Assessment of Wind Energy Resources for Residential Use in Victoria, BC, Canada

by

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A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science

in the School of Earth and Ocean Sciences

University of Victoria

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Abstract

Using the wind speed measurements collected at the University of Victoria School-based Weather Station Network over the last several years, an assessment of the local wind power potential is presented focusing on its residential use. It is found that, while the local winds are generally characterized by relatively small mean values, their spacial and temporal variability is large. More wind power is potentially available during the winter season compared to the summer season, and during daytime compared to nighttime. The examination of wind characteristics at 32 stations in the network reveals areas with wind energy potential 1.5-2.3 times larger than that at the UVic location, which represents a site with average wind power potential. The station with the highest potential is found to be that of Lansdowne. The probability distribution of the local wind speeds can be reasonably well described by the Weibull probability distribution, although it is recommended that seasonal variability of local winds be taken into consideration when estimating the Weibull fitting parameters. Based on a theoretical and statistical analysis, wind power output and its dependence on wind power density are estimated for five different locations in Victoria, B.C. Overall, it is found that the largest amount of power can be produced from the wind at Lansdowne during winter where, among the micro and small turbines considered, the *FD2.5-300* and *ARE10kW*, respectively, would produce the largest amounts of power.

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Acknowledgements

I am very grateful to my supervisor, Andrew Weaver, for his support and many suggestions on how to improve my thesis. His enthusiastic approach to the research on sustainable energy was tremendously encouraging. The friendly and comfortable atmosphere he has created in the Climate Lab was also very important for me.

My thanks to Ed Wiebe for technical support and to everyone in the Climate Lab for their help when I needed it.

Special thanks to Wanda Lewis for keeping things neat in the Climate Lab.

Finally, I wish to thank my family for the wonderful support.

Chapter 1

Introduction

1.1 Renewable energy resources

Since the Industrial Revolution in the late 18th and early 19th centuries, the anthropogenic influence on the environment has been rapidly increasing. The transition to the industrial use of steam power and heat engines, while of enormous economical benefit, has also had important environmental side effects. In the atmosphere, there has begun an accumulation of radiatively active gases. These gases are capable of changing the climate on our planet through global warming. In particular, since the Industrial Revolution the concentration of carbon dioxide – the most important of the global warming gases – has increased by 30%. According to some of the scenarios used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (*IPCC* 2007), by the end of the 21st century the concentration of carbon dioxide may increase from two to three times relative to its preindustrial level. This, according to experts, may result in a significant warming on our planet, particularly amplified in polar regions. An increase in the frequency of the extreme weather events, such as droughts and floods, and a permanent disappearance of some of the species living on our planet have also been mentioned among the many consequences of the global warming.

Another growing concern is the direct impacts on health. Particulate matter present in the air along with other pollutants has contributed to make asthma one of the fastest growing childhood ailments in industrial and developing countries alike, and it has also recently been linked to lung cancer. Similarly, urban smog has been linked to low birth weight, premature births, stillbirths and infant deaths. Nitrogen oxides from burning fuel in cars and trucks and from energy generation using combustion engines and power plants lead to the formation of smog.

What might be the solutions? A development of more environmentally-friendly technologies, including energy technologies, has been named as one of the key ways to address the problem. In addition, an increase in the proportion of the energy sources which do not rely on carbon-based natural resources such as coal, oil, or gas may also help. One such energy source is wind. Wind power is a clean, renewable form of energy, which during operation produces no carbon dioxide. While some emissions of carbon dioxide take place during manufacture and installation of wind turbines, these emissions are about 130 times lower than from coal-fired generation (*AWEA* 2008). When wind farms are dismantled (usually after 20-25 years of operation) they leave no legacy of pollution for future generations. Modern aerodynamics and engineering have improved wind turbines. They now provide reliable, cost-effective, pollution-free energy for individual, community, and national applications.

The use of the wind energy is not a new idea. Humans have been using wind energy for thousands of years. Ancient Persians used wind energy to pump water before the birth of Christ. The world was explored by wind-driven ships long before engines were invented. As recently as the 1920s, over a million wind turbines pumped water and provided electricity to farms in North America. At the end of 2006, worldwide capacity of wind-powered generators was 73,904 megawatts (*WWEA* 2007). Wind power currently produces just over 1% of world-wide electricity, according to the World Wind Energy Association Statistics, whereas it accounts for approximately 20% of electricity production in Denmark, 9% in Spain, and 7% in

Germany. Canada's installed capacity by the end of 2007 is 1,770 megawatts, which is equivalent to 0.75% of the total electricity demand (*CanWEA* 2007c). Globally, wind power generation more than quadrupled between 2000 and 2006.

What is the cost of wind energy? The cost is mainly determined by the initial cost of the wind turbine installation, the interest rate on the money invested and the amount of energy produced. Other factors, which may affect the final cost of produced energy include maintenance during the turbine's life time, the cost of connection to the utility grid (in order to sell excess of power) or the cost of an energy storage system. The use of the latter is unavoidable in the absence of the grid connection due to the intermittent nature of the wind. Any wind turbine that is installed in a very windy area generates less expensive electricity than the same unit installed in a less windy area (*Clarke* 2003). So it's important to assess the wind at the potential site. Based on the level of wind power available at a site, the wind energy conversion system is chosen depending on the cost.

Numerous studies have undertaken assessments of potential wind resources, including the estimation of output from wind powered generators. For different regions of the world, energy resource maps have been plotted. One such study evaluating global wind power was conducted by *Archer and Jacobson* (2005). They assessed the wind power potential at a height of 80 m. Since there are not enough wind speed measurements at such a height, a Least Squares extrapolation technique was used to obtain estimates of wind speeds at 80 m given widely available wind speed data at 10 m. The wind power classes at both 80 m and 10 m for the entire world and at 80 m for every continent were then plotted.

Li and Li (2005) made and assessment of wind power potential for the Waterloo region, Canada. They examined annual, seasonal, monthly and diurnal wind speed variations. In their study they used the Maximum Entropy Principle to determine wind speed frequency distributions. The wind speed data at this region revealed that the daytime of the Cold season had the highest wind power potential, which coincided with the highest power demands.

A wind energy resource map of Newfoundland was developed by *Khan and Iqbal* (2004). They stressed the importance of developing micro-scale maps of wind energy resources, which could be used in selecting suitable wind sites, because the existing mesoscale maps with 50-100 km resolution neglected the local effects of topography, surface roughness and thermally-driven flows.

With growing environmental concern around the globe and because of the increase in cost of non-renewable energy resources, wind energy becomes more attractive in developing countries. Small energy conversion systems are growing in popularity around the world (*AWEA* 2007c). In a wind energy analysis of Grenada, *Weisser* (2003) underscored the importance of differentiating between hours of the day and between months of the year in determining the wind energy potential. Assessments of wind characteristics and wind turbine characteristics such as power output and capacity factors were done by *Justus et al.* (1976), *Chang et al.* (2003) and *Akpinar and Akpinar* (2005). The purpose of their studies was to determine the areas with energy potential suitable for medium and large scale applications. The article by *Mulugetta and Drake* (1996) focuses on the potential of wind power to provide Ethiopia with viable renewable energy source. In this study their effort was targeted on assessing the spacial distribution of the wind energy resource. The values of the Weibull distribution parameters were derived and assigned to 60 stations which only had monthly mean speed values to calculate their respective energy densities. *Lu et al.* (2002) and *Ahmed et al.* (2006) analyzed local wind data and estimated the power output by small (under 20kW) wind turbines.

Except for *Li and Li* (2005), in all assessments the Weibull function was used to describe the wind speed distribution.

1.1.1 Purpose of thesis work

The main purpose of this work is to make an assessment of the local wind energy potential at 10 m height, at which the wind data is currently available. In addition, the power output from different types of micro and small wind turbine generators at different locations around Victoria is estimated in order to assess the suitability of these wind turbines for electricity generation. Such small scale generators could be useful as an alternative non-polluting energy source for individual households.

The results may provide some practical recommendations for the southern part of Vancouver Island in terms of potential wind energy utilization.

1.2 Outline of thesis research

The next chapter of my thesis describes the local wind climate. Wind speed characteristics such as averages and probability distributions were analyzed for 32 UVic School-based weather stations. The seasonal and diurnal variations in wind speed were plotted for one station to estimate the general pattern in wind speed variations. Then statistical methods were applied to describe the wind speed variations. The two Weibull fitting parameters were calculated for cold/warm seasons as well as for daytime and nighttime. Using obtained probability density functions, the wind power densities were calculated for all of the stations.

In Chapter 3 an assessment on turbine power output is performed. Different types of micro and small scale wind power generators are described. From the manufacturers' power curves the coefficient of performance curves as a function of wind speed are obtained. Using the coefficients of performance and wind power density profiles, the power outputs of the different turbines' are found as a function of wind speed. Average power output and annual energy production are calculated for all the turbines at five locations. Monthly energy production is plotted for selected turbines at two locations to see the difference in energy production from month to month and from location to location.

Chapter 4 concludes this thesis and finishes by suggesting future work that could further advance understanding of the local wind energy resources and their suitability for small applications in electric energy production.

Chapter 2

Wind Energy Assessment

2.1 Introduction

Information on the wind characteristics is of great importance in selecting an appropriate wind energy conversion system for any application. In this study, a wind energy assessment is done to find out the level of suitability of wind power resources for utilization by an individual household through the use of micro and small scale wind generators in the southern part of Vancouver Island.

Wind power resources estimates are expressed in wind power classes (*Elliot and Schwartz* 1993, *AWEA* 2007b). There are 7 wind power classes. Each class represents a range of mean wind power density and corresponding mean wind speed at standard exposure height (10 m) of wind measurements above the ground and at other specified heights: 30 m and 50 m. Because of the lack of wind speed data available at heights other than 10 m, the wind power density and wind speed extrapolation to the desired heights are carried out using the 1/7 power law. It is widely accepted that Class 4 and higher, with wind power density greater than 250 $\mathrm{W/m^2}$ and mean wind speed greater than 6 m/s at 10 m above the ground, are suitable for large scale electricity generation. Class 2 areas may be suitable for small scale turbines to supply electricity at a reasonable cost. Wind power density in this class ranges from 100 $\mathrm{W/m^2}$ to 150 $\mathrm{W/m^2}$, and mean wind speed is between 4.4 m/s and 5.1 m/s. Class 1 is unsuitable for wind energy development, according to *Elliot and Schwartz* (1993). At today's level of wind technology development the cost of generated electricity at Class 1 areas is non-competitive on the market. Moreover, unreliability due to the intermittent nature of the wind resource adds even more cost. The unsuitability for wind energy development applies to large scale wind generators, although it is believed that 100 W/m^2 may be usable for specific application such as battery charging and mechanical conversion systems.

The Canadian Wind Energy Atlas provides an overview of the wind resources of Canada with limited resolution (5 km). On their website (*CWEA* 2005) we can find maps of wind power densities over Canada at different heights: 30 m, 50 m and 80 m. These maps are useful only for rough estimation of wind power resources in different parts of the country. At 50 m height the wind power density of the southern part of Vancouver Island is under 200 W/m^2. According to wind power classification, wind power density under 200 W/m^2 at 50 m corresponds to wind power density under 100 W/m^2 at 10 m height. The southern part of Vancouver Island falls into Class 1 of wind power density.

Currently available mesoscale maps with resolution of about 100 × 100 km do not document the variability in wind power density on smaller (under 5 kilometers) scale. Because of the data availability, scientific curiosity and a desire to make a contribution to renewable energy research, it was decided to explore this area on wind energy potential and its variability on the terrain at micro scale resolution. Similar works had been done for different locations in Canada and in the world, but, to my knowledge, none of the wind power spatial distribution analysis was done based on data from such a dense network of meteorological stations.

In wind energy assessment, several steps should be performed to obtain a clear picture. First of all, it is important to have information on the general pattern of the wind flow in the geographical area of interest. Then, spatial and temporal variability of wind speed should be examined in detail.

2.2 Wind climate

Climate is commonly defined as the weather averaged over a long period of time. It can be characterized by a statistical description of such variables as air temperature, precipitation and wind. To understand the wind climate of a particular site, it is important to know the forces maintaining the local wind pattern. Then, suitable statistical methods can be applied, depending on the purpose.

The global winds are driven by differential heating of the surface by the sun. At the equator, more solar radiation is absorbed than at the poles. In the absence of rotation, the air would rise at the equator and sink at the poles. Low pressure zones are formed at the areas of ascending air and vice versa. A pressure gradient would drive the flow of air from high to low pressure, thereby forcing the major wind patterns to blow across the lines of constant pressure. The rotation of the Earth, however, significantly modifies this picture by means of the Coriolis force. Rather than blowing across lines of constant pressure, the major winds sufficiently high above the ground are directed along lines of constant pressure. Other factors, such as, for example, orography and atmospheric stability, also play a role in maintaining the pattern of global and local winds in the atmospheric boundary layer (*Stull* 2000).

Atmospheric boundary layer

The atmospheric boundary layer is the lowest part of the troposphere where the wind, temperature and humidity are strongly influenced by the surface (*Peixoto and Oort* 1992, *Hartmann* 1994). The thickness of the boundary layer varies from tens of meters to several kilometers. Generally, the boundary layer is deeper when the surface is being heated, or when the winds are strong.

In the “free atmosphere” above the boundary layer, the mean wind speed is large and, away from the Equator, is well approximated by the geostrophic balance (*Peixoto* *and Oort* 1992):

$$\mathbf{v_g} = \frac{1}{\rho f}\mathbf{k} \times \nabla P \qquad (2.1)$$

where $\mathbf{v_g}$ is the vector of geostrophic wind, ρ is the density, f is the Coriolis parameter, and ∇P is the pressure gradient.

Towards the surface, the geostrophic balance does not apply any more. Instead, across the boundary layer, the effects of viscosity and turbulence become very important. In order to maintain the turbulent flows in the presence of continuous dissipation, the energy must be continuously supplied. The energy maintaining the boundary layer turbulence is supplied from potential energy, through the direct transfer of energy from the mean wind, or through an indirect transfer from eddies (*Peixoto and Oort* 1992). Thus, there are two main types of turbulence: thermal and mechanical. The former is mainly generated by heating at the surface, whereas the latter is generated by the conversion of the energy of mean winds to turbulent motions.

Under neutral stability, buoyancy effects do not play a significant role in the budget of turbulent kinetic energy of the boundary layer. Instead, the main source of turbulent energy is the kinetic energy of the mean wind of the free atmosphere (*Peixoto and Oort* 1992, *Hartmann* 1994). The turbulence generates a strong flux of momentum to the surface, where it represents a drag, τ, on the wind speed, U. Under neutral conditions, dimensional analysis suggests that the scaled vertical gradient of wind speed should be constant (*Peixoto and Oort* 1992, *Hartmann* 1994):

$$\frac{z}{u_*}\frac{\partial U}{\partial z} = \frac{1}{k} \qquad (2.2)$$

where z is the height, k (≈ 0.4) is the von Karman constant, and $u_* = (\tau/\rho)^{1/2}$ is the friction velocity with a typical value of 0.2 to 0.4 m/s. Integrating this equation with respect to height, one obtains the familiar logarithmic velocity profile:

$$U(z) = \frac{u_*}{k} ln(\frac{z}{z_0}) \tag{2.3}$$

where z_0 is the roughness length, which ranges from about a millimetre to more than meters for cities with tall buildings.

In a stratified boundary layer, buoyancy effects begin to play an important role in the vertical wind distribution. In the presence of wind shear, the vertical stability can be described with the Richardson number, R_i. This number is defined as the ratio of the destruction of turbulent kinetic energy by buoyancy forces to the production from the shear flow. Making traditional approximations (*Peixoto and Oort* 1992), it can be shown that the Richardson number is

$$R_i = \frac{g}{\theta} \frac{\partial\theta/\partial z}{(\partial U/\partial z)^2} \tag{2.4}$$

where θ is the potential temperature.

The Richardson number provides a criterion for the existence of turbulence in the case of stable stratification, i.e. $\partial\theta/\partial z > 0$. In order for the turbulence to develop, the Richardson number must be less than one. However, according to observations, the critical Richardson number, which sets the transition from a laminar to a turbulent regime, is about 0.25 (*Peixoto and Oort* 1992). When $R_i < 0$, the stratification is unstable and the flow is clearly turbulent, whereas for large positive values of R_i the turbulence tends to decay.

During the day, it is common for the boundary layer over land to become unstable; the resulting efficient mixing of momentum causes the wind speed near the surface to increase. During the night, the surface temperature normally drops; the greater stability suppresses the downward mixing of momentum, causing the near-surface wind speed to decrease (*Hartmann* 1994). As we shall see in section 2.2.3, such a diurnal cycle also characterizes the mean wind speed measured in the Victoria area.

2.2.1 Local climate characteristics

The local climate is strongly influenced by the geographical location. The city of Victoria is located on the southern tip of Vancouver Island at 123°22′W and 48°25′N in a northern sub-Mediterranean zone. It has a temperate climate which is usually classified as Marine west coast, although sometimes arguably classified as Mediterranean. Winters are damp, whereas summers are relatively dry. The proximity to the ocean plays a key role in maintaining the local temperature regime. Thus, both winters and summers are mild, so that the annual temperature range is quite small. The daily temperature range in summer is larger than in winter. On average during summer months, the daily maximum temperature is $19.3°C$, whereas the daily minimum temperature is $11°C$; during winter, they are $7.6°C$ and $3.3°C$, respectively (*NCDIA* 2007). These temperatures are for Gonzales Heights HTS. This station is located at an elevation of 70 m and its meteorological data are greatly influenced by the Strait of Juan de Fuca. At other locations in the Victoria area, which are farther from the water, the temperature and its range are different. For example, the air temperature variations during a year at station UVicISC for the period from March 2002 to December 2006 are shown in Figure 2.5.

The general pattern of the near-surface winds in the northeast Pacific (Figure 2.1) is set by the major pressure systems in the region (Figure 2.2), as well as by the proximity to the Coast Mountains. The Aleutian Low and Hawaiian High pressure systems are known to dominate the weather of the northeast Pacific and much of the climate of western North America. The large-scale upper air winds generally tend to follow isobars. They are deflected across the isobars near the surface due to frictional effects. Locally, diurnal variations in the winds can be affected by diurnal variations in the near-surface air pressure gradient as it is affected by air temperature. Therefore, information about local temperature variations can sometimes be used as

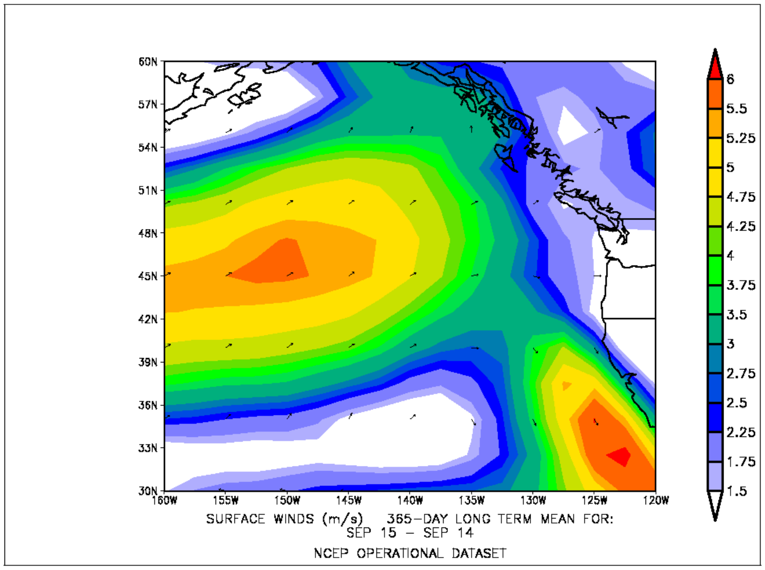


Figure 2.1: The general pattern of annually-averaged near-surface winds in the northeast Pacific. Units are *m/s*. Source: *ESRL* (2007)

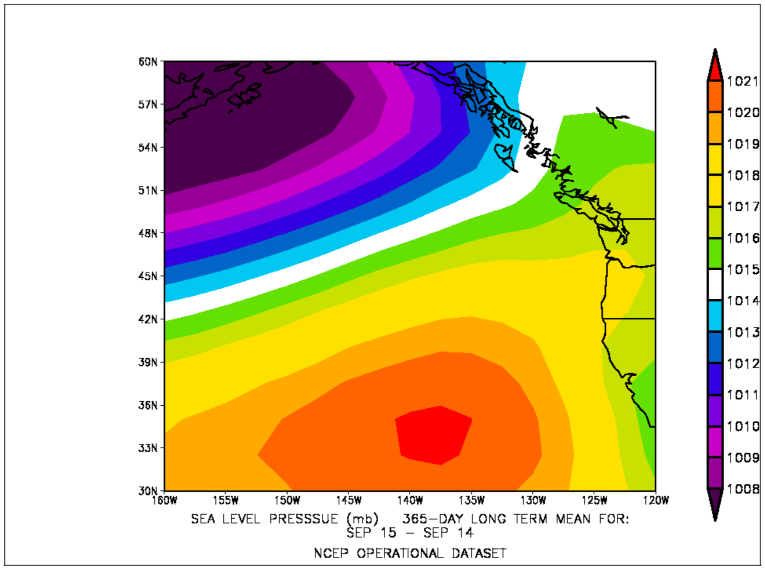


Figure 2.2: The major annually-averaged sea level pressure system in the northeast Pacific. Units are *mb*. Source: *ESRL* (2007)

a proxy to the local wind speed variations during a day.

