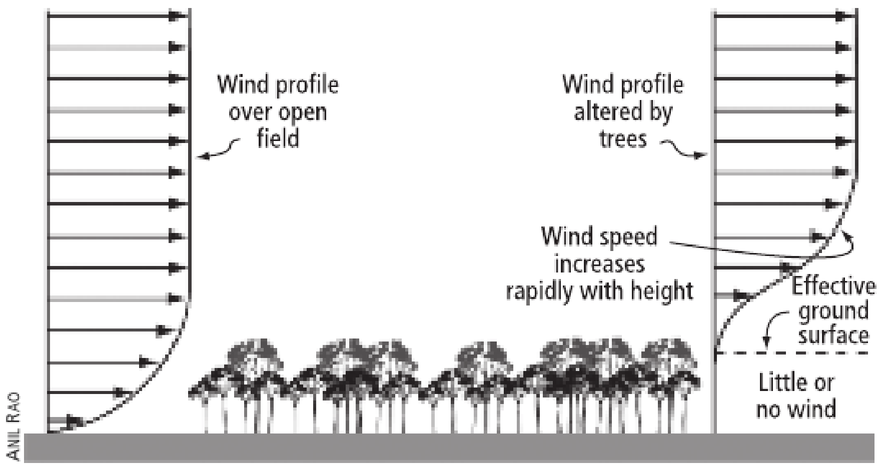

Figure 4 The wind speeds in boundary layer is directly proportional to the elevation and when there are trees, it increase the roughness of the ground and lower the wind speed(Stull, 1988).

Figure 5 Examples of sonic anemometers

Figure 6 Photograph of instrument tower site 1 located on the upwind NE side of GPQ. It measures wind speed at 2m and 10m.

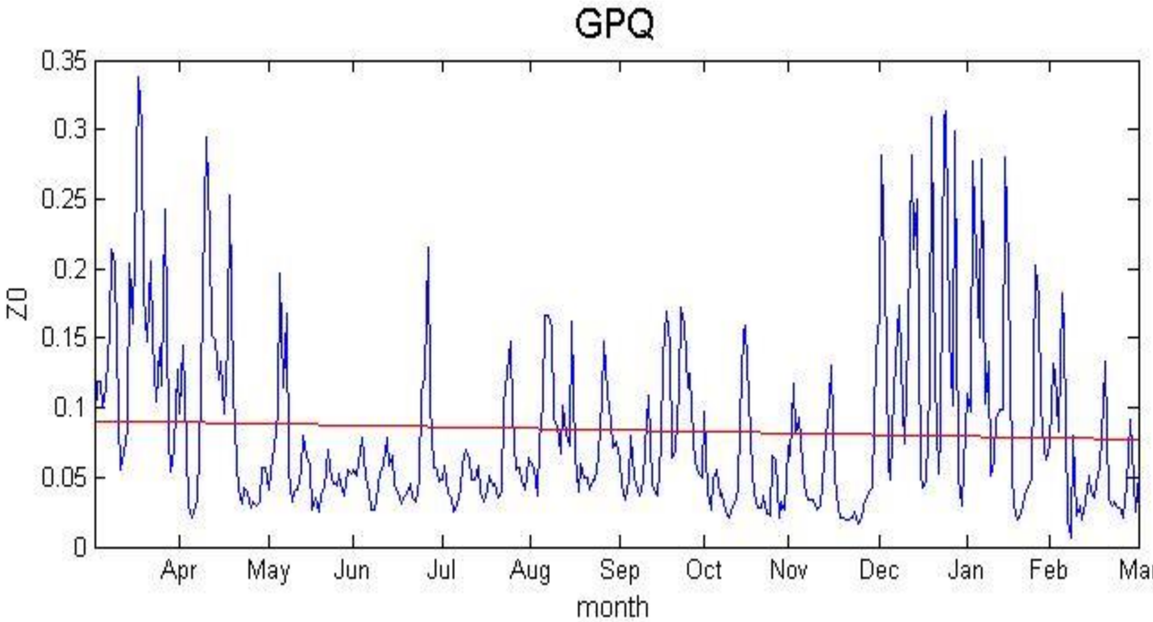

Figure 7

It is the daily average of the roughness length at GPQ. The red line is the best fit line of the graph.