2.2.2 School weather stations. Wind speed measurements

Meteorological data, used in this study, are collected at weather stations operated by the University of Victoria (UVic). The primarily purpose of the UVic School-Based Weather Station Network (*Weaver and Wiebe* 2006) is to assist teachers in their efforts to promote and support children's interest in physical sciences. Therefore, the data are mainly collected to serve educational purposes. The wind speed is measured using meteorological stations mounted on the schools' roof tops (if possible, on the south-facing side, clear of obstacles such as trees, telephone poles, chimneys, vents etc.) at 107 schools in School Districts 61, 62, 63, 64, 68, 69 and 79. The UVic stations were not installed following the guidance of the Meteorological Resource Centre of site selection criteria (*WebMET.com* 2007). For example, in most cases, the main criteria for the wind speed measurements are not met at the school-based weather stations. These criteria include:

1) the standard exposure height of wind instrument over open terrain should be 10 m above the ground;

2) the distance between the instrument and any obstruction should be at least ten times the height of that obstruction.

In most cases instruments are placed on the roof tops, not over open terrain, and a building itself is an obstacle for the free wind flow. In addition, in the case where a weather station is installed on a pole, the distance between the pole and the nearby obstruction (either a building or a big tall tree) is the same order as the height of an obstruction.

However, it should be taken into consideration that the representativeness may have an entirely different interpretation for different applications. For non-steady state modelling, such as an assessment of wind power resources available in the area of interest (in particular, in Victoria's urban and suburban locations), these data can be used. This is because the possible locations of wind power generators for individual household use can be quite similar to those of the locations of the wind speed and temperature sensors (roof tops or owners' properties).

The wind speed data used in this work is wind speed sampled with a cup anemometer, averaged over 1-minute interval and stored in meters per second. Before October 2004, the wind speed was stored with a resolution of 0.01 m/s. From October 2004 to April 2005, the wind speed measurements were stored with five decimal point precision. Starting from April 2005 the precision is varying depending on the value of the wind speed: four decimal points for wind speeds greater than 10 m/s; five decimals for wind speeds from 1 m/s to 9.99999 m/s; six decimals for speeds from 0.1 to 0.999999 and seven decimals for wind speeds lower than 0.1 m/s.

From anemometer records, it can be seen that wind speed is constantly fluctuating, varying from minute to minute, from hour to hour, from day to day, and year to year. Furthermore, the nature of the wind speed variability may depend on timescale, so that the statistical methods most suitable for describing the characteristics of the wind may also vary. For example, the timescale of the dominant energy built in the wind has a period of a few days. It is associated with a passage of large-scale synoptic pressure systems. Another energy peak has a period of a few seconds (up to 1 min). It is associated with small-scale turbulence. The energy of this turbulence can be seen in the gustiness of the wind. While it does not contribute to the energy production directly, the small-scale turbulence must be considered when designing a turbine because of its implications on the dynamic loads of the turbine's components. The above statement is referred rather to a wind turbine with diameter much larger than the size of small turbulent eddies.

In wind energy applications, the wind speed averaged over the period from 10 min up to 1 hour is usually used. Averaging over this co-called spectral gap eliminates the small-scale turbulent component. Averaging over 24 hour periods would remove the diurnal fluctuations (*Weisser* (2003), *Li and Li* (2005)), and averaging over a long period of time would remove all sorts of variations in wind speed.

Uncertainties associated with time-averaging of wind data

Uncertainties associated with the time-averaging of wind data must also be considered in wind energy applications. Unfortunately, there are no standards for wind averaging times. Most regions of the world use a 10-minute average, following the World Meteorological Organization guidelines. Nevertheless, shorter time intervals are used as well; for example, a 1-minute average is widely used in the USA. For specific applications, such as forecasting of the intensity of tropical cyclones, the wind averaging time appears to be very important. The forecast of a storm's maximum wind speed is based on the current maximum speeds measurements (*NRL* 2007). It is well known that longer averaging times yield lower values of maximum winds recorded. Since many meteorological stations use 10-minute averaging, the wind data has to be converted from 10-minute averages to 1-minute averages to make an accurate forecast. Conversion factors are used for such purposes. The maximum wind speeds recorded based on 1-minute averaging can be about 15% higher than maximum speeds of 10-minute averages. A conversion factor is not constant and must be obtained, empirically or theoretically. It depends mainly on frictional characteristics of the surface and the atmospheric stability.

Are the time averaging intervals important for the assessment of wind energy potential and the estimation of a turbine's output? In applications such as turbine power output assessment, 10-minute average wind speeds are used, as a rule. The reason for this is that such an averaging eliminates the small-scale turbulent component, which does not carry the energy valuable for a wind turbine. This is true for the wind turbines with a rotor diameter much larger than the length scale of turbulent motion. As for turbines with a diameter under 3 m, the impact of small-scale turbulent processes on their power output needs to be further investigated. The duration of a micro-scale atmospheric motion with a typical size of about 2 m is under 20 seconds. Averaging over a 1-minute period eliminates the gusts and lull values from a record. For example, a wind gust can be about 25-30% greater than a 10-minute average over the ocean, and about 40% greater over the land (*AGBOM* 2008). Winds are gusty over rough terrain and near the buildings.

In wind energy assessments, the probability distribution of different wind speeds plays an important role. If instantaneous wind speeds are used in calculating probabilities of different wind speeds, it would result in higher probabilities of higher wind speeds. As will be shown later, the power in the wind is proportional to the cube of the wind speed. Therefore, higher probabilities of higher wind speeds may result in a significantly higher calculated power in the wind, and vice versa.

As a result, the estimated power output based on 1-minute average wind speed should be taken with caution. This level of uncertainty needs to be carefully investigated in future work on wind energy assessment in urban areas. The power output is very likely to be underestimated for very small turbines or overestimated for large turbines, depending on "sensitivity" of a wind turbine to atmospheric motions with different length scales. Based on a simple logical approach, the smaller and lighter the turbine, the easier it responds to frequent changes in wind speed, typical for locations with high level of turbulence. On the other hand, larger turbines do not "feel" the energy of micro-scale motion with a size much smaller than a size of a turbine and with a lifespan from seconds to a few minutes.

For turbines under 3 m in diameter, 1-minute averaged data is insufficient and wind gust data should be incorporated to improve the accuracy. For larger turbines the 1-minute data needs to be converted to 10-minute data. The conversion factors, mentioned above, are used to convert maximum wind speeds only. The probability of wind speeds over the whole possible wind speed range will be affected if different time averaging interval are used, except for the averaging in the spectral gap. To find out how they differ, it is better to look at 10-minute average data collected at the same location for the same period of time and compare it with 1-minute average data. A conversion factor may appear to be a function not only of the frictional characteristics of the surface and the atmospheric stability, but the wind speed as well. Calculation of conversion factors for a particular location is a complex task. For this reason the use of conversion factors is omitted from the power output assessment in this work.

2.2.3 Wind pattern (UVicISC)

For the wind energy assessment in Victoria the wind speed characteristics such as averages and probability distributions were analyzed for all the stations which have data available for at least one year. By the end of 2006 the network had 24 stations with data recorded from January 1, 2006 or earlier to December 31, 2006 and 10 stations with data recorded since the middle of January, 2006. However, because the station UVicISC is the oldest station in the network, installed in March 2002, it was decided to analyze its data for the total period first. The annual mean wind speed was calculated for each year starting from 2002 to see the inter annual variability in the mean wind speed at this station. In 2002, there is missing data for the first quarter of the year, so this year was omitted from the analysis of seasonal (from month to month) and diurnal variability. Nevertheless, the whole set of data available at the UVicISC station was used for an analysis of the statistical distribution of wind speeds and wind power density profiles.

Annual and overall wind speed

Figure 2.3 presents the wind speed averaged over the whole period of the currently available data (from March 2002 to December 2006), and for each year separately. While the record is relatively short, these values give a sense of the amplitude of inter-annual wind variations. The inter-annual variability (if data is available) can be taken into account while forecasting short term wind energy production for the

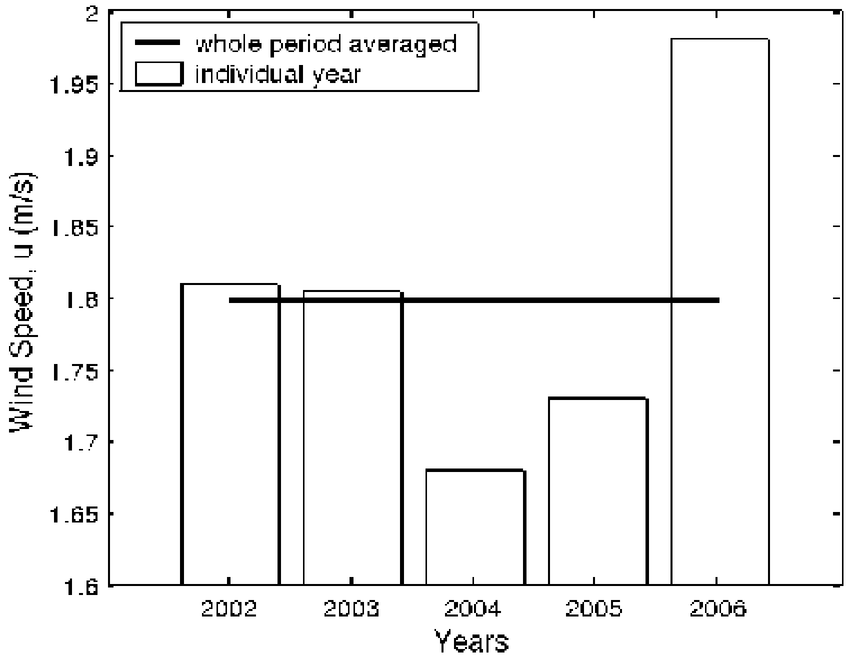


Figure 2.3: Wind speed in m/s averaged over the whole period (from March 11, 02 to December 31, 06) and yearly mean wind speed.

next few years. The annually-averaged wind speeds at UVicISC site vary from 1.68 m/s to 1.98 m/s, which are too low to be of interest in terms of their potential for wind energy generation. For the site to fall at least into Class 2, which is suitable for wind energy development, the average wind speed should be above 4.4 m/s (*Elliot and Schwartz* 1993). That is why it is important to find out if the winds characterizing shorter timescales and/or particular seasons and/or time of the day may contain a larger wind energy potential.

Monthly and seasonal wind speed variations

The mean annual cycle at the UVicISC station for the period from 2003 to 2006 is shown in Figure 2.4, using monthly wind speed data. For individual years, the deviations from the mean monthly wind speeds are similar, with the largest deviations tending to occur during the winter months. The winter of 2006 was somewhat windier than the previous three winters. The average wind speed for the cold season is about

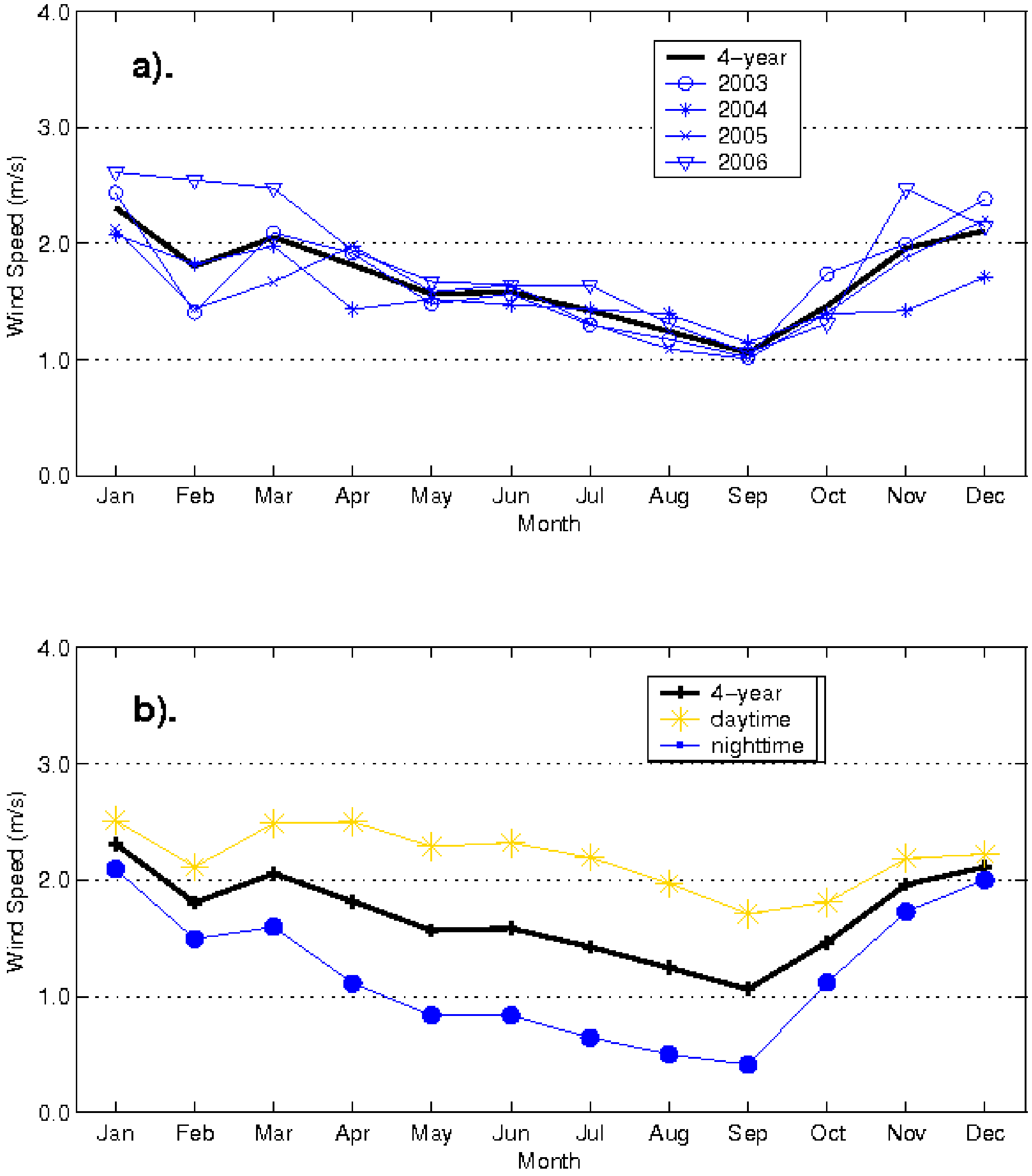


Figure 2.4: Monthly mean wind speed variation in m/s at station UVicISC. a) for overall and individual four years. b) overall and daytime/nighttime mean.

2 m/s, with the largest values in January and December. The average value for the warm season varies between 1 and 1.5 m/s. The windiest month is January, with the monthly-mean wind speed varying from year to year between 2.1 and 2.7 m/s. September is the calmest month of the year, with mean wind speed slightly above

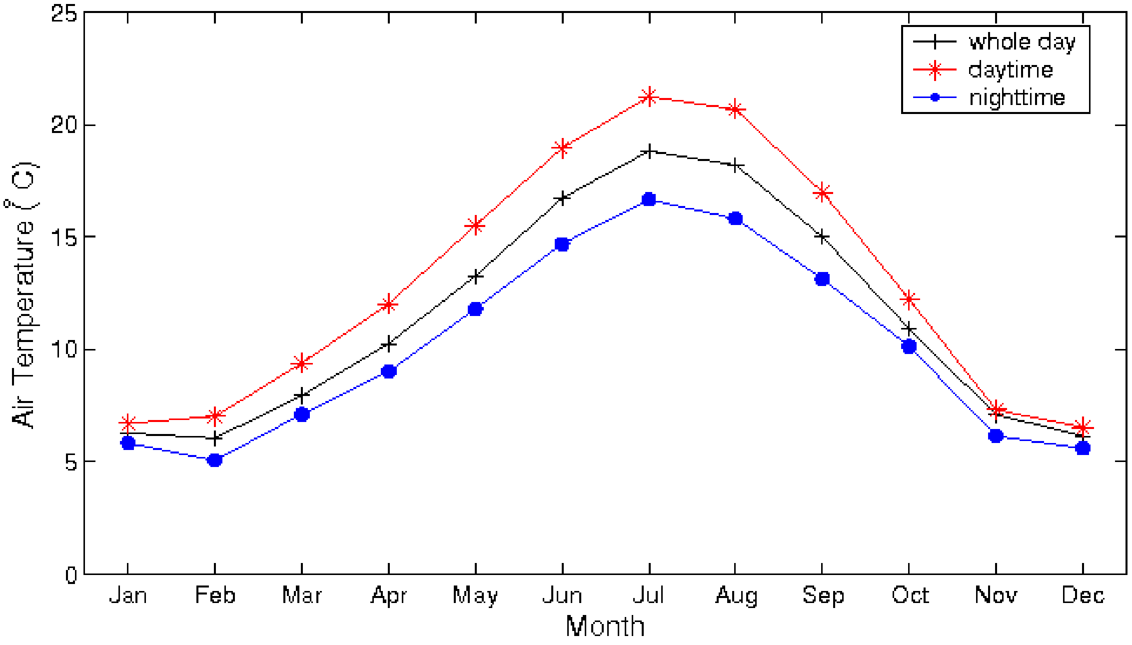


Figure 2.5: Air temperature variations in °C during a year.

the value of 1 m/s and without significant inter-annual fluctuations.

The daytime and nighttime monthly mean values are shown in Figure 2.4(b). Cold season daytime and nighttime monthly mean wind speeds do not vary notably, which means that during the cold season there is comparable wind energy potential during the day and during the night. Daytime average wind speed was at maximum value of 2.5 m/s in January, March and April during the 4-year period of observation (Figure 2.4(b)). The difference between daytime and nighttime mean wind speed is about half a meter per second on average with nighttime mean of 1.67 m/s and daytime mean of 2.22 m/s. In contrast, from April to September the daytime and nighttime mean wind speed differs significantly (on average from 2.16 m/s during the day to 0.72 m/s at nighttime, with the calmest nights from May to September). It is important to note that from April to August, the afternoon hours are windy almost as much as those of cold season. The difference between daytime and nighttime mean wind speed, shown in Figure 2.4(b), correlates with the difference between daytime and nighttime monthly mean temperature (Figure 2.5).

For daytime/nighttime energy potential estimates, the warm season can be defined as the season with a significant diurnal variation in the wind speed. If defined this way, the warm season would include 6 months, from April to September. However, for an overall seasonal wind energy potential estimate, April fits better into the cold season because of it's higher mean wind speed (1.81 m/s) and lower monthly mean temperature (10.53 °C). October, with a mean wind speed of 1.40 m/s and mean temperature of 11.18 °C, should be included in the warm season.

Diurnal wind speed variations

Mean (averaged between 2003-2006) diurnal wind speed variations for the individual months are shown in Figure 2.6 (a). In general, as summarized in Figure 2.6 (b), the cold season months show a smaller diurnal range of the wind speeds. In January and December, which are also the windiest months in the cold season, the mean diurnal range is only about 0.5 m/s. In contrast, from July through September, this range is about 2 m/s. We also note that the month with the windiest daytimes is March, with the values of wind speed reaching 3 m/s at noon.