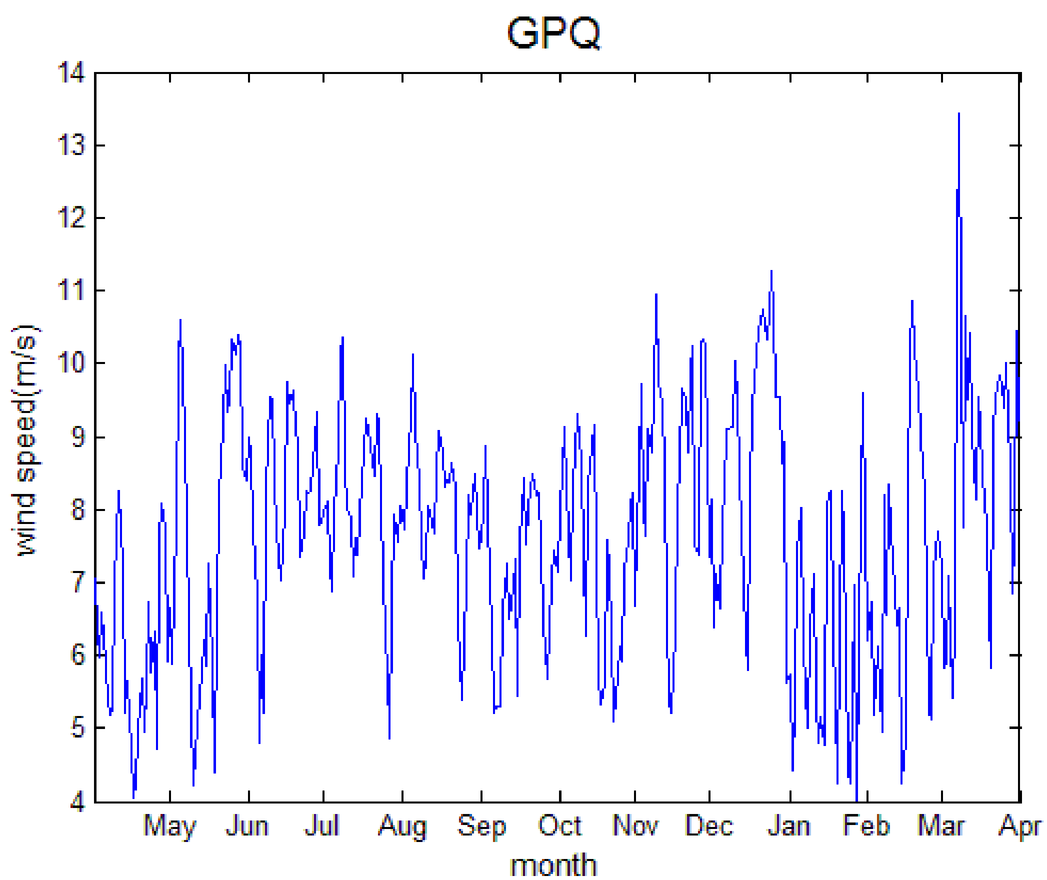

Figure 8 The daily average wind speed measured at GPQ.