The diurnal variations for the cold and warm seasons and for the whole year are shown in Figure 2.6 (b). Both seasons have a similar shape to the curves. In particular, in both seasons the daytime is windier than the nighttime. The calmest period during the warm season lasts approximately from midnight until 6 am. During the cold season the wind slows down after 8 PM and speeds up after 8 AM.

Despite these slight differences in cold and warm seasons for the diurnal wind speed variations, it is more convenient to split a day into two equal periods for any season (day - from 8 AM. to 8 PM., night - from 8 PM. to 8 AM.), so that a comparative analysis for daytime versus nighttime wind energy potential could be based on equal data sets.

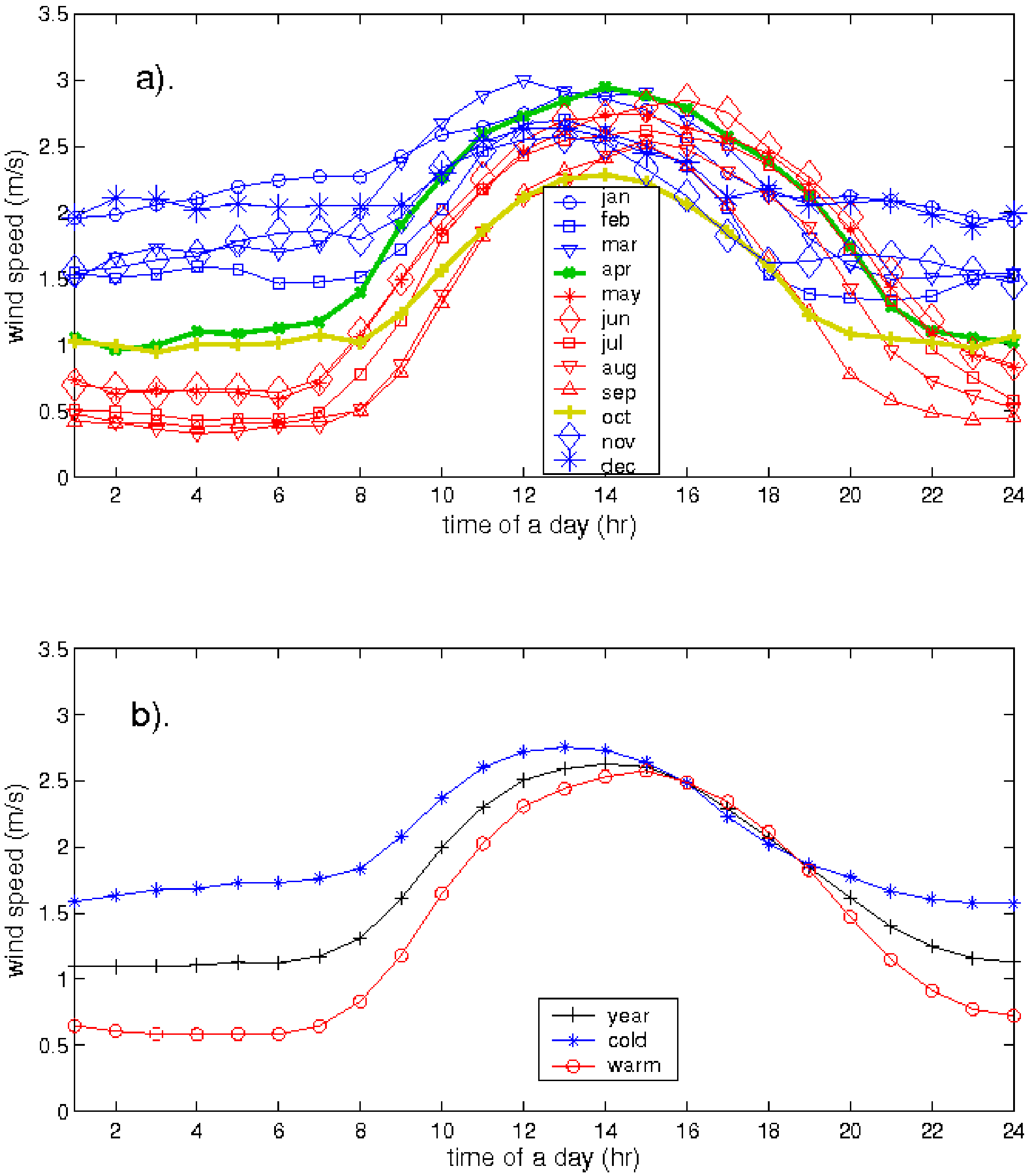


Figure 2.6: Diurnal mean wind speed variations in m/s for each month (a) and for the cold and warm seasons and the whole year, based on 4-year data (2003-2006) at station UVicISC.

2.3 Statistical distribution of wind speeds

Mean wind speed cannot be representative for estimating the available power. Two sites with the same long-term mean wind speed may return a different amount of power. A site with a higher probability of strong winds will return more power. For estimating the energy potential, one needs to know when the productive wind speed occurs and how long it lasts. Hence, it is of great importance to know the probability of different wind speeds for each location.

Using discrete measurements, the probability can be computed as follows:

$$p(u_j) = \frac{m_j}{n} \tag{2.5}$$

where m_j is the number of observations of a discrete wind speed u_j and n is the total number of observations. However for many modelling purposes, it is also convenient to describe the wind speed frequency distribution by a continuous mathematical function such as the probability density function (PDF), rather than by the probability calculated from a table of discrete values. This is because in many cases, the calculated probability can be approximated by an analytical function with well-known properties and with only a small number of fitting parameters. If the same analytical function is used for different sites, then one can conveniently describe the differences in the wind speed probability distribution by comparing the fitting parameters obtained for the different sites (*Mulugetta and Drake* 1996). In addition, for many purposes it is useful to be able to integrate and differentiate the probability density function analytically.

2.3.1 Weibull distribution

Wind speed variations at a certain location are given through the so-called wind profiles or probability density functions. The most often used PDF for the wind speed distribution analysis is the Weibull function (*Justus et al.* 1976, *Seguro and Lambert* 2000). The Weibull density function fits the wind speed frequency curve quite well at many locations of the world if the data are collected for periods of more than several weeks. The Weibull PDF is a two parameter distribution, defined as follows

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{2.6}$$

where c is the scale parameter and k is the shape parameter; u is the wind speed (assumed positive). The fitting parameters are also constrained such that $k > 0$ and $c > 1$. From the definition, it can be seen that if k is greater than unity, $f(u)$ becomes zero at zero wind speed. In reality, however, the frequency of zero wind speed is greater than zero. For example in Victoria, the frequency of calm spells or wind speeds less 0.5m/s is quite high, which is typical for urban areas, where the roughness of the surface is relatively high, which may significantly contribute to the general weakness of the local winds.

The Weibull density function does not fit well over the wind frequency curve close to zero wind speed (*Deaves and Lines* 1997). Moreover, in trying to obtain a PDF satisfying all the data, the fit over the frequency curve for wind speeds of our interest may be affected in some cases. I found, therefore, that the best agreement between the Weibull curve and the raw data can only be achieved if very small values of wind speeds are ignored in the fitting procedure. This can be done without sacrificing the precision in energy potential calculation. This is because typically, the winds under the so-called cut-in wind speed are not utilizable for electricity generation in wind turbines. The reason is that in a mechanical device, winds with speeds below a certain level cannot generate power, largely because a certain amount of mechanical energy is always required to overcome friction. Thus, the cut-in wind speed is defined as the speed at which a wind turbine starts rotating and generating electricity (*CanWEA* 2007a). It is different for different types of turbines. As a rule, the heavier the turbine is the higher the cut-in wind is. The cut-in wind speed can range from as low as 1.5m/s to more than 4m/s.

Determining the Weibull parameters

There are several different methods available to obtain an optimal fit of a theoretical PDF curve to that estimated from the raw measurements. One of them is the Least Squares Method (*Seguro and Lambert* (2000), *Stevens and Smulders* (1979)), which is also used here for calculating the two Weibull fitting parameters c and k from the site wind speed measurements. This method allows one to find a theoretical PDF curve with the best, in a least squares sense, fit to the real data.

In order to obtain simple expressions for the fitting parameters, it is convenient to move from the complex original Weibull PDF shape to a curve which would have a simpler, more liner shape and, at the same time, is easily related to the original PDF. Therefore, one way to proceed is to move from the differential PDF to cumulative PDF which are related to each other through the equation

$$f(u) = \frac{dF(u)}{du} \tag{2.7}$$

The cumulative PDF can then be obtained from the original differential Weibull PDF as follows

$$F(u) = 1 - exp\left[-\left(\frac{u}{c}\right)^k\right] \tag{2.8}$$

with the properties F(0) = 0 and $F(\infty) = 1$. It can then be further linearized by taking the logarithm twice (because the exponent itself is raised to a power). We obtain an expression

$$\ln[-\ln(1 - F(u))] = k \ln u - k \ln c \tag{2.9}$$

which has a form of a straight line

$$y = ax + b \tag{2.10}$$

It is then easy to see that x and y are related to u, whereas the new fitting a and b parameters are related to k and c. These relations are as follows

$$\begin{aligned} y &= \ln\left[-\ln\left(1 - F(u)\right)\right] \\ a &= k \\ x &= \ln u \\ b &= -k \ln c \end{aligned} \tag{2.11}$$

A cumulative PDF $F(u_i)$, used in the procedure for determining the Weibull parameters, is found by summing up the probabilities of discrete wind speeds u_i. Since the wind speeds recorded are continuous, not discrete, variables, the wind speed data was divided into N numbers of bins with intervals $d = 1 m/s$ to satisfy the statement that

$$u_i - d \leq u_n < u_i$$

where u_i ranges from 1 to N (m/s) and u_n is a wind speed from the dataset.

The next step is to find a and b which minimize a functional J of the form

$$J = \sum_{i=1}^{N} \left[y_i - (a x_i + b)\right]^2 = \min \tag{2.12}$$

where N is the number of pairs of x_i and y_i.

The expressions for a and b are then easy to determine. Following a standard procedure by taking derivatives of J with respect to a and b, equating the obtained two expressions to zero and solving for a and b, one obtains:

$$\begin{aligned} a &= \frac{\overline{x \cdot y} - \overline{x} \cdot \overline{y}}{\overline{x^2} - \overline{x}^2} \\ b &= a\overline{x} - \overline{y} \end{aligned} \tag{2.13}$$

where

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{2.14}$$
$$\overline{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$$
$$\overline{x \cdot y} = \frac{1}{N}\sum_{i=1}^{N} x_i \cdot y_i$$

Once the values of a and b are obtained for given x and y (i.e., for a given wind speed dataset and the computed from the data $F(u)$), we can calculate the Weibull parameters k and c:

$$k = a \tag{2.15}$$
$$c = exp(-b/a)$$

2.3.2 Results and discussion

From my experience when determining the fitting parameters k and c, it is useful to operate with different wind speeds intervals for different time frames such as seasons, months, etc. Determining the frequency distribution within certain intervals is widely used for different applications, which require obtaining the best fit over the wind speeds relevant to particular application (*Deaves and Lines* 1997). Finding the best fit over the moderate winds, which means very low and very high wind speeds are ignored, is useful for wind energy applications. In cases where it is important to obtain a good fit over the low wind speeds for use in such applications as risk assessment, methods other than the least squares approximation are used for determining Weibull parameters (*Seguro and Lambert* 2000). In cases where the two parameter Weibull function is not accepted for a reason that it does not accurately represents the probabilities of very low wind speeds, different methods of analytical determination of wind speed distributions are used. For example, *Li and Li* (2005) developed an approach based on the maximum entropy principle.

Therefore, it is also worth experimenting with different upper and lower limits to find the best fit over the wind speed range which has a higher wind energy potential for a given probability distribution. In my opinion; such an approach is acceptable, since most wind turbines do not start rotating at wind speeds lower than 3 m/s. From this follows that estimated power output, based on a PDF obtained for wind speeds higher than cut-in wind speed, is quite accurate.

Overall and Cold/Warm season distribution of wind speeds and PDF

Figure 2.7 shows the fit for the whole year dataset and separately for the cold and warm seasons. Different wind speed intervals were taken to find the best fit. That is, a fit was done to maximize the fit relative to turbines. I found that in some cases when trying to satisfy the fit over the whole wind speed range (from minimum to maximum), the fit over that wind speed range relevant to a wind turbine was not satisfactory. This could result in over estimating or under estimating the turbine power output. Since most turbines do not start rotating at wind speeds lower than 3 m/s, wind speeds under 3 m/s were ignored in the fitting procedure. Also, I found that if an upper limit is set for wind speeds greater than 12 m/s, the fit over the major numbers of wind speeds is affected too.

For the whole dataset available at station UVicISC, the fit was found to be very good for wind speed range from 1m/s to 12m/s. The same result applies for the cold season. However, for the warm season, the use of a somewhat narrower wind speed range (3-10m/s) was found to give a better fit. Therefore for further calculations, it was decided to keep the wind speed range in the fitting procedure from 1m/s to 12m/s for the whole dataset and also for the cold season data, but have it set to be from 3m/s to 10m/s for the warm season.

From Figure 2.8 (b), it can be seen that the best fit of PDF to the data probability

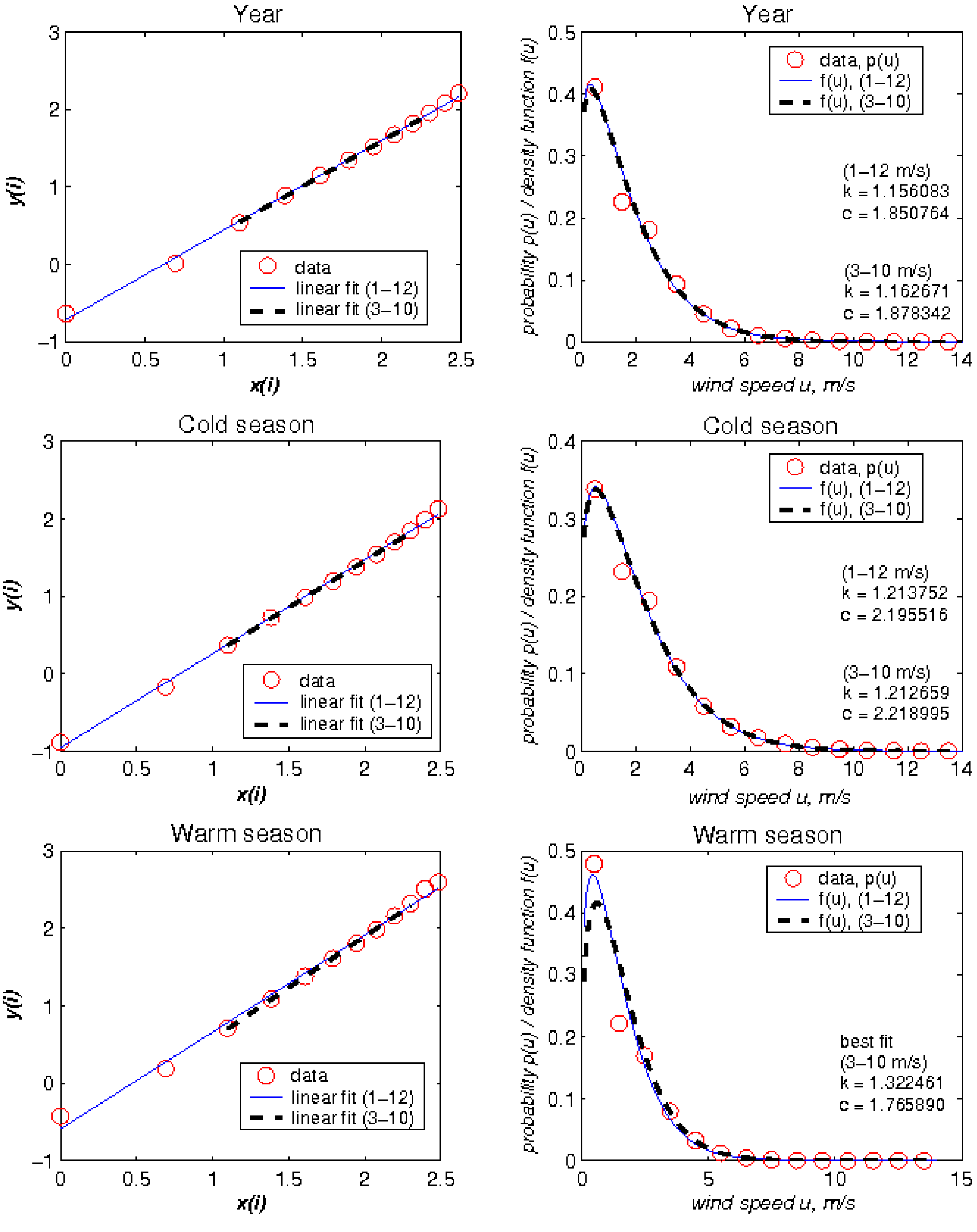


Figure 2.7: Obtaining the best fit of the probability density function with data for the whole year and for the cold and warm seasons (right column) using the least squares method (left column).

distribution is achieved for wind speeds in a range from 1 m/s to 12 m/s for January and from 2 m/s to 8 m/s for July. It is important to note that the cold season

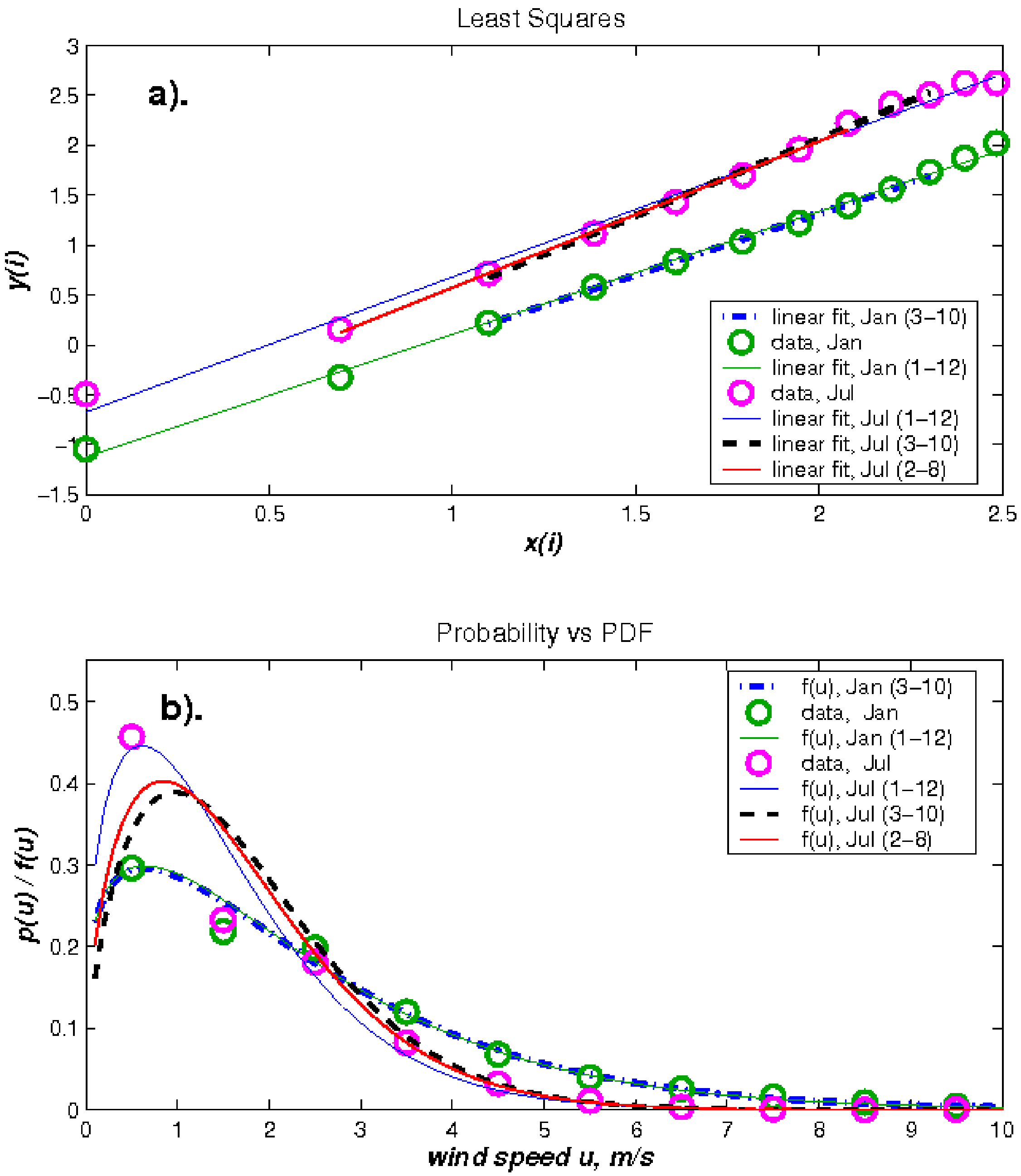


Figure 2.8: Obtaining the best fit of the probability density function with data (b), using the least squares method (a) for two individual months: January and July.

Weibull distribution curve fits quite well to the original data-estimated probability at the upper limit of the wind speed range. For the individual cold season months, the Weibull PDF's fit well over the same wind speed range. Despite the fact that the warm season best fit is obtained if calculated for the wind speeds from 3m/s to

10m/s (Figure 2.7), a wind PDF profile for any individual warm season month and for April are more accurate over the wind speed range of 2-8 m/s. This should be considered for monthly power output calculations.

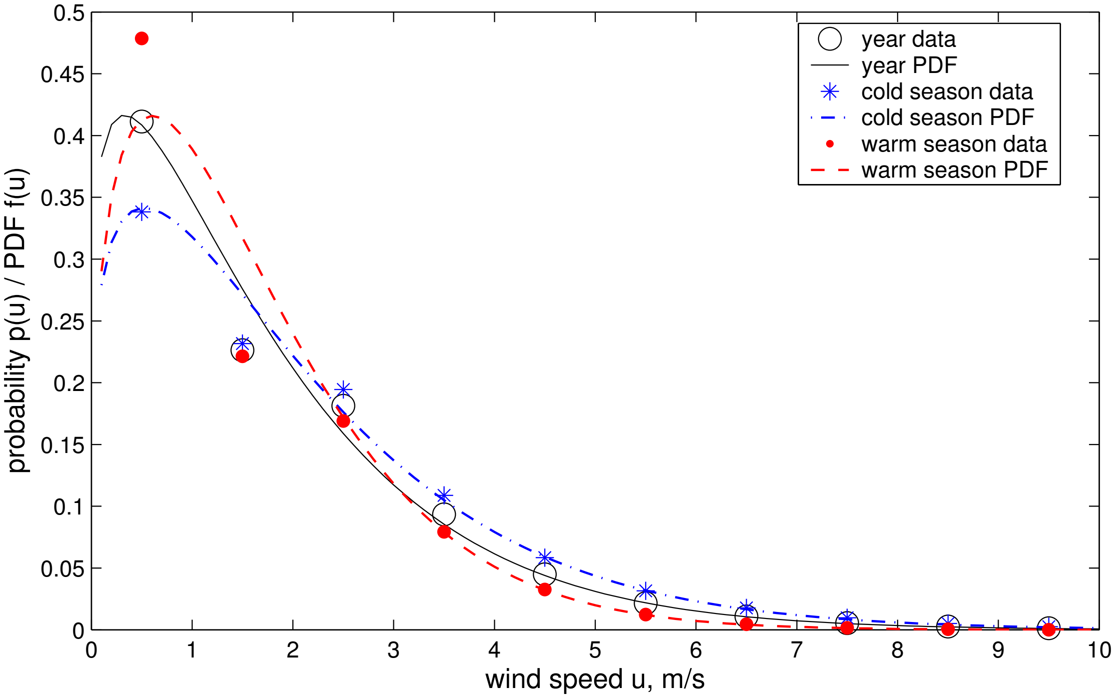


Figure 2.9: Wind speed frequency distribution for the whole year and for the cold and warm seasons (years 2002-2006) at station UVicISC.

Figure 2.9 shows the wind PDF's for the whole year and for both seasons. This way it is better to see the difference between the seasons than from Figure 2.7. The probability of low wind speeds during the warm season is higher than during the cold season, and vice versa.

Daytime/nighttime distribution and PDF

As shown earlier in this work (Section 2.2.3), the wind speed can change dramatically during a day. Daytime mean wind speed is higher than nighttime wind speed. The probability profiles for daytime and nighttime hours and for the cold and warm seasons are shown in Figure 2.10. Although the average daytime wind speed does not differ very much between the cold and warm seasons, an important result I obtain is that the wind power density of cold season daytime hours is likely to be much bigger because of the higher probability of greater than 3.5m/s wind speeds. At nighttime, the probability of calm spells (wind speed is <0.5m/s) is higher than 50% during both seasons.

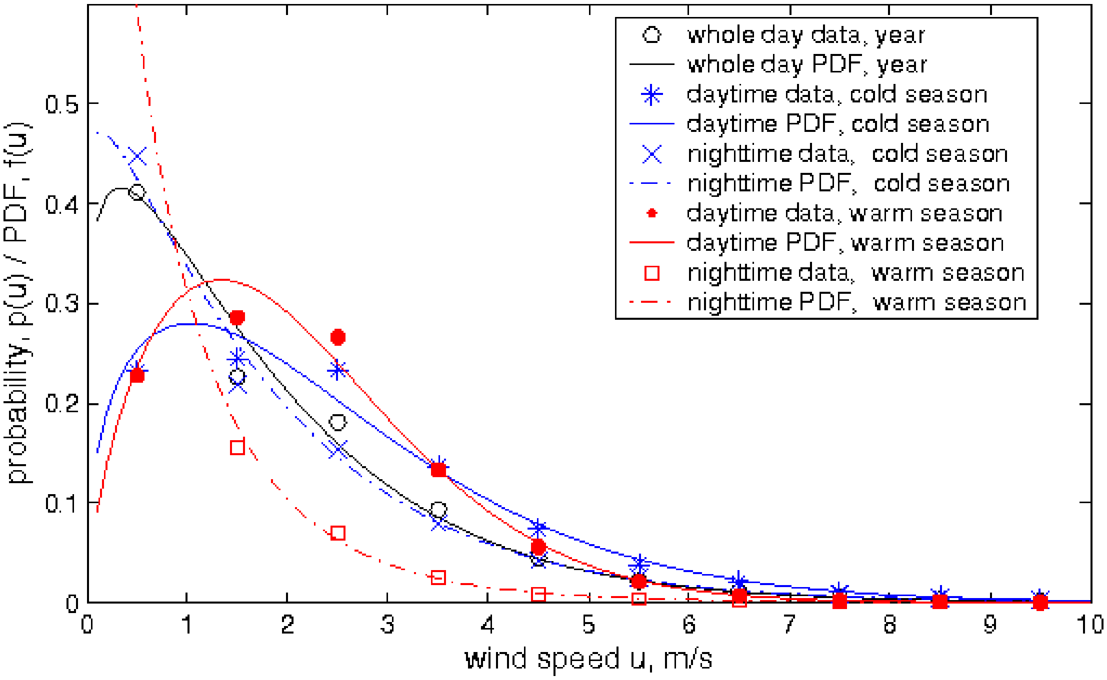


Figure 2.10: Wind speed frequency disribution for the daytime and nighttime data and both seasons (years 2002-2006) at station UVicISC.

2.4 Wind power density

In wind power generation it is important to know the power in the wind available at a given location for conversion into electric power by a wind turbine. A useful way of evaluating the wind power resource is the estimation of the wind power density (WPD) at a site of interest.

2.4.1 Instantaneous WPD

Wind power density is the power in the wind available per unit of area, measured in watts per m^2, and derived from the kinetic energy equation, since the power, by definition, is the energy divided by time (*Johnson* 1985). Of particular interest is the kinetic energy (KE) contained in the moving air that can be converted to electrical energy by a wind turbine. In general, the KE of an object or an air parcel of total mass m moving through the plane of a wind turbine's blades with velocity u is given by

$$\mathrm{KE} = \frac{1}{2} m \cdot u^2 \tag{2.16}$$

where mass, m, is the product of density, ρ, and volume. The volume of the air moving onto a turbine depends on the area of a wind turbine's generator, A, the speed u, with which the air is moving, and the amount of time it travels, t. After substituting of m by its expression

$$m = \rho \cdot A \cdot u \cdot t \tag{2.17}$$

into Eq. 2.16, and remembering that the power is given by energy divided by time, the equation for the power can be written as:

$$\mathrm{WP} = \frac{1}{2} \rho \cdot A \cdot u^3 \tag{2.18}$$

where ρ is the air density. Since the size of a swept area of different turbines is different, for measuring the power available in the wind it is convenient to use an expression which does not depend on the size of a swept area. The Wind Power Density (WPD) is simply the wind power divided by the area A, and represents the power available in the wind, which depends only on the density of the air and the wind speed:

$$\mathrm{WPD} = \frac{1}{2} \rho \cdot u^3 \tag{2.19}$$

Thus, for generating power from the wind, the most important thing to know is the speed of the wind. This is because the WPD depends on the cube of the wind speed value. For example, an increase in the wind speed by a factor of two would result in an increase of WPD by a factor of eight.

As for the air density, a constant value of $\rho = 1.225 kg/m^3$ of dry air at a standard atmospheric pressure at sea level and at 15 °C can be used for rough calculations of WPD based on annual-mean wind characteristics. (Such a procedure, however, may lead to significantly distorted estimates of WPD because the cube of a mean wind speed will differ significantly from the mean of cubed wind speeds – see next section). However, for more accurate calculations, especially for estimating the seasonal distribution in wind energy resources, the air density value at the moment when the wind speed was measured should be taken into consideration as well. At mid-latitudes, seasonal variations in WPD depend on the seasonal distribution of wind speeds and air density. On average, the winds are stronger in winter than in summer in temperate climates, and may also be stronger during daytime than at nights. Moreover, the wind power potential increases during winter time because of the higher air density, because cool air is more dense than warm air. Warmer air is also more frequently humid and becomes less dense with an increase in humidity. However, the effect of humidity is less important than the effect of air temperature and pressure on air density. As a result, the power output of a wind turbine is proportional to air density, which in turn is directly proportional to air pressure and inversely proportional to air temperature. The air density can be determined from the ideal gas law

$$\rho = \frac{P}{RT} \tag{2.20}$$

where P is an atmospheric pressure in N/m^2 (for example, $P_0 = 101325 N/m^2$ at sea level), R is a specific gas constant (287 $J/[kg \cdot Kelvin]$), and T is an air temperature in $Kelvin$ ($^\circ\mathrm{C} + 273.15$).

2.4.2 Average WPD at a site

The wind power density equation should only be used for instantaneous wind speed u_i.

$$\mathrm{WPD}_i = \frac{1}{2}\rho \cdot {u_i}^3 \tag{2.21}$$

Because of the wind speed's variability and of the effect of this variability on the cube of the wind speed, long term averages of wind speeds cannot be used for calculating the power density of wind. The average wind speed depends on the probability of each discrete wind speed

$$\bar{u} = \sum_{j=1}^{m} u_j \cdot p(u_j) \tag{2.22}$$

where m is the number of intervals of discrete wind speeds u_j. By analogy, average WPD depends on probability of wind speeds too:

$$\overline{\mathrm{WPD}} = \sum_{j=1}^{m} \mathrm{WPD}_j \cdot p(u_j) \tag{2.23}$$

or

$$\overline{\mathrm{WPD}} = \frac{1}{2}\rho \sum_{j=1}^{m} {u_j}^3 \cdot p(u_j) \tag{2.24}$$

where

$$\sum_{j=1}^{m} {u_j}^3 \cdot p(u_j) = U^3 \tag{2.25}$$

In the expression 2.25 U is the *wind power weighted average of wind speeds.* The wind speed U represents the wind speed at which the wind flowing through the rotor produces the same energy as the wind flowing at variable speeds (*Li and Li* 2005).

From this, it follows that the average wind power density is

$$\overline{\mathrm{WPD}} = \frac{1}{2}\rho \cdot U^3 \tag{2.26}$$

Using the probability density function $f(u)$ instead of probability of discrete values $p(u_j)$, the expression 2.24 can be rewritten as follows (*Chang et al.* 2003):

$$\overline{\mathrm{WPD}} = \frac{1}{2}\rho \int_0^\infty u^3 \cdot f(u)du \tag{2.27}$$

where the expression $\frac{1}{2}\rho u^3 \cdot f(u)$ is statistically weighted wind power density plotted in Figure 2.11 verses wind speed.

WPD seasonal and monthly variability

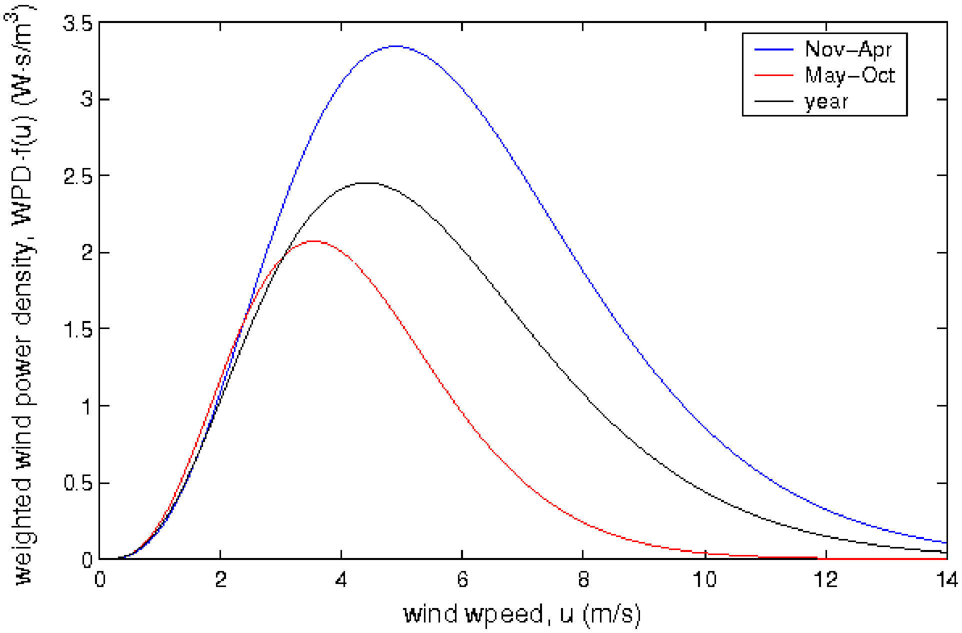


Figure 2.11: Statistically weighted WPD in W·s/m^3 verses wind speed for the whole year and cold/warm seasons for period from March 11, 2002 to December 31, 2006 at station UVicISC.

Annually-averaged wind power density profiles do not give us an idea as to what the energy productivity corresponding to different seasons is and how much it varies from season to season. The wind profiles shown in Figure 2.9 look similar at first glance. However, slightly higher probabilities of stronger wind speeds during the cold season result in much higher wind power density, as can be seen from Figure 2.11.

One year of data from 2006 was analyzed to see the difference in WPD at those weather stations where the data record contains wind speed measurements for the whole year (January 1st to December 31st). Several additional stations were also included if they were installed in January 2006. These stations with the date of installation, shown in brackets, include the following: Doncaster (Jan 16), George Jay (Jan 19), Glanford (Jan 19), Hillcrest (Jan 12), Lansdowne (Jan 16), Northridge (Jan 19), Reynolds (Jan 23) and Sundance (Jan 20). It was decided to include these stations, because January isn't a transitional month, and the data available for at least several days can be quite representative and may not affect seasonal averages at these stations very much. This allows us to have a denser network of stations to create wind power density plots for the Victoria area. Also, the data for the cold and warm seasons were analyzed separately to see the difference between seasons.

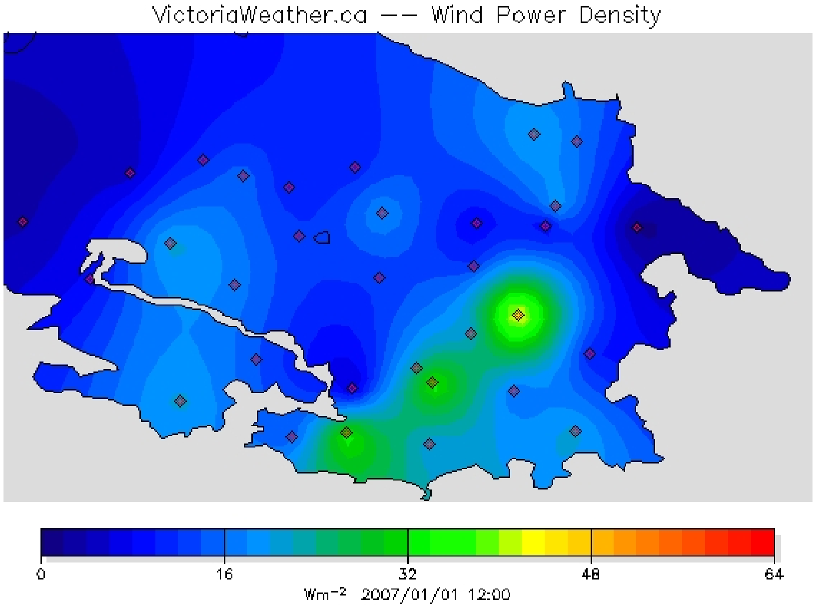


Figure 2.12: Victoria area map of one year averaged WPD based on wind speed data recorded in 2006.