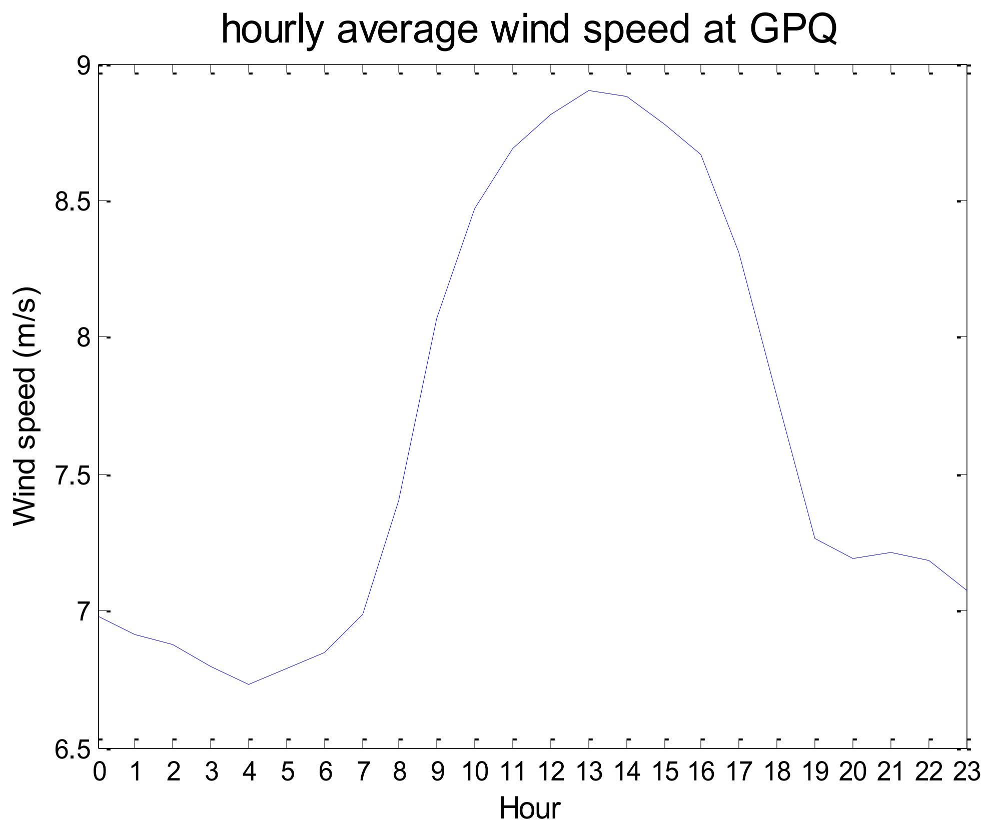

Figure 9 The hourly average wind speed calculated from a one-year record of GPD wind data.

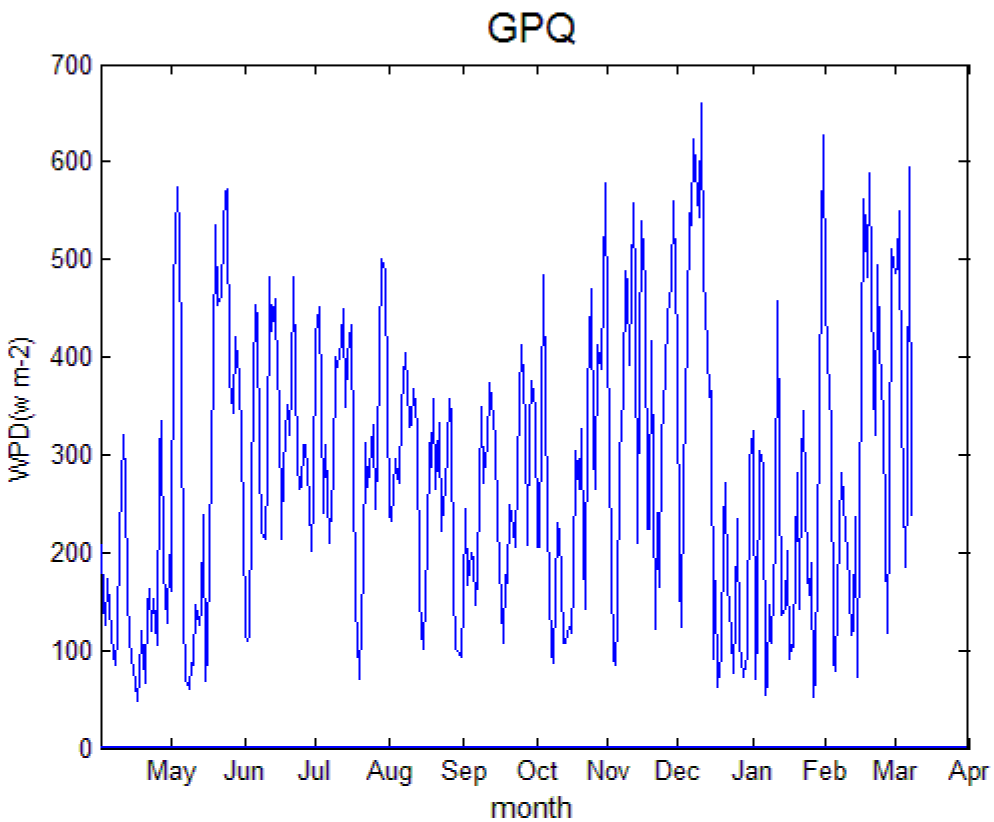

Figure 10   The daily WDP observed at GPQ.