All the WPD values are shown in Table 2.1. The mean wind speed $\bar{u}$, the power weighted average of wind speeds U and the Weibull parameters k and c are shown there as well. The WPD values from this table were used to make the maps of

	Year					**Cold season**					**Warm season**				
Station	$\bar{u}$	WPD	U	k	c	$\bar{u}$	WPD	U	k	c	$\bar{u}$	WPD	U	k	c
AChannel	1.23	4.81	1.99	1.13	1.24	1.42	7.19	2.25	1.18	1.48	1.05	2.00	1.48	1.24	1.02
Campus View	1.33	7.37	2.29	1.14	1.45	1.52	10.66	2.56	1.19	1.70	1.14	4.38	1.93	1.18	1.27
Cedar Hill	1.25	7.92	2.35	0.88	1.06	1.47	13.69	2.78	0.94	1.40	1.03	2.24	1.55	1.29	1.09
Cloverdale	1.56	12.47	2.73	1.02	1.52	1.82	19.04	3.11	1.06	1.82	1.32	6.78	2.24	1.09	1.35
Doncaster	1.69	12.19	2.71	1.16	1.75	1.90	17.91	3.04	1.17	1.98	1.50	6.55	2.21	1.52	1.77
Eagle View	1.03	3.69	1.82	1.06	1.06	0.97	3.77	1.81	0.95	0.91	1.08	3.74	1.83	1.24	1.26
Frank Hobbs	0.79	1.22	1.26	0.93	0.61	0.84	1.74	1.40	0.96	0.71	0.75	0.62	1.01	0.94	0.49
George Jay	2.12	23.26	3.36	1.19	2.23	2.31	36.86	3.87	1.10	2.38	1.96	12.73	2.80	1.69	2.34
Glanford	1.67	15.27	2.92	1.04	1.68	1.80	23.18	3.32	0.97	1.73	1.55	8.97	2.46	1.43	1.89
Hillcreast	1.91	16.08	2.97	1.19	1.97	2.25	24.22	3.37	1.27	2.37	1.55	7.78	2.34	1.38	1.75
James Bay	1.79	14.41	2.87	1.13	1.81	2.07	22.70	3.30	1.18	2.17	1.51	6.52	2.21	1.45	1.71
Lake Hill	1.39	10.43	2.57	1.02	1.44	1.50	14.53	2.84	0.98	1.51	1.28	6.53	2.21	1.35	1.63
Lansdowne	2.56	45.65	4.21	1.11	2.62	2.87	63.24	4.64	1.16	3.01	2.29	33.12	3.79	1.16	2.45
MacAulay	1.88	20.73	3.23	1.00	1.78	2.26	35.51	3.83	1.05	2.23	1.49	6.68	2.23	1.37	1.66
Marigold	1.91	20.93	3.24	1.06	1.91	2.15	30.10	3.62	1.07	2.14	1.67	12.75	2.76	1.16	1.78
Monterey	1.90	20.87	3.24	1.05	1.89	2.15	32.40	3.71	1.05	2.15	1.60	7.87	2.35	1.57	1.92
Northridge	1.54	11.36	2.65	1.06	1.55	1.67	15.75	2.92	1.03	1.65	1.43	7.74	2.34	1.23	1.59
Oaklands	1.98	20.80	3.24	1.14	2.06	2.22	30.58	3.64	1.12	2.27	1.75	11.71	2.68	1.39	2.02
Reynolds	1.95	18.64	3.12	1.22	2.11	2.20	28.13	3.54	1.19	2.35	1.74	10.51	2.60	1.64	2.16
Rogers	1.38	10.32	2.56	0.97	1.34	1.50	15.26	2.89	0.93	1.41	1.27	5.81	2.12	1.32	1.54
Shoreline	1.21	8.49	2.40	0.88	1.07	1.32	13.41	2.76	0.85	1.18	1.09	3.91	1.86	1.33	1.35
SJD	2.05	20.44	3.22	1.24	2.22	2.07	25.54	3.43	1.15	2.19	2.02	15.39	2.94	1.51	2.34
South Park	2.44	34.22	3.82	1.20	2.56	2.63	46.94	4.20	1.18	2.77	2.24	21.29	3.28	1.43	2.52
Strawberry	1.17	5.03	2.02	1.03	1.13	1.35	7.81	2.31	1.08	1.38	0.99	2.31	1.56	1.23	1.06
Sundance	1.88	15.79	2.95	1.16	1.91	2.11	24.50	3.38	1.13	2.13	1.68	8.08	2.37	1.69	2.01
Swan Lake	1.41	12.25	2.71	0.95	1.38	1.69	20.14	3.17	0.99	1.70	1.16	5.12	2.04	1.23	1.39
Tillicum	1.78	17.24	3.04	1.07	1.80	1.92	25.37	3.42	1.01	1.88	1.65	10.14	2.56	1.35	1.89
Torquay	1.97	20.54	3.22	1.08	1.94	2.44	35.10	3.81	1.19	2.52	1.50	6.93	2.25	1.34	1.65
UVicISC	1.98	19.99	3.20	1.16	2.06	2.41	32.55	3.72	1.25	2.57	1.56	6.94	2.25	1.36	1.67
Vic High	2.35	34.33	3.83	1.13	2.42	2.59	50.16	4.29	1.11	2.66	2.11	18.27	3.11	1.28	2.21
Vic West	1.80	14.19	2.85	1.21	1.91	1.94	19.64	3.14	1.17	2.05	1.66	8.89	2.45	1.54	1.97
Willows	1.53	10.23	2.56	1.10	1.57	1.85	16.65	2.97	1.21	2.00	1.21	4.30	1.92	1.15	1.23

Table 2.1: Annually-averaged and seasonally-averaged wind speed u in m/s, WPD in W/m^2, wind power weighted wind speed U in m/s and corresponding Weibull parameters at 32 stations in 2006.

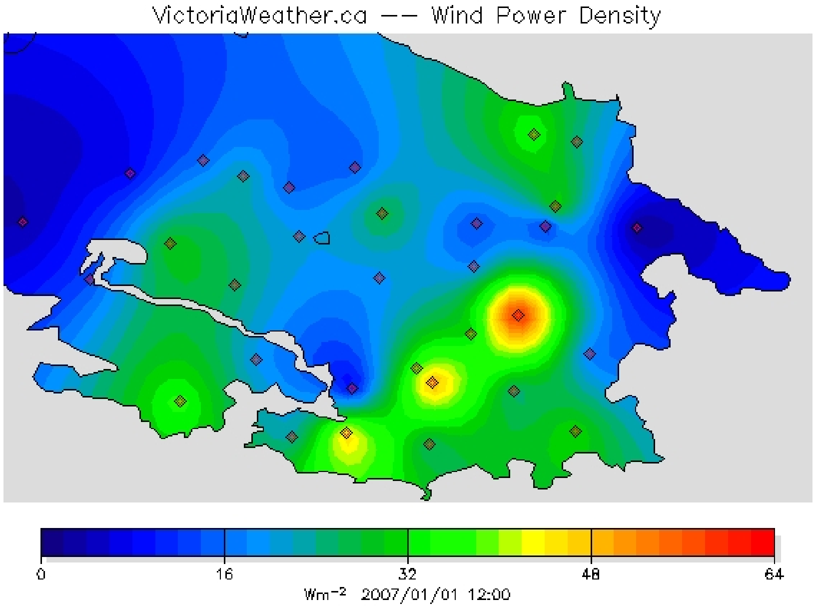


Figure 2.13: Victoria area map of cold season averaged WPD based on wind speed data recorded in 2006.

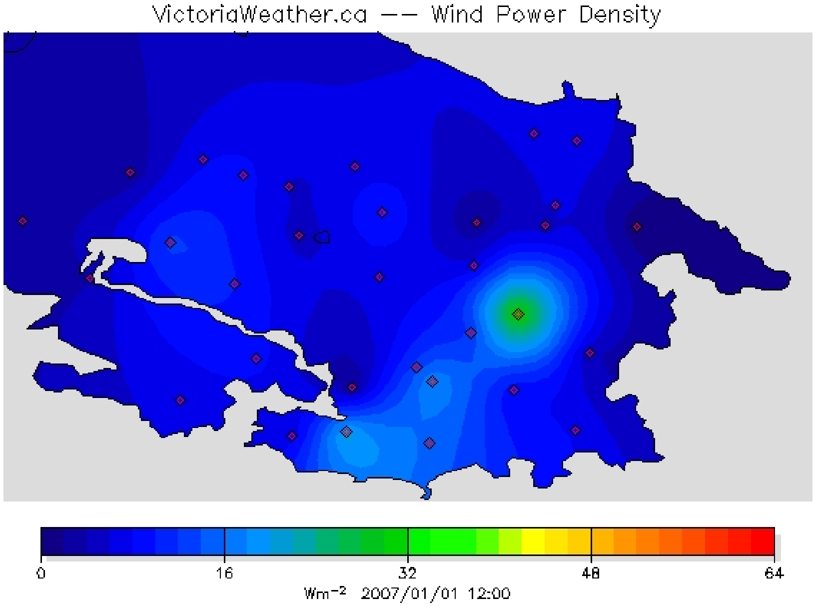


Figure 2.14: Victoria area map of warm season averaged WPD based on wind speed data recorded in 2006.

WPD for Victoria area (Figures 2.12, 2.13 and 2.14). The bar scales in these plots are chosen to be the same for all the plots to see the difference from season to season and the deviation of seasonal values from annually-averaged values. The maps showing the WPD distribution over Victoria area are included herein for illustrative purposes only and, therefore, the correct value of WPD at any other location between stations may differ from that shown in the map. To interpolate WPD values between stations a method called *Kriging* is used. This enables the creation of two-dimensional contours. This method does not account for the effect of the topography and land cover, resulting in a bull's-eye pattern of a spatial distribution of WPD around the stations with very high and very low values.

From Figure 2.12 we can conclude that in the Victoria area there is no promising location where the wind energy potential is feasible for any scale utilization. Most of this area has WPD under 20 W/m^2 (blue shaded). Only a small area (shown as green shaded in the picture), where Lansdowne, South Park and Vic High are located, has higher (from 20 $\mathrm{W/m^2}$ to 45 $\mathrm{W/m^2}$) wind power density. The warm season potential is about 1/3 less than the annual average. The cold season potential is higher by the same fraction. The maximum WPD of 63.24 W/m^2 was experienced at Lansdowne school during the cold season in 2006 (see Table 2.1). From the wind energy potential point of view, Lansdowne is the best site in the network, though the level of WPD during the windiest year and season is still below of 100 $\mathrm{W/m^2}$, the level which is widely accepted to be satisfying for wind energy utilization by small and micro scale wind turbine generators.

In the next chapter it will be shown that there is no WPD level that would be considered as “cut off”. Micro and small scale wind turbines are designed for different levels of WPD and able to generate usable power at locations with the lowest wind speeds. However, the feasibility of the wind energy source in Victoria area is quite questionable. At the present time individuals may not find the financial support from the government because the wind power is not a feasible source for electricity at locations such as Victoria due to the fact that this area falls in Class 1, based on assessment conducted in my study. Moreover, the manufacturers of small and micro turbines, when advertising their products, highly recommend that in order to get from the turbine what is promised, the annual average wind speed must be over 4 m/s. Small-scale wind energy technology is still at its early stage of development; and the feasibility depends less and less on wind power density class, but more on design of the turbine and most importantly on its cost and the cost of the conventional electric power.

Based on the results obtained five stations were chosen for further detailed analysis:

1) UVicISC (the station with the longest observation period; also, it represents a site with average wind power potential)
2) Campus View (station with very low potential, though located close to UVicISC)
3) Lansdowne (the station with the highest potential)
4) Vic High (high potential)
5) South Park (high potential).

The last two stations have almost the same level in wind power potential, however it is interesting to see the difference (if any) in power production at these two stations.

Annually-averaged WPD's for 2006 from the five stations considered are shown in Figure 2.15. It is interesting to note how different wind power density could be at different sites, which are located in a single School District #61 (Victoria), simply because of the slight difference in topography and/or surface roughness. Variations in WPD from month to month at these stations in 2006 are shown in Figure 2.16. In parentheses near the station name in both figures there are shown average WPD for each individual station.

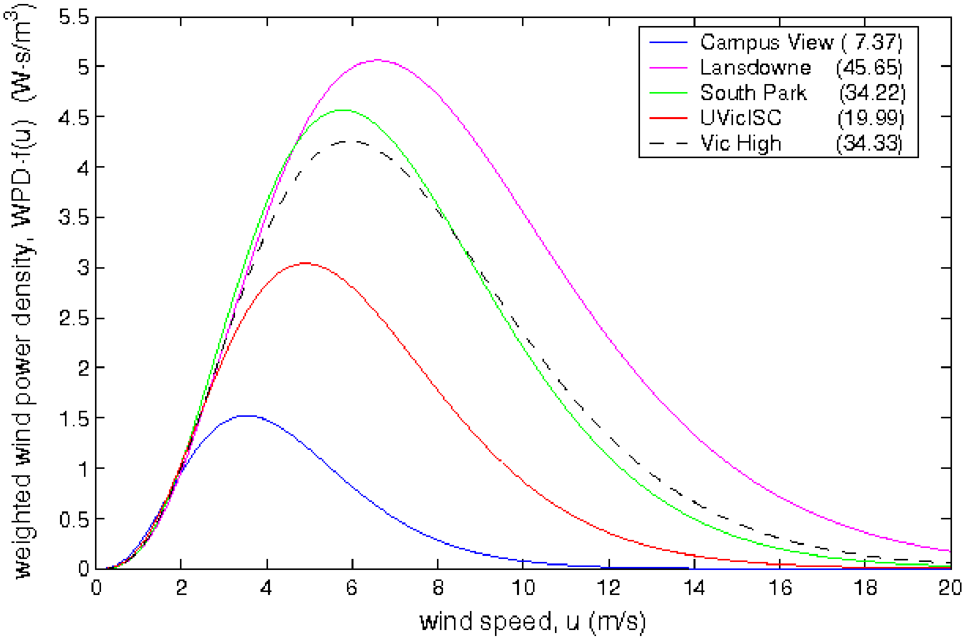


Figure 2.15: Statistically weighted WPD in W·s/m^3 verses wind speed for a whole year 2006 at five different stations.

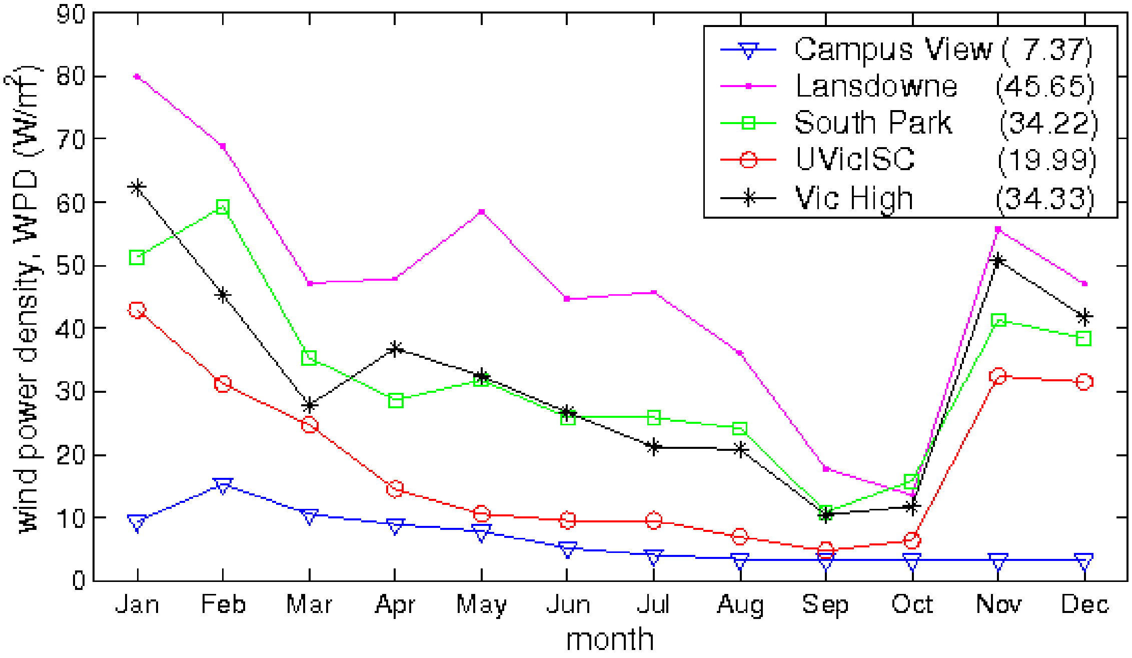


Figure 2.16: WPD monthly variability at five different stations in 2006.

WPD dependence on seasonally variable air density

Since there are seasonal variations in the local wind speeds, the power available in the wind also varies seasonally. Seasonal variations in air density may also contribute to the seasonal variability in the wind power. Therefore, it may be important to know to what extent the local air density variation could affect the power production of a wind turbine, especially if a seasonal forecast of the wind power production has to be done.

In Figure 2.17 we see variations in air density from month to month at the UVicISC location. The values were calculated based on monthly-averaged air temperature measurements at this station, and on annually-averaged atmospheric pressure, since there is no substantial differences in average pressure values from month to month.

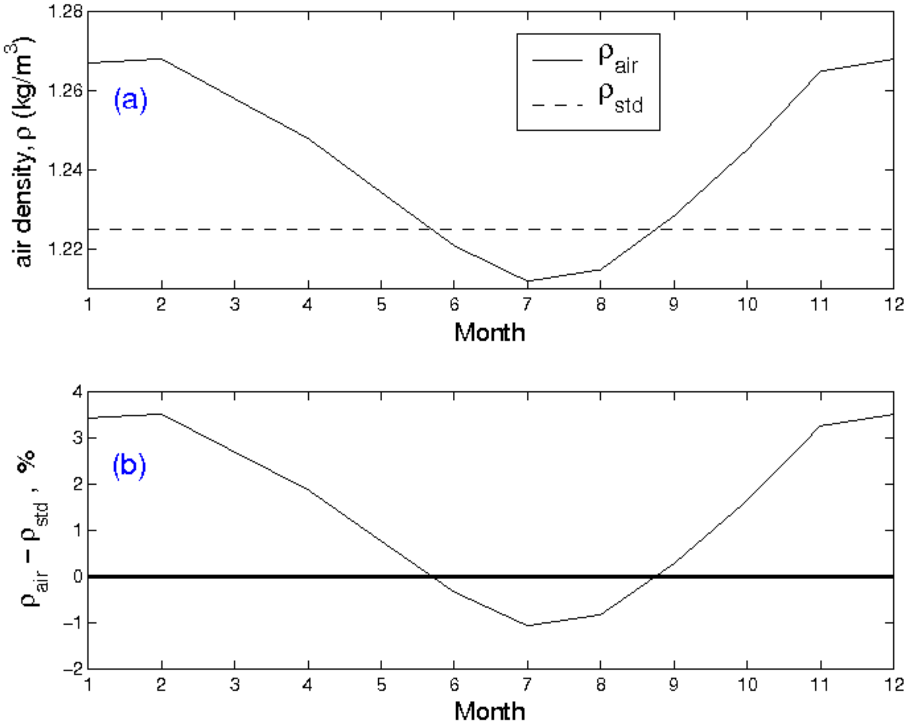


Figure 2.17: Air density seasonal variability around standard air density (a); difference between seasonally variable air density and standard air density in percents (b).

From Figure 2.18 we can see that seasonal variation in air density does not play a key role in WPD variations as much as seasonal variations in wind speed does. Moreover, inter-annual variability in wind speed can affect the yearly power output of a wind turbine much more strongly than the variable air density. A site may experiences big differences in WPD from year to year, especially during winter months.

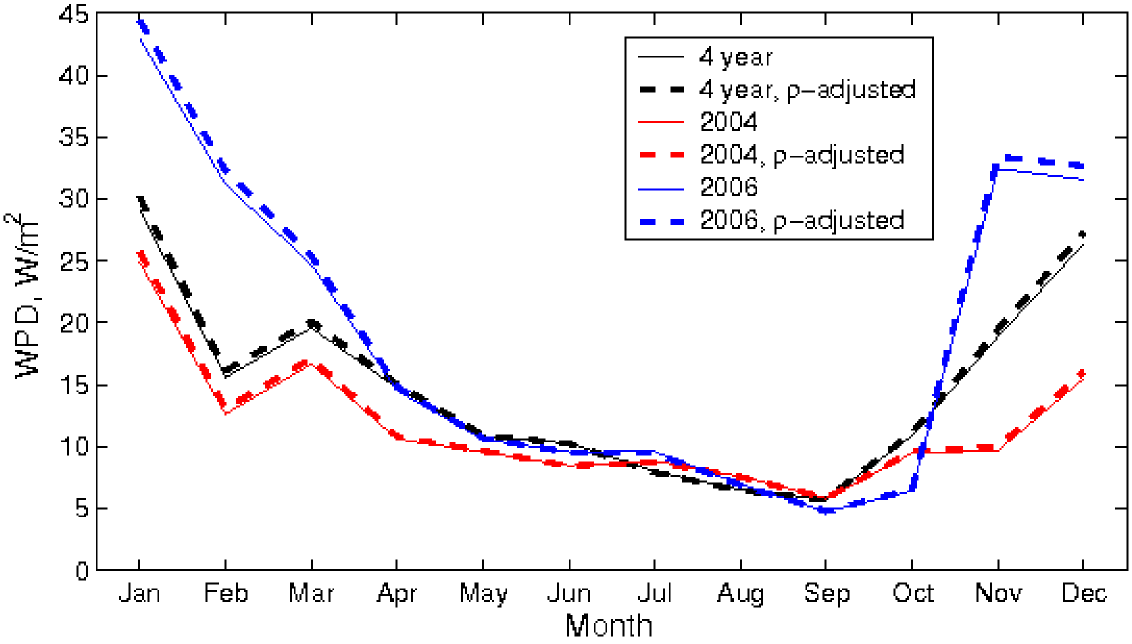


Figure 2.18: WPD monthly variability for period from March 11, 2002 to December 31, 2006 and for two individual years with highest (2006) and lowest (2004) year-averaged WPD with standard air density (solid lines) and variable air density (dashed lines) at station UVicISC.

As an example, Figure 2.18 shows seasonal variability in WPD during two extreme years (2004 and 2006) in the almost 5-year period of observations.

2.5 Summary

We have used the wind speed measurements collected over the last several years at the UVic School-based Weather Station Network to provide a statistical description of the local near-surface winds and to assess the wind power. The most important results obtained can be summarized as follows:

1) While the local winds are generally characterized by relatively small values, being mostly within 1.5-2.5 m/s, the annual and diurnal variability is relatively large;

2) The annual cycle of monthly-averaged winds is characterized by larger wind speed values in winter than in summer;

3) The mean diurnal cycle is characterized by stronger winds during daytime than during nighttime;

4) The amplitude of the diurnal cycle is much larger in summer than in winter, so that the summer daytime winds are comparable in magnitude to those of the winter winds;

5) It is found that the probability distribution of the local winds can be reasonably well described by the Weibull function;

6) It is found that to give the best fit, the procedure for computing the Weibull fitting parameters may differ for different seasons. It is suggested that this should be taken into consideration in the monthly power output calculations;

7) The estimated wind power density for the local conditions is a strong function of the time of the year, with more power available during the cold season lasting from November to April;

8) Because of cubic dependence on the wind speed, the wind power density strongly depends on wind variability, whereas its dependence on variations in air density can be neglected.