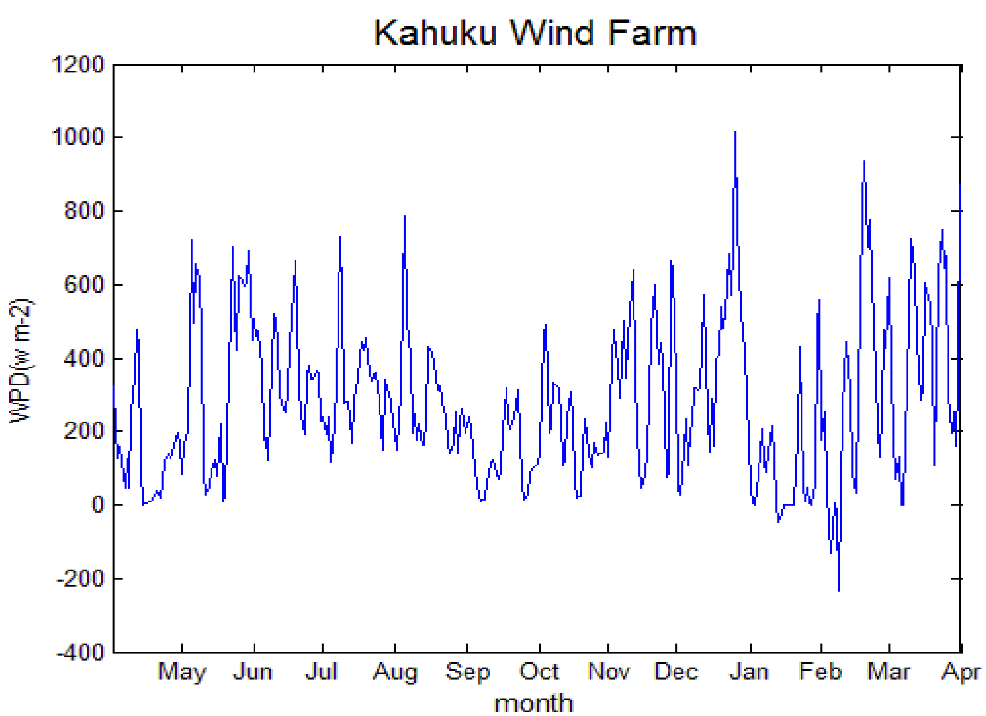

Figure 11 The daily WPD at Kahuku wind farm.

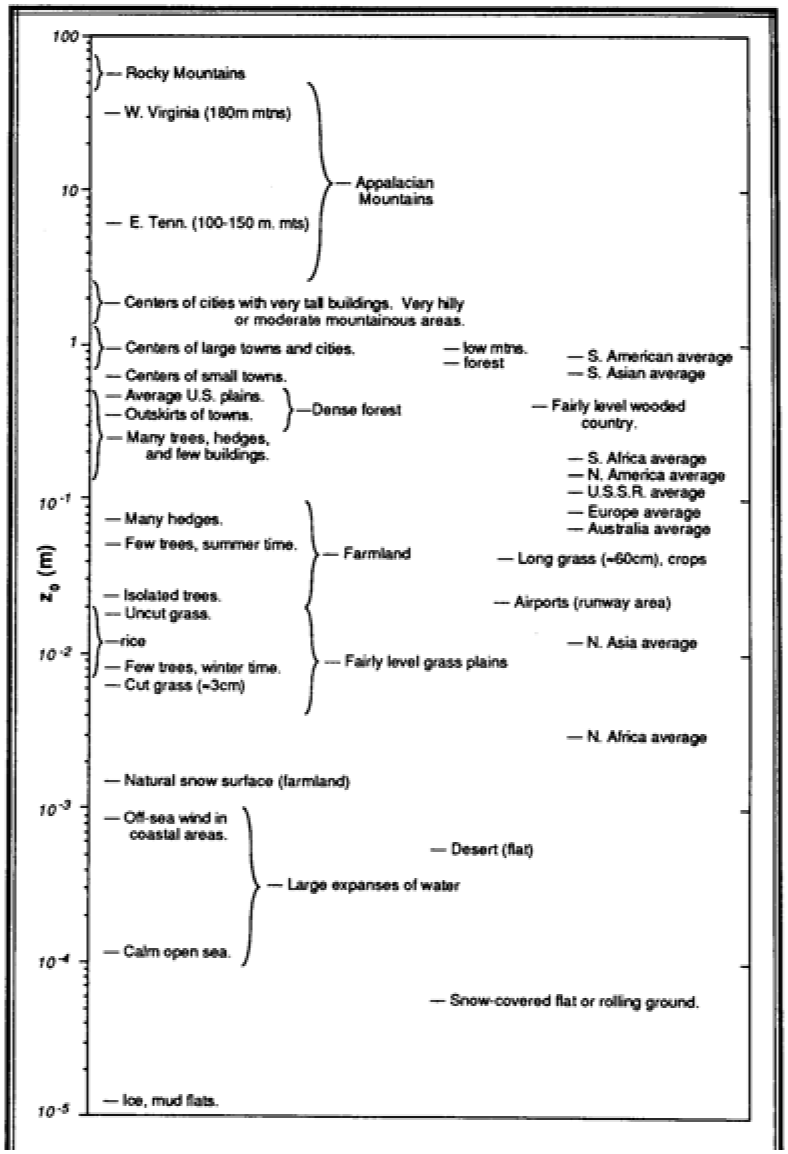

Figure 12 Roughness lengths for typical terrain types

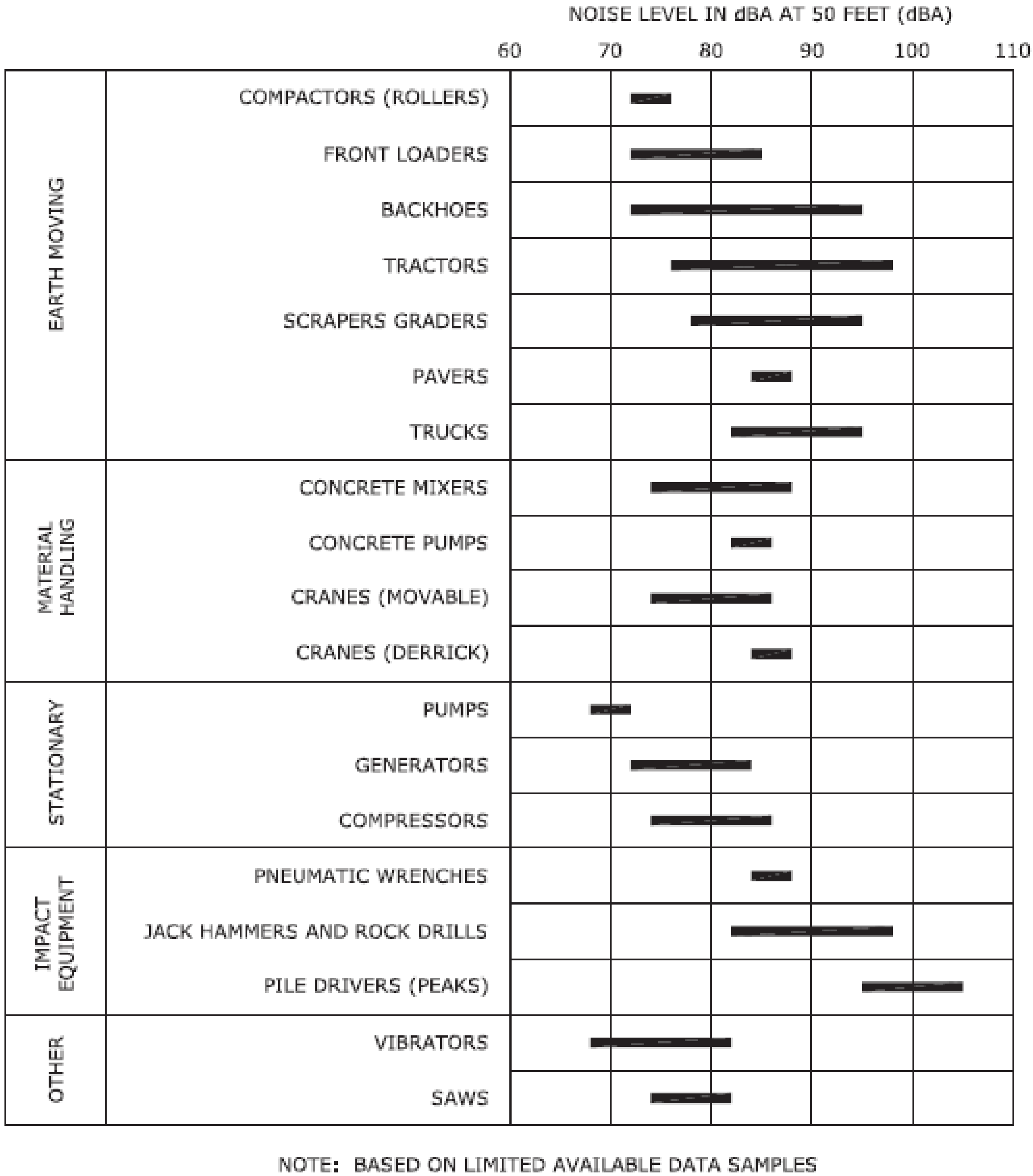

Figure 13 Typical sound levels produced by construction equipment