Chapter 3

Turbine Power Output Assessment

3.1 Introduction

Using measurements of the wind speed at a site, it is possible to determine whether the site is a good candidate for harvesting wind power. The conversion of wind kinetic energy into mechanical energy is done by wind turbines. As I describe below, there are different types of wind turbines. Therefore, it is important that specific recommendations take into consideration not only the wind regime specific to the selected site, but also some other factors, including the advantages and disadvantages of a particular turbine type. Based purely on the operation, however, the performance of a wind turbine is determined by the so-called power curve. This curve represents the relationship between the electrical power output and wind velocity, forming the basis for estimating the energy which can be expected under given wind conditions at a specific site. In this chapter, I consider the local wind regime to provide an assessment of turbine power for the Victoria area. Several local sites will be considered. One of my main findings here is that, despite the relative proximity to each other, the power which can be generated at different sites differs significantly.

3.2 Types of turbines

There are two main types of wind turbines, based on orientation of rotor axis. Horizontal axis wind turbine (HAWT) has its rotor axis parallel to the wind flow (*CanREN* 2007). Being a propeller-type wind turbine, HAWT must be pointed into the wind to capture as much wind energy as possible. To point a small turbine of this type toward the wind, a tale vane is needed. To rotate a propeller-type wind turbine, a lift force is required. It is recommended to mount a home-sized HAWT at least 100 m away from nearby obstruction to avoid large scale eddies (*ZAP* 2007).

Vertical-axis wind turbine (or VAWTs) has the main rotor shaft running vertically. Depending on the force required to rotate them, there are two types of VAWT (*AWEA* 2007d). The Savonius type of turbine is a drag-type VAWT with S-shaped rotor (when viewed from above). Lift-type VAWT's include Darrieus (with C-shaped blades) and Giromill (a version of Darrieus turbines, but with straight vertical blades) turbines. The main advantages of VAWT turbines are that they do not need to be pointed into the wind and that they produce virtually no noise due to a low rotational speed. The main disadvantage of VAWT's is that the amount of energy produced by most of them is only a fraction of that produced by HAWT's, largely because of the additional drag that they have as their blades rotate. The Darrieus is also not self starting, which is not a major problem.

According to the classification system for wind turbines, there are four types based on size: Micro, Small, Medium and Large. For small application such as residential use only the performance of two types of wind generators (Micro and Small) is analyzed in this work. Micro turbines are turbines with rotor diameter less than 3 m and power rating under 2 kW. The small turbine group includes turbines with diameter from 3 m to 12 m and with rated power from 2 kW to 40 kW (*Gipe* 1999). It is hard to imagine that 10 kW and larger turbines could be used in urban areas for domestic electricity generation. Because of this reason, it was decided to limit to the discussion to turbines with power capacity under 10 kW. The list of the turbines used in the power output estimation as well as some of their technical characteristics are shown in Table 3.1. The turbines have the swept areas ranging from 1 m^2 to 50 m^2.

HAWT models	$\mathbf{D}_{Rotor}$ (m)	$\mathbf{A}_{Swept}$ (m^2)	$\mathbf{P}_{Rated}$ (Watt)	**cut-in** (m/s)
AirX400	1.2	1.08	400	2.7
Lite Breeze	1.5	1.77	150	1.8
FD2.5/300LH	1.5	1.77	300	2.7
FD200	2.2	3.80	200	3.0
FD300	2.5	4.91	300	3.0
FD500	2.7	5.73	500	3.0
FD1kW	3.1	7.55	1000	3.0
FD3kW	5.0	19.63	3000	2.0
FD10kW	8.0	50.27	10000	2.0
ARE10kW	7.2	40.72	10000	2.5
BergeyXL.10	6.7	35.26	10000	3.1
Whisper100	2.1	3.46	900	3.1
Whisper200	2.7	5.73	1000	3.1
Whisper500	4.5	15.90	3000	3.4
AWP3.6	3.6	10.18	950	2.5
BergeyXL.1	2.5	4.91	1000	2.5
Skystream3.7	3.7	10.87	1800	3.5
VAWT models	**width** x **height**	$\mathbf{A}_{Swept}$ (m^2)	$\mathbf{P}_{Rated}$ (Watt)	**cut-in** (m/s)
SeaHawk	0.76 x 1.22	0.93	1000	3.6
WS-2B	1.00 x 2.00	2.00	1000	2.0
WS-4C	1.00 x 4.00	4.00	1500	1.5
WPU2500	1.80 x 2.20	3.96	1500	4.0
CFE3500	2.75 x 3.00	8.25	3500	3.0

Table 3.1: Wind turbine generator models, including HAWTs and VAWTs, and their technical specifications such as rotor size, swept area, rated capacity and cut-in wind speed.

3.2.1 Power curve

A power curve is defined as a chart showing a wind turbine's power output across a range of wind speeds (*CanWEA* 2007a). In other words, a power curve shows instantaneous power output of a wind turbine at different wind speeds at a constant air density. Power curves are obtained from laboratory or field tests, or determined theoretically by aerodynamics of the rotor and it's power control mechanism. Published power curves are typically presented for standard conditions of temperature and pressure. The air density value, used for calculating the power in the wind at standard conditions is derived from expression 2.20. At a standard temperature of 288°Kelvin (15°C) and sea level pressure of 1013.25 mb ($P_0 = 101325\text{N/m}^2$), air density is 1.225 kg/m^3. Sometimes, 0°C is used as a standard temperature.

The power curve of a wind turbine is its most important characteristic used in the theoretical calculation of turbine power output for different wind speed regimes. Two important characteristics of a wind turbine can be derived from the power curve: *capacity factor* (C_f) and *coefficient of performance* (C_p). The capacity factor is a measure of energy production. This value is not constant since it is influenced by the variable nature of the wind resource (*Pitt et al.* 2005). It also represents, to some extent, the feasibility of a wind energy system at a particular site. The coefficient of performance is a measure of turbine's capability to extract the energy available in the wind. This coefficient is used in turbine power output calculations.

Figure 3.1 shows the power output of various types of wind turbines at different wind speeds. In many cases, the turbine power output is given by a single curve, which means that such a curve has most likely been obtained theoretically based on the turbine's design. In some cases, the power curve represents an average output from the field test results. To obtain such a curve, the power output is plotted against the instantaneous wind speed, which is measured at the hub height simultaneously. Then, the average power output is found for each wind speed and plotted as a power curve (*Anahua et al.* 2007). Sometimes, it is the wind speeds averaged over the same period (typically 10-15 min) and electric power outputs which are plotted. The power curves of small wind turbines are produced by manufacturers. In some cases,

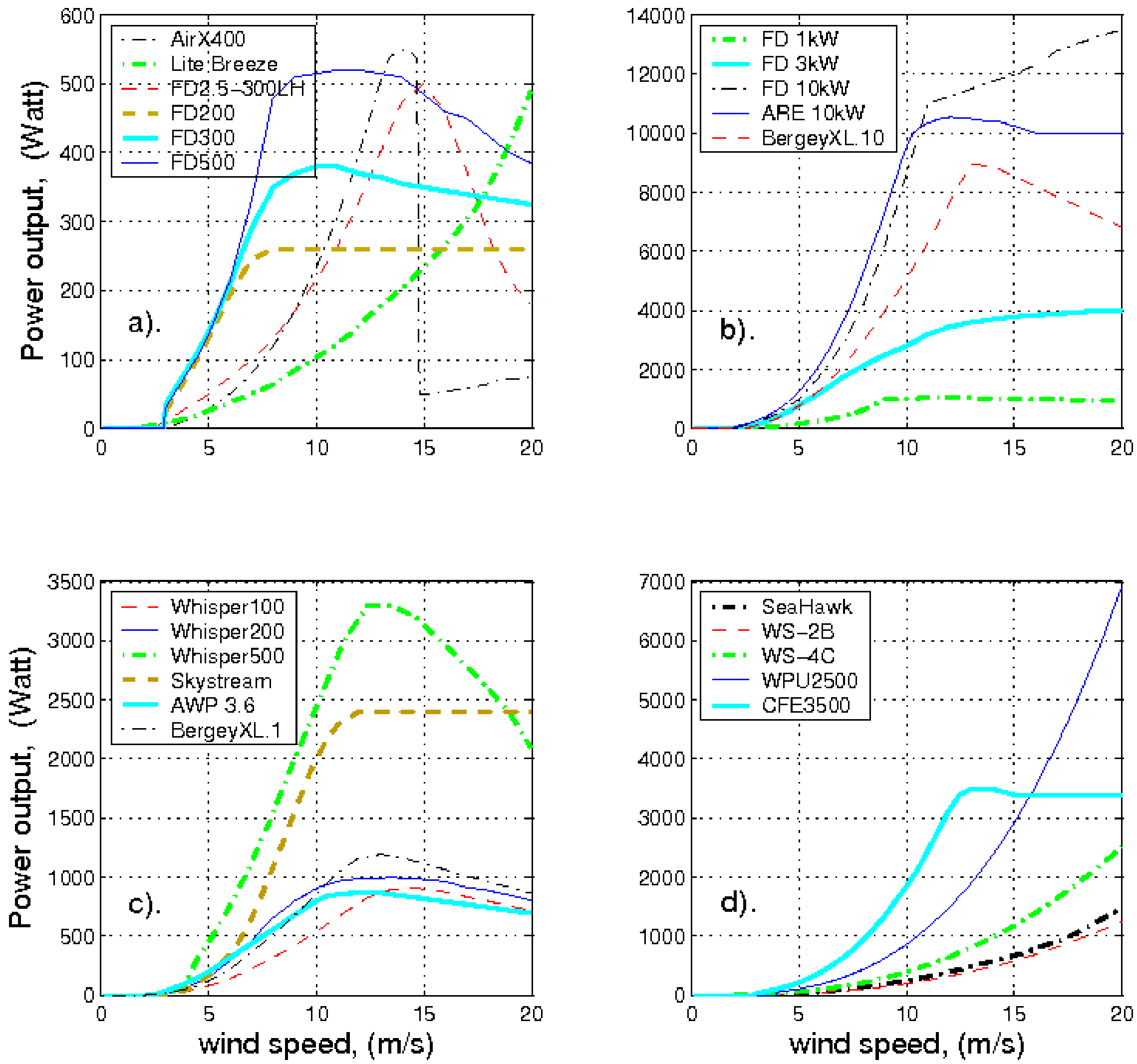


Figure 3.1: The power curve charts of wind turbines: a) micro HAWT, rated from 150Watt to 500Watt; b) HAWT, rated from 1000Watt to 10kWatt; c) various HAWT, rated from 900Watt to 1800Watt; d) VAWT, rated from 1kWatt to 3.5kWatt.

the manufacturers provide a detailed explanation on how the power curves have been derived and under which conditions (*ARE* 2007). Unfortunately, the power curves are not produced or tested by a recognized testing institute; and there is no industry standard for that (*WWO* 2003).

3.2.2 Capacity factor

The capacity factor of a wind turbine is the ratio of the actual productivity or output of a turbine over a period of time to its theoretical maximum output, as if it had operated at the full capacity over the same time period (*AWEA* 2007a). The capacity factor is a measure of wind generator efficiency. C_f is calculated by totalling the energy the turbine produced and dividing it by the energy it would have produced at full capacity:

$$C_f = \frac{P_{out}}{P_R} \tag{3.1}$$

where P_{out} is the turbine's power output, P_R is the rated power capacity (or nameplate capacity) of a turbine. Both the power curve and the rated power capacity are provided by a manufacturer. A turbine's power output at standard conditions, if it cannot be measured directly, is calculated from the power curve chart (*Justus et al.* (1976)):

$$P_{out} = \int_a^b P_{curve}(u)\cdot f(u)du \tag{3.2}$$

where a is the cut-in speed; b is the cut-out wind speed; $P_{curve}(u)$ is the power curve of the turbine; and $f(u)$ is the probability density function.

Typically, a turbine's rated power capacity is the power output at the rated wind speed, i.e. the wind speed at which the conversion efficiency is near its maximum. However, this is not always the case. Quite often a turbine may be rated at 12-13 m/s, while the maximum power the turbine is capable of extracting may be at higher wind speeds. In the case when a turbine reaches its maximum power output at wind speeds lower than 12-13m/s, the rated power is about the same as the maximum power. If the turbine is rated 1000W at 6-7m/s, and the output is not dropping sharply at wind speeds higher than this limit, this could be a rather good turbine for use at locations with average wind speed ranging from low to medium. This is because such a turbine would work at its full capacity a good fraction of a time. Therefore, for each particular type of wind turbine it is important to look at which wind speed the turbine is rated and why.

On average, at locations with good wind energy resources, a capacity factor of

25% to 40% is common for a wind turbine (*AWEA* 2007a). During windy weeks or months, a turbine may achieve higher capacity factor. The capacity factor, however, does not indicate the overall performance of a wind turbine. Rather, it represents a measure of productivity of a wind turbine at a particular location. A capacity factor of the same wind turbine may differ significantly from site to site.

3.2.3 Coefficient of performance

Not all the power available in the wind can be captured by a wind turbine. Power output from an "ideal" turbine will be less due to deflection of the wind flow. Any wind turbine can extract only a fraction of the wind energy available in a wind stream.

For an "ideal" turbine, the mechanical power it can extract is given by the difference between the input and output power in the wind. When the local air speed and pressure are modified (which means that some of the wind's energy is used to overcome the changes in the pressure across the turbine's blades causing the velocity to drop), the usable energy decreases. It can be shown that, due to the physical presence of a wind turbine in a moving air mass, the power extracted by an ideal wind turbine cannot be higher than 59.3% of the power available in the wind stream (*Dwinnell* 1949).

$$\mathrm{P}_{ideal} = \frac{1}{2}\rho\left(\frac{16}{27} \cdot A \cdot u^3\right) \tag{3.3}$$

where $16/27 = 0.593$ is the *Betz coefficient*, or the maximum value of coefficient of performance for the ideal turbine.

In addition, due to mechanical imperfection of a real turbine, the fraction of the power extracted from the wind will be less than that for an ideal turbine. The coefficient of performance of a turbine (C_p) is given by the ratio of the turbine power output to the wind power available in the same swept area as the swept area of the turbine. In other words, this coefficient tells us how effectively a turbine converts the energy in the wind into electricity. Sometimes, this ratio is called the "Power

Coefficient". For any particular wind speed

$$C_p = \frac{P_{curve}}{WP_{std}} \tag{3.4}$$

where P_{curve} is the turbine's power output according to manufacturer's power curve.

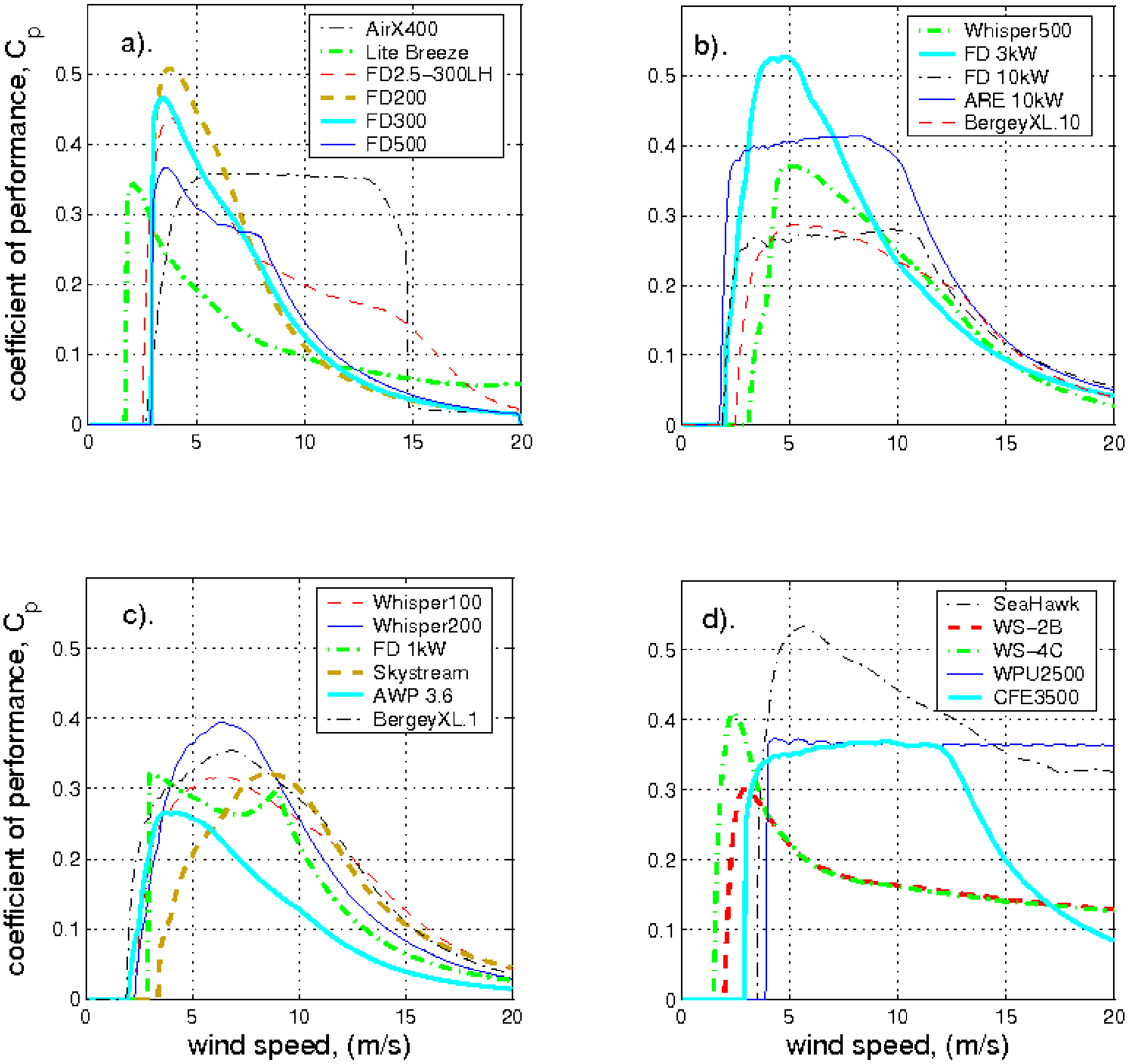


Figure 3.2: Coefficient of performance of wind turbines: a) micro HAWT, rated from 150Watt to 500Watt; b) small HAWT, rated from 3kWatt to 10kWatt; c) micro HAWT, rated from 900Watt to 1800Watt; d) VAWT, rated from 1kWatt to 3.5kWatt

To see how the different turbines perform over the wind speed range from cut-in to cut-out C_p curves were plotted for each turbine, listed in Table 3.1. Figure 3.2 shows the C_p versus wind speed for various types of micro and small wind turbine generators, including HAWT and VAWT wind turbines, rated from 150 Watt to 10kWatt. C_p curves do not give us the idea of the size of turbine, because C_p does not depend on the size of the turbine. For information on turbine swept areas and their rated capacity power refer to Table 3.1.

As we can see from Figure 3.2, the power coefficient varies with wind speeds. Depending on the wind turbine design, this coefficient may reach its maximum value at a particular wind speed, remaining at this level until the cut-off wind speed is reached. Or, instead, it may drop after reaching its maximum. A wind turbine with C_p being, on average, from 35% to 40% is normally considered to be a good turbine. Some turbines may extract as much as 50% of the power available in the wind, but only at some limited wind speed ranges. Therefore, it is important to determine which turbine would be the most suitable one for a given wind speed distribution. In the literature, one can often find the charts where C_p is shown against the tip-speed ratio (TSR), the ratio between the rotational speed of a wind turbine and the free stream velocity (*Johnson* 1985). Such charts are important in designing turbines which would give the best performance. This subject will not be covered in this work. Thus, rather than designing a new turbine for the local wind regime, we aim here to assess the performance of different wind turbines that already exist on the market. Nevertheless, it is hoped that the results of this assessment will be used by experts if it comes to manufacturing turbines more suitable for the Victoria area wind characteristics.