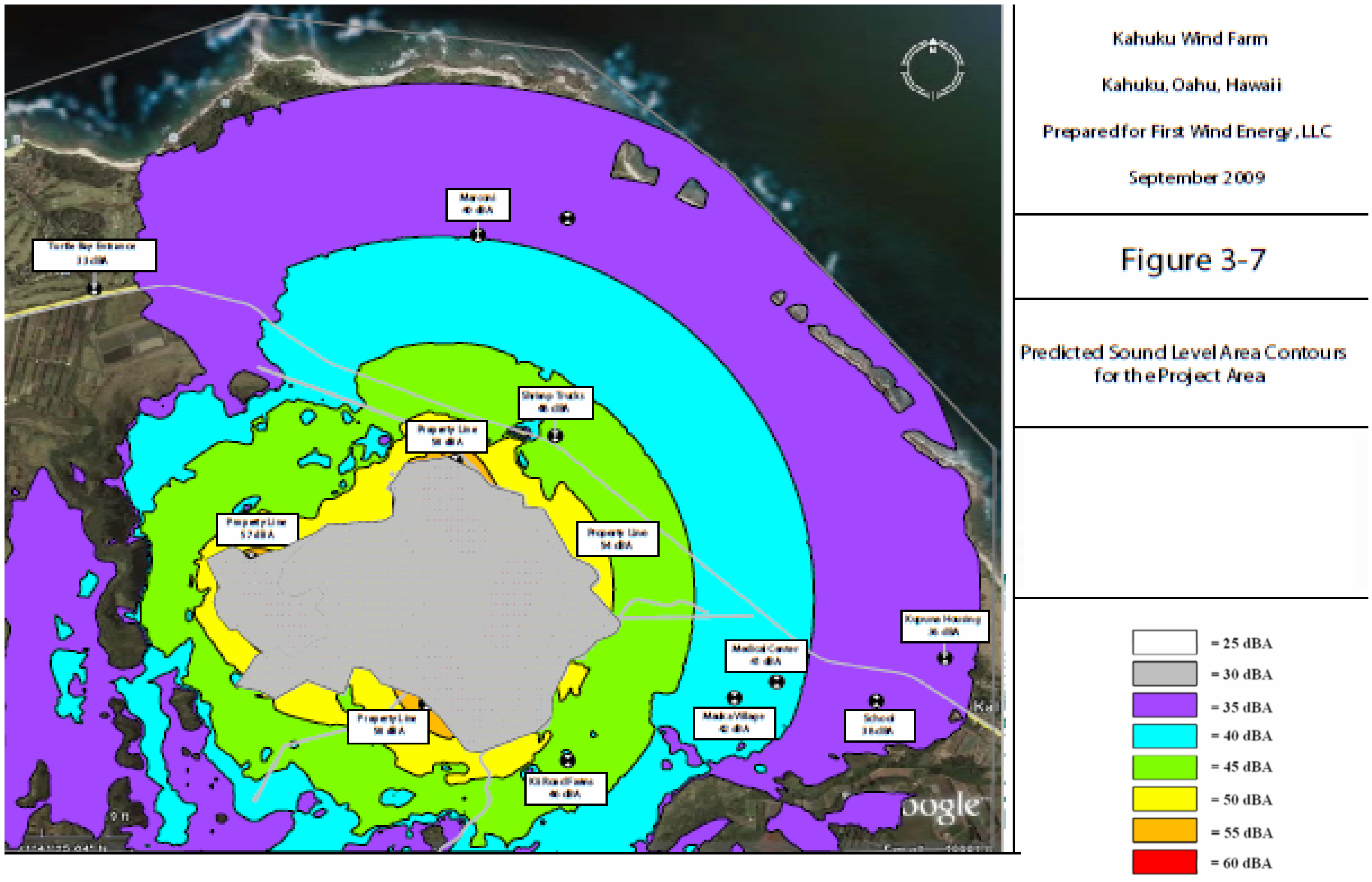

Figure 14 The map shows the predicted sound level for the Kahuku wind farm. The loudest area is about 50db, which is at the sound level of an ambient urban noise.

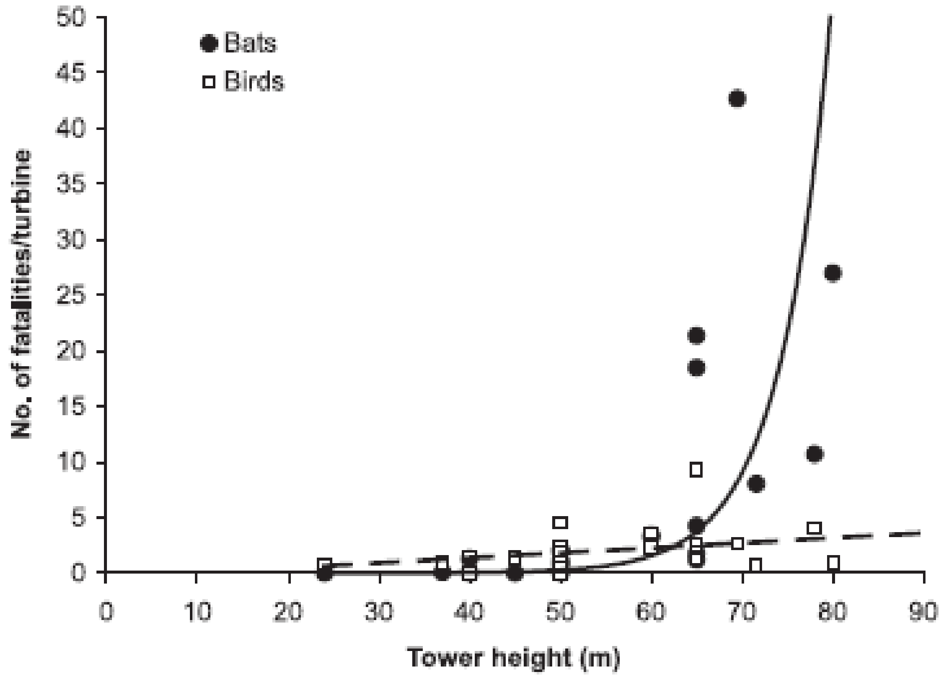

Figure 15 Relationship between corrected annual bat and bird fatalities per turbine and the height of wind turbine towers at wind energy facilities in North America.

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