3.3 Power output

A turbine's power output (P_{out}) depends on the cube of the wind speed. This is because it is proportional to the wind power density which, in turn, depends on the cube of the wind speed (Equation 2.19). Thus, we have

$$P_{out} = \mathrm{WPD} \cdot C_p \cdot A \qquad (3.5)$$

where A is the area swept by the wind turbine. For the wind speed ranging from a to b, at which the turbine is capable of extracting the power, the average power output is

$$\overline{\mathrm{P}_{out}} = \frac{1}{2}\rho \mathrm{A} \int_{a}^{b} u^3 \cdot \mathrm{C}_p \cdot f(u) du \tag{3.6}$$

If the purpose is to find the power output for the different seasons or months and, in particular, to account for the effects of seasonally varying air density, this expression should be modified accordingly.

WP_{std} is calculated for standard conditions:

$$\mathrm{WP}_{std} = \frac{1}{2}\rho_{std} \cdot A \cdot u^3 \tag{3.7}$$

If we substitute C_p from Equation 3.4 in Equation 3.6, we obtain an expression which includes both the standard and variable air density:

$$\overline{\mathrm{P}_{out}} = \frac{\rho}{\rho_{std}} \int_{a}^{b} \mathrm{P}_{curve} \cdot f(u) du \tag{3.8}$$

Equation 3.8 can be used for calculating the total power output under variable air temperature conditions, or at the elevations where atmospheric air pressure differs significantly from standard atmospheric pressure and, therefore, affects air density.

3.3.1 Results and discussion

As implied by Equation 3.6, the average turbine power output depends on several characteristics. These include air density, the turbine's swept area, its coefficient of performance and the wind probability density function. Therefore, for any particular wind turbine, the power output varies from location to location in the same way as does the wind power density.

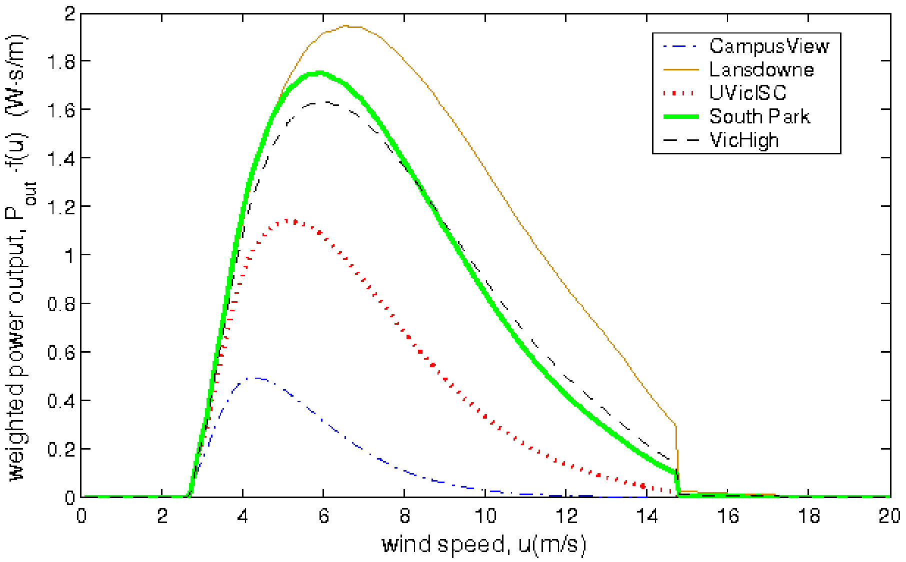


Figure 3.3: Statistically weighted power output by the AirX400 wind turbine in W·s/m. Five locations are shown: Campus View, Lansdowne, South Park, UVicISC and Vic High

WPD dependant power output

Figure 3.3 shows statistically weighted power output by the AirX400 turbine for five different local sites. The power output differs considerably, being the lowest at the Campus View site. The largest wind power output is found at the Lansdowne, South Park and Vic High. The power outputs of this turbine at chosen locations, totalled over all wind speeds, are shown in Table 3.2 in the P_{out} columns. At Campus View, the maximum power output is estimated for wind speeds of about 4 m/s, whereas at Lansdowne, South Park and Vic High it is shifted toward higher speed values.

While assessing the power output of any particular turbine at different locations with different levels of wind power resources is of considerable interest, it is also important to be able to assess the power output for different wind turbines at a given location. The corresponding plots would tell us, in particular, the role of C_p and swept area in producing electric power from the wind power.

In Figures 3.4, 3.5, 3.6 and 3.7 are shown the power output, weighted over the wind speed probability density function, for HAWTs and VAWTs. The sites selected

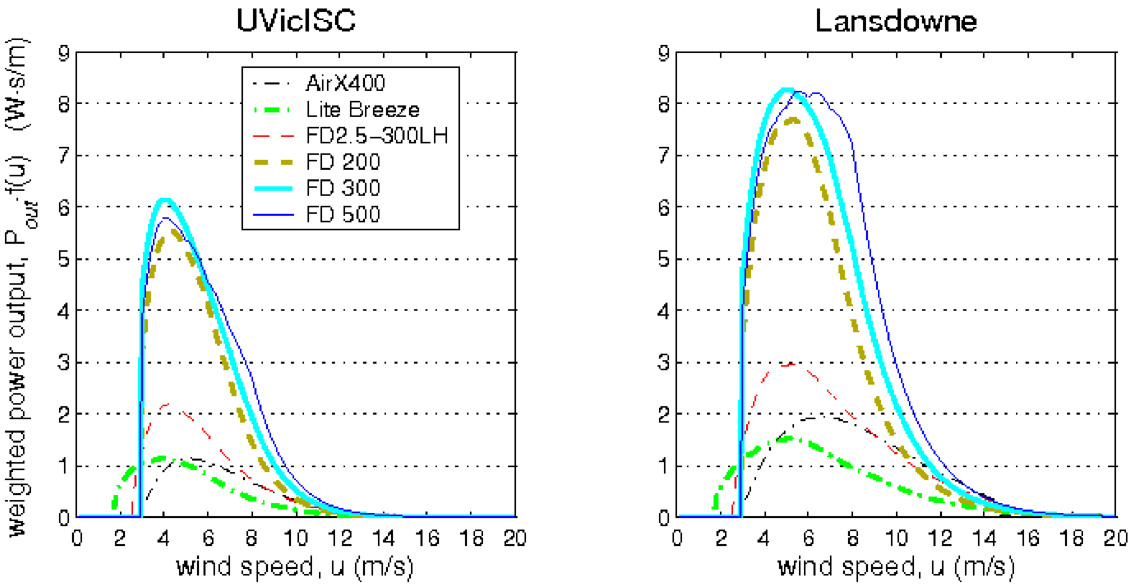


Figure 3.4: The amount of wind power, weighted over the wind speed probability density function, extracted by micro HAWT: AirX400, Lite Breeze, FD2.5-300, FD200, FD300 and FD500 at the UVicISC (Left)and Lansdowne (Right)locations

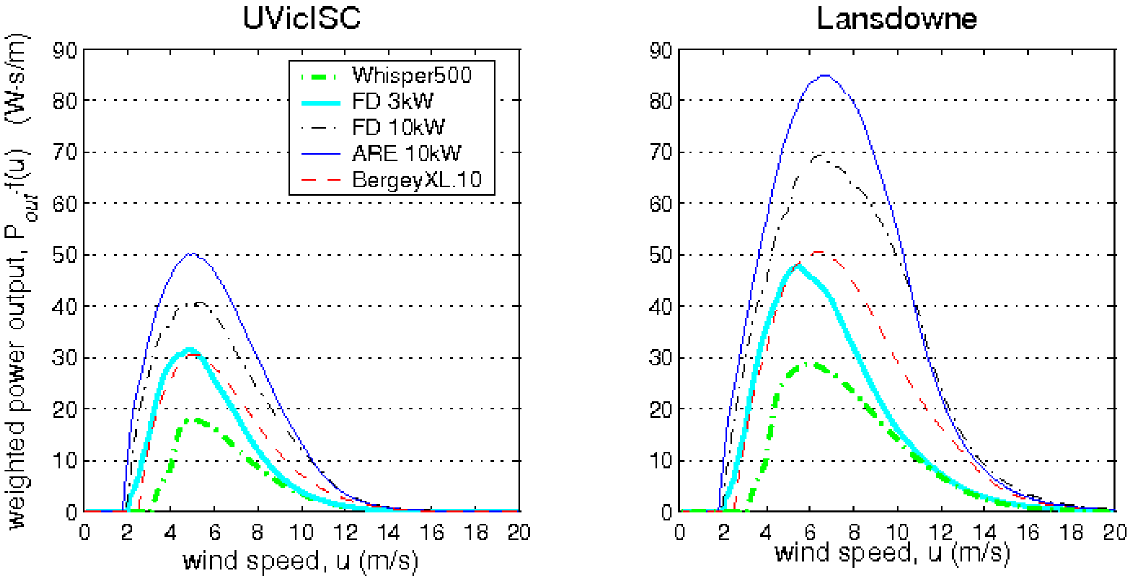
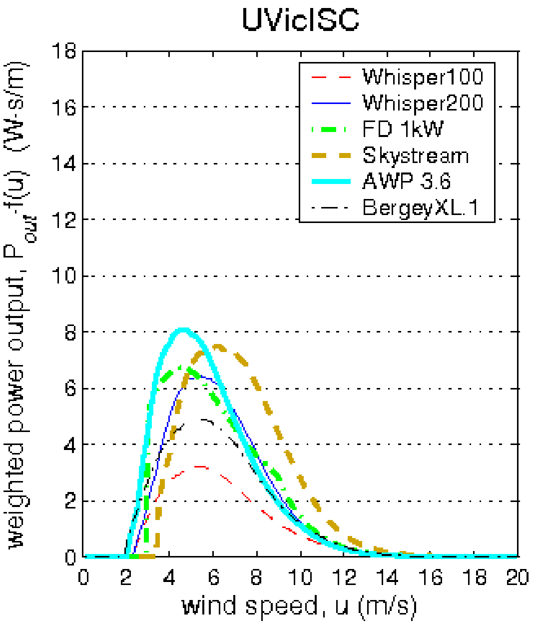


Figure 3.5: The amount of wind power, weighted over the wind speed probability density function, extracted by small HAWT with rated power capacity ranging from 3kWatt to 10kWatt: Whisper500, FD3kW, FD10kW, ARE10kW and BWC XL.10kW (BergeyXL.10) at the UVicISC (Left) and Lansdowne (Right) locations

are UVicISC and Lansdowne. In all the figures, the limits of the axis y in the plots at the *right* was left the same as the limit in the plots at the *left*. This allows us to see better the difference in the magnitude of the turbines' outputs at two selected



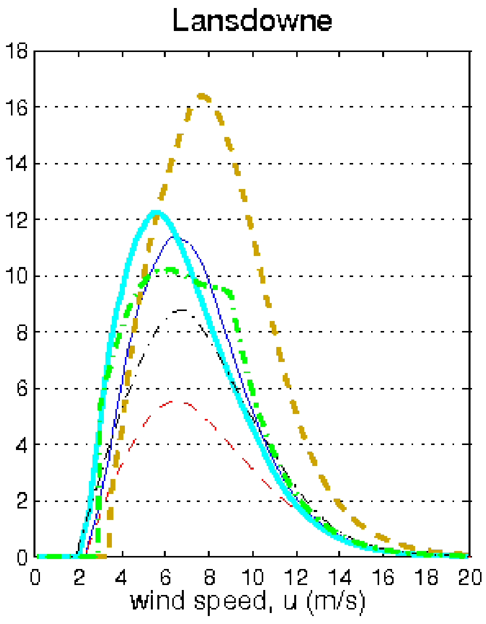


Figure 3.6: The amount of wind power, weighted over the wind speed probability density function, extracted by micro HAWT with rated power capacity ranging from 900Watt to 1800Watt: Whisper200, Whisper100, FD1kW, Skystream,AWP3.6, BergeyXL.1 at the UVicISC (Left) and Lansdowne (Right) locations

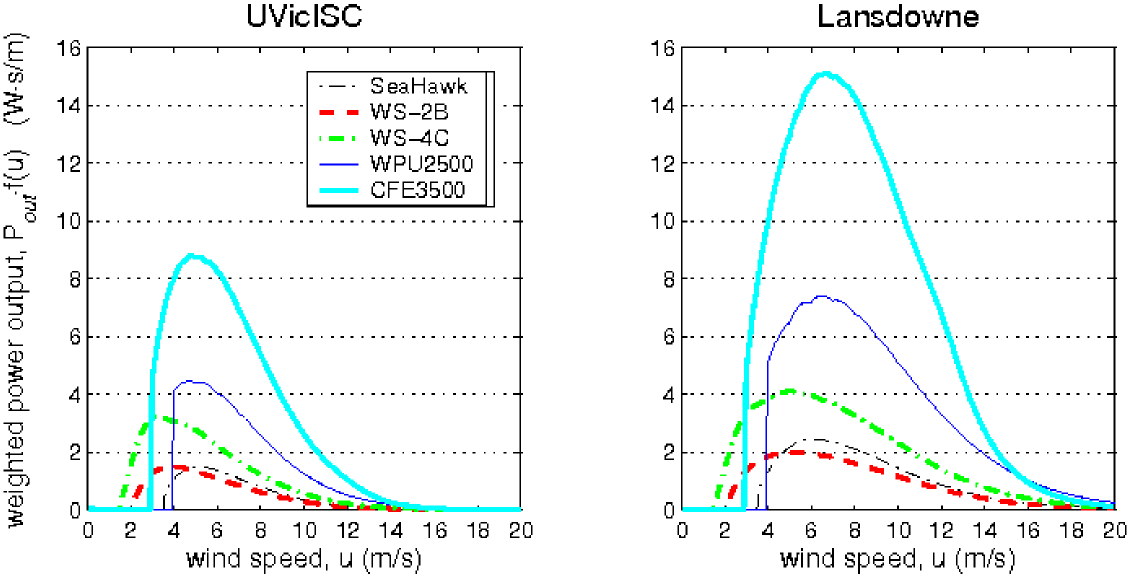


Figure 3.7: The amount of wind power, weighted over the wind speed probability density function, extracted by VAWT with rated power capacity ranging from 1kWatt to 3.5kWatt: SeaHawk, WS-2B, WS-4C, WPU2500 and CFE3500 at the UVicISC (Left) and Lansdowne (Right) locations

sites.

From Figure 3.4 we can conclude that outputs of all the *FD* turbines at both sites mostly depend on wind power density, the swept area of the turbine and a bit on the C_p curve distribution over the wind speeds. The output of two turbines, *AirX400* and *Lite Breeze*, cannot be predicted easily from the analysis of their C_p curves until we see their power output at places with different wind speed regimes. Overall, the *AirX400* is a well designed generator, with C_p of about 35% at a broad range of wind speeds. As we can see, this turbine's output is higher at the Lansdowne location and the same as *Lite Breeze* turbine's output at the UVic location. The *Lite Breeze* turbine has a larger swept area and lower cut-in wind speed. Moreover, its peak of performance falls at around 2.5m/s wind speed. This turbine is a good candidate for harvesting wind energy at sites with low wind speeds. However, both produce such a low amount of power, neither would be worth using (Table 3.2).

The output of larger (3-10kW) turbines is shown in Figure 3.5. As a rule, larger turbines perform better at windier sites, according to their power capacity and swept area. When it comes to selecting a good turbine at a site with lower WPD and higher probabilities of lower wind speeds, a turbine's lower cut-in wind speed and higher C_p at wind speeds ranging from low to moderate can play a more important role than its rated power capacity and the size of its swept area. For example, at the UVic location the 3kW rated turbine *FD3kW* with 19.63 m^2 swept area can extract about the same amount of power as the 10kW rated *BergeyXL.10 (BWC XL.10)* with a larger swept area (35.26 m^2). At Lansdowne,*BergeyXL.10* has larger power output than *FD3kW*.

Another example of a generator that gives larger power output at sites with lower average wind speeds, can be seen in Figure 3.6. *AWP3.6* turbine has, on average, the lowest C_p, and its peak of performance is shifted toward the lowest wind speeds. It generates almost the same amount of power as *Skystream3.7* at UVic, while it gives about 30% less power than *Skystream3.7* at the Lansdowne location. These two turbines have about the same swept area, though their rated power capacities are different, (see Table 3.1). *Skystream3.7*, with its higher capacity, produces more power at windier sites.

In Figure 3.7 the power outputs of different VAWT are shown. The power output of *SeaHawk* is almost the same order as the power output of *WS-2B* at both locations, despite the fact that the swept area of the *SeaHawk* is only one-half that of *WS-2B*. *SeaHawk* produces more power at the windier sites. As we can see from the C_p curve chart, the wind speed at which this turbine can extract energy at maximum rate is about 6m/s, while *WS-2B* performs well at lower wind speeds (around 3m/s). *WS-2B* gives slightly larger power output than *SeaHawk* at the UVic location because of its lower cut-in speed and larger swept area which allows the catching of more energy at locations with low WPD.

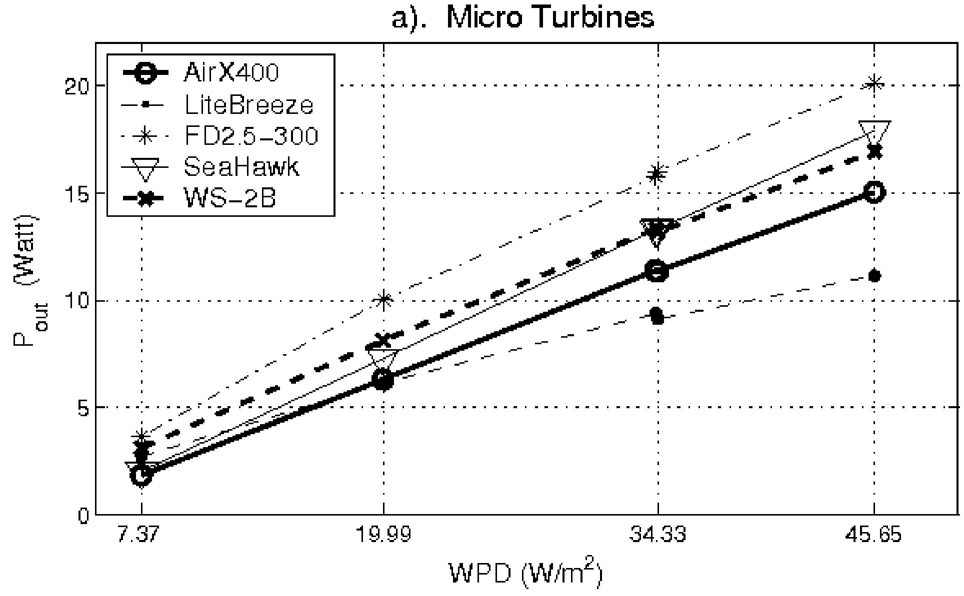
Power output and annual energy production

A summary of the power output, averaged over a whole year period, together with the annual energy production that the selected types of micro and small wind turbines would generate at five different locations in Victoria is shown in Table 3.2. The magnitude of the relative difference in the energy production that the warm and cold seasons would contribute to the total amount of energy produced can be roughly estimated from seasonal wind power density values at each location (Table 2.1). From the table it is easy to see that the power output of any turbine depends on the WPD of a site. However, to see the trend in power output by wind turbines depending on WPD of different sites, the turbines' power outputs were plotted against the WPD at those locations (Figure 3.8).

Figure 3.8(a) shows the power output of the smallest of the HAWT and VAWT turbines with swept areas under 2 m^2, which make them suitable turbines to be placed on a roof top of a house or recreational vehicle. The power output of two

Station name	**CampusView**		**Lansdowne**		**SouthPark**		**VicHigh**		**UVicISC**	
WPD (W/m^2)	**7.37**		**45.65**		**34.22**		**34.33**		**19.99**	
Turbine models: **HAWT**	P$_{out}$ (Watt)	AEP (kWh)	P$_{out}$ (Watt)	AEP (kWh)	P$_{out}$ (Watt)	AEP (kWh)	P$_{out}$ (Watt)	AEP (kWh)	P$_{out}$ (Watt)	AEP (kWh)
AirX400	1.83	16.06	15.04	131.73	11.38	99.71	11.35	99.45	6.31	55.25
Lite Breeze	2.70	23.63	11.14	97.61	9.38	82.22	9.12	79.86	6.13	53.72
FD2.5/300LH	3.64	31.87	20.12	176.26	15.76	138.05	16.01	140.32	10.03	87.8
FD200	8.64	75.65	40.51	354.89	34.69	303.86	33.94	297.27	22.79	199.66
FD300	9.96	87.29	48.50	424.90	41.95	367.45	40.21	352.28	26.58	232.87
FD500	9.82	86.01	54.06	473.56	45.44	398.02	43.89	384.48	27.86	244.05
FD1kW	12.03	105.63	76.25	668.17	61.51	538.78	60.15	526.90	36.30	318.01
FD3kW	55.57	486.83	293.18	2568.22	245.47	2150.29	237.60	2081.38	161.63	1415.89
FD10kW	86.33	756.23	556.73	4876.93	433.92	3801.10	429.35	3761.14	252.72	2213.79
ARE10kW	100.93	884.15	639.24	5599.74	508.39	4453.46	499.60	4376.46	298.55	2615.25
BergeyXL.10	50.02	438.22	368.43	3227.44	285.78	2503.45	282.60	2475.54	162.73	1425.53
Whisper100	5.28	46.26	39.16	343.07	30.42	266.47	30.06	263.34	17.30	151.55
Whisper200	10.06	88.14	71.32	624.75	57.12	500.35	55.88	489.50	32.97	288.77
Whisper500	22.75	199.30	180.37	1580.02	141.44	1239.05	139.18	1219.23	79.71	698.28
AWP3.6	14.45	126.69	76.68	671.74	64.31	563.34	62.21	544.98	39.73	348.01
BergeyXL.1	9.36	81.98	62.29	545.66	49.17	430.70	48.40	424.01	28.57	250.29
Skystream3.7	10.54	92.32	108.47	950.20	80.32	703.62	80.47	704.92	42.44	371.77
VAWT	P$_{out}$	AEP	P$_{out}$	AEP	P$_{out}$	AEP	P$_{out}$	AEP	P$_{out}$	AEP
SeaHawk	2.02	17.71	17.89	156.74	13.29	116.46	13.31	116.59	7.28	63.77
WS-2B	3.11	27.26	16.93	148.34	13.33	116.80	13.17	115.41	8.12	71.10
WS-4C	7.72	67.63	35.87	314.26	28.77	252.03	28.34	248.29	18.15	158.97
WPU2500	5.80	50.85	59.17	518.36	42.21	369.77	42.81	375.01	22.35	195.82
CFE3500	15.60	136.65	121.86	1067.48	92.01	806.02	91.80	804.16	51.45	450.68

Table 3.2: Power output (P$_{out}$) and annual energy production (AEP) by different types of wind turbine generators at five locations: Campus View, Lansdowne, South Park, Vic High and UVicISC


a). Micro Turbines

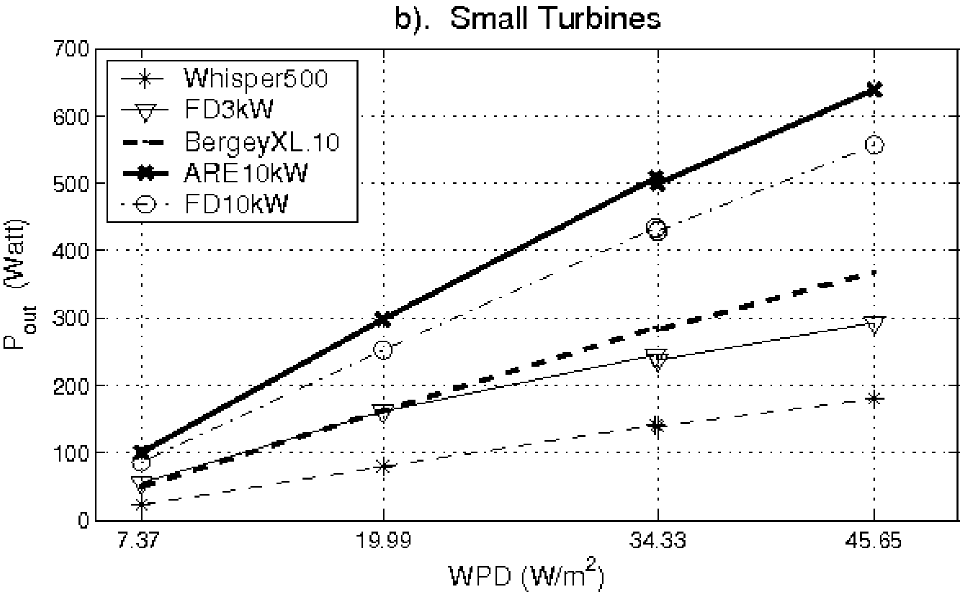

b). Small Turbines

Figure 3.8: WPD dependant tendency in power output for selected micro (top figure) and small (bottom figure) wind turbine generators.

turbines with different characteristics depends on the swept area and rated power. Cut-in wind speed is also important in some cases. For example, *Lite Breeze* captures more wind power than *AirX400* at a site with very low WPD because of the higher probabilities of low wind speeds at that site, which satisfy the wind turbine design (*Lite Breeze* has a much lower cut-in wind speed than *AirX400*, and its peak of performance falls around the lowest wind speeds). Upon comparing the turbines of the same size, *FD2.5-300* produces more energy than *Lite Breeze* at any location, despite the fact that cut-in wind speed of this turbine is higher. Two turbines with the same swept area may produce different amounts of power depending on their rated power. For example, the *SeaHawk* turbine, rated at 1000 W, produces more energy than the 400 W rated *AirX400* at all five selected locations. The power output of this turbine is lower than the outputs of turbines with larger swept areas such as *Lite Breeze* and *WS-2B* at locations with lower WPD, but higher at Lansdowne. Its power output curve is steeper, which means that increasing wind speeds make this turbine spin faster than the *AirX400*, *Lite Breeze* and *WS-2B* turbines. By comparing two turbines of the same type and the same rated power like *SeaHawk* and *WS-2B* it can be concluded that the larger swept area of *WS-2B* compensates for the lower available power in the wind at Campus View and UVicISC. The *WS-2B* turbine also has a much lower cut-in speed than does the *SeaHawk*. At Lansdowne *SeaHawk* produces more energy.

Figure 3.8(b) shows the output of small HAWT turbines with rotor diameters from 4.5 m to 8 m. Three turbines, rated at 10 kW, produce different amounts of power at all the locations considered. The best turbine is *ARE10kW*. The *FD10kW* turbine has the largest swept area, but generates less than *ARE10kW*. The 3 kW rated *FD3kW* turbine is competitive with the 10 kW *BergeyXL.10* at Campus View and UvicISC. *BergeyXL.10* is a better turbine to chose at locations with higher WPD. *Whisper500* and *FD3kW* are both rated at 3 kW, but the lower cut-in wind speed and the larger swept area make the *FD3kW* a better turbine.

Monthly variability in energy production

Since there is a considerable difference in wind power density from location to location, it could be that the power production also varies significantly from month to month. Furthermore, the rate of such a variability in time may differ for different turbines and at different locations. The monthly variability in power production is analyzed for two locations, UVicISC and Lansdowne. The former site has an average wind power potential, whereas, the latter site is the location with the best wind power potential in the Victoria area, based on the wind speed measurements we use. Obviously, the overall wind power production should be better at the places with better wind power resources. As follows from Equation 3.5, the ratio of power output at the Lansdowne site to power output at the UVicISC site for the same turbine is the same as the ratio of WPD at Lansdowne to WPD at UVicISC. However, it is not obvious how the monthly power production would vary for different turbines.

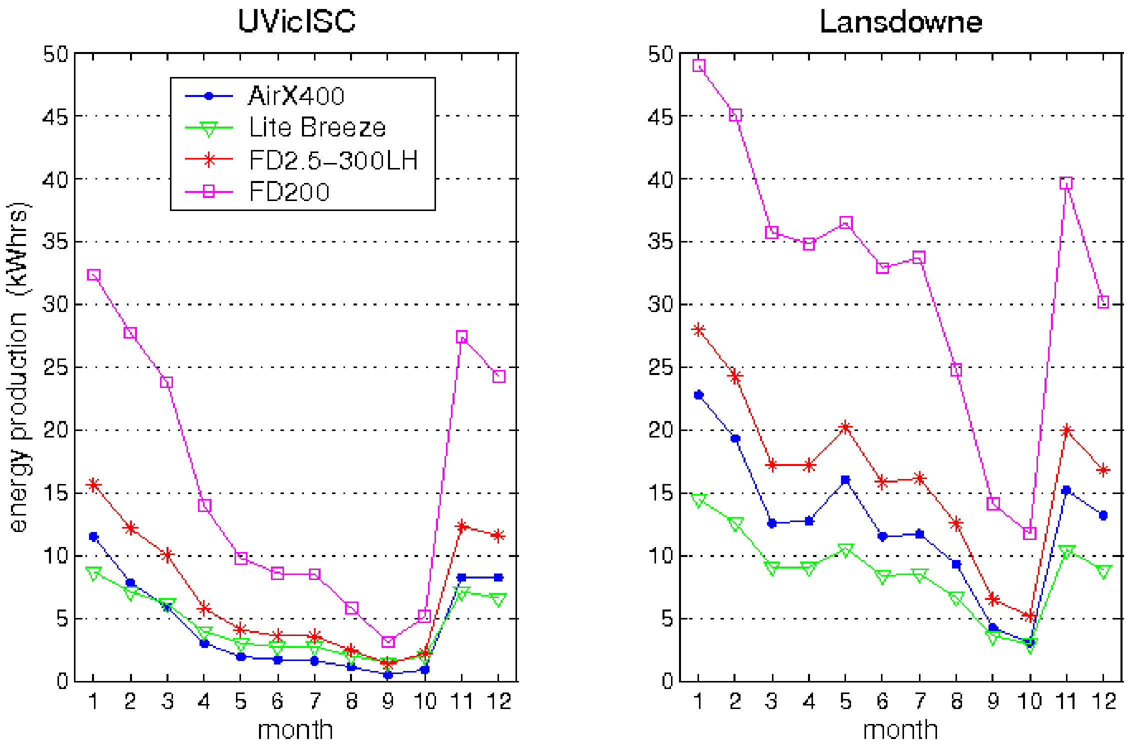


Figure 3.9: Estimated monthly energy production at UVicISC and Lansdowne locations by micro wind turbines: AirX400, Lite Breeze, FD2.5-300LH and FD200.

To analyze the productivity of different wind turbines, the monthly power production is plotted for two sites, UVicISC and Lansdowne. The power production of selected micro turbines is shown in Figure 3.9; and the power production of selected small turbines is shown in Figure 3.10. It is found that the power output of a turbine

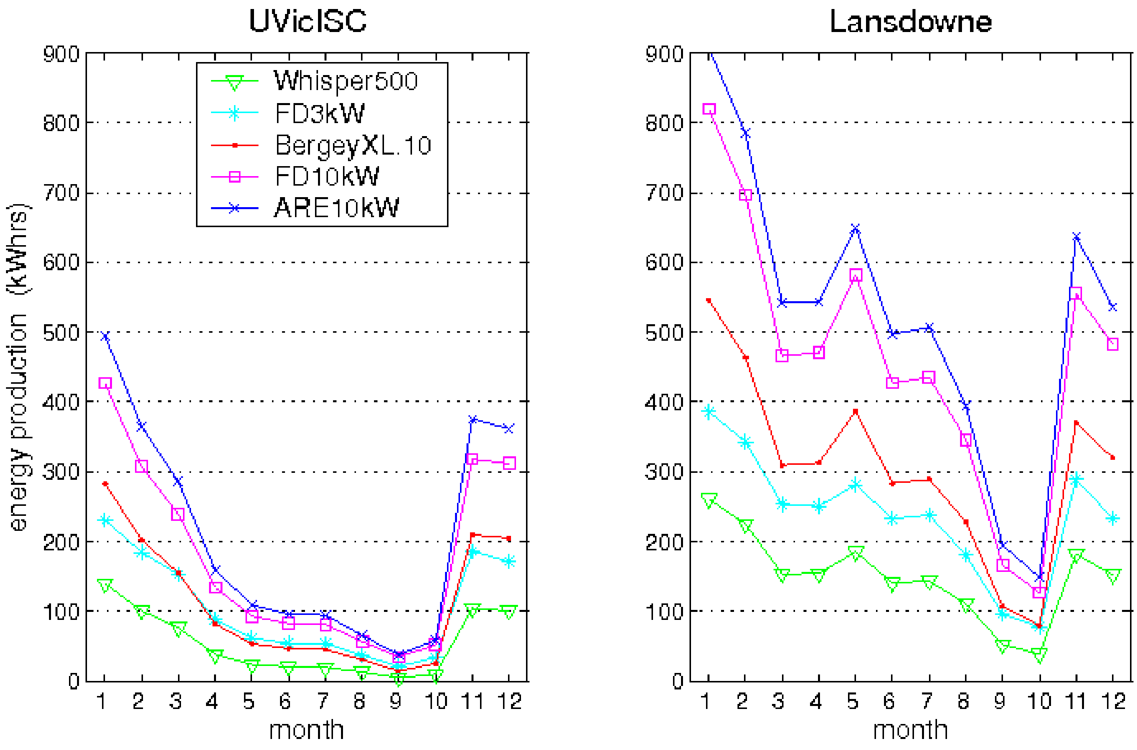


Figure 3.10: Estimated monthly energy production at UVicISC and Lansdowne locations by small wind turbines: FD3kW, Whisper500, BergeyXL.10, FD10kW and ARE10kW.

depends not only on a turbine's average coefficient of performance and swept area, but also on the wind speed frequency distribution, which varies from month to month during a year. For example, we can see that the *AirX400* wind turbine produces more power than *Lite Breeze* in winter, but it produces less than *Lite Breeze* in summer at UVic. At the location with the higher WPD than at UVicISC, *AirX400* turbine's productivity is better than *Lite Breeze* all year round. *Lite Breeze* was designed to perform better at locations with very low average wind speeds where no other wind turbine is able to catch the wind. The same can be pointed out when comparing the performance of the *FD3kW* and *BergeyXL.10* wind turbines. The 3kW wind turbine *FD3kW* performs as good as the larger turbine of 10kW power capacity at the UVicISC location on average, and even better during the warm season months. But at a location with higher WPD, *BergeyXL.10* produces more energy most of the year. Only in September and October the difference is negligible. In both cases the low cut-in wind speed of the turbine plays a significant role when the peak of the WPD curve is shifted toward the lower wind speeds.

A common feature in the power output curves shown in Figures 3.9 and 3.10 is that a minimum in energy production falls in September and October. This is related to fact that the local wind speed is weak, so that other energy resources need to be considered particularly during this time of a year.

3.4 On feasibility of using wind generators in the Victoria area

The main concern for the consumer: is a wind generator a good investment, is the local wind as a source of energy feasible? The feasibility assessment is based, in the first place, on a wind power resource estimate, then on a turbine's suitability for the local wind environment and, of course, on the total price of the wind energy system.

Turbines' energy production estimates were done for the same height of the wind speed (assumed to be 10 m above the ground). Wind speed sensors are located in most cases on the roof tops of the buildings. While the same placement of micro wind turbines is acceptable, a small scale wind turbine cannot be placed on a roof top because of its weight and size. In addition, a small wind turbine needs a tower of 24-37 m height in order to have access to stronger winds, so that it is more economically feasible. Changing the height of the rotor location means that it will be exposed to stronger winds since the wind speed increases with height. That means that calculated power output is underestimated for those turbines which in reality cannot be placed on the roof tops of the residential buildings.

More accurate estimate of the power output of a wind turbine requires either additional measurements of wind speeds at the height of the turbine's rotor, or an extrapolation of existing data to that height. For such a purpose the equation describing the vertical wind profiles above a solid boundary is used:

$$\frac{\bar{u}(h)}{\bar{u}(h_r)} = \left(\frac{h}{h_r}\right)^{\alpha} \tag{3.9}$$

where h_r and $u(h_r)$ are a reference height and a measured wind speed at this height, h and $u(h)$ are new height and the expected wind speed at this height, α is a wind shear exponent. In many cases, in order to calculate the expected mean wind speed at a new height, a wind shear exponent value of approximately 0.14 (or 1/7) is used to describe atmospheric wind profiles. The empirically derived power low exponent of 1/7 for height extrapolation is correct only for a flat, airport-like terrain and neutral stability. Very often, small wind energy systems may be located in residential areas with a number of buildings and tall dense trees. To obtain a shear exponent value at a particular site located in a residential area, additional measurements of wind speeds at different heights and different seasons need to be done. In case additional measurements are not planned to be taken, the power coefficient can be estimated theoretically. The effect of surface roughness and atmospheric stability on the coefficients of a power law must be considered at each particular location and during different seasons. Wind direction probability distribution should be taken into consideration as well, because the wind flow is affected when passing over various surface conditions during different seasons or days. The exponent value can be as high as 0.3 for small towns and areas covered with tall trees (*van Lieshout* 2004). The study on seasonal variability of shear exponent was conducted by *Farrugia* (2003). He calculated the shear exponent in a Mediterranean island climate, using the wind speed data at different heights and different times of the year. The type of terrain, characterized by land cover on that island, is quite similar to that of the city of Victoria. The author showed that the exponent value may vary from 0.29 in summer to 0.45 in winter. The estimated long-term wind shear exponent is 0.36.

My preliminary estimates of the effect of 0.36 exponent and 0.14 exponent on wind speed increase with height revealed that WPD values may differ substantially if the corrected exponent were used instead of the traditional. By using the exponent of 0.36 the estimated wind speed at 20 m height may be about 30% greater than wind speed at reference height, instead of 10 % if the 1/7 power law were used for vertical wind speed extrapolation. A 30% increase in wind speed could give an increase in WPD by a factor of two, while a 10% increase could give only 33% more power. At 30 m height WPD may be more than 3 times greater, instead of 60%. An accurate estimate of the exponent value may reveal that locations such as Lansdowne, South Park and Vic High fall into Class 2 of wind power density a good fraction of the year.

As it is shown in my work, micro and small scale wind turbines are designed for different levels of WPD and able to generate usable power at locations with the lowest wind speeds. The manufacturers of small and micro turbines, when advertising their products, highly recommend that in order to get from the turbine what is promised, the annual average wind speed must be over 4 m/s. However, we could see that some turbines are particularly designed to be used in areas with average wind power density as low as 20 W/m^2, while at areas with better wind power resource they cannot compete with other turbines. In such a case, the choice primarily depends on the cost of a turbine and on necessity of its use as a source of electric energy. An assessment of feasibility can be based on the capacity factor value. An average capacity factor of a wind power system of 30-35% is considered to be good. For the capacity factors of the turbines considered in this work, with the highest being at Lansdowne location, the values are less than 10%. This is much below the feasible level.

Also, additional cost may be added for the use of energy storage systems. If wind energy were available at an hourly average rate, there would be a need to store electricity due to the mismatch between peak production (in mid-afternoon) and peak demand (in early evening). However, because of low energy resources in the Victoria area, we cannot expect that the energy will be produced in amounts close to the calculated average for a particular time of a year or a day. During some days we may have energy in larger amounts than the energy storage system is able to store because of its limited capacity. During other days we may have no energy from the wind at all. In any case, there is a need for electrical energy storage. In the case of battery use, we would also need to account for the energy losses associated with battery efficiency.

3.5 Summary

1) The Victoria area wind resources differ considerably from place to place. Hence, there is no a single wind power generator which would be most suitable for any location. The wind turbine industry is a developing industry, and manufacturers are constantly working on improving the performance of wind turbines. Since the structure of the local wind speed distribution is not unique, there is a need for different types of wind turbines. Such turbines should be designed for use under different wind regimes and, at the same time, for different applications. The latter may include battery charging, remote off-grid power supply, etc. The main purpose of such a diversity is to provide the consumer with the best suitable choice for a particular location. Ideally, one would like to have an economically efficient wind turbine, which would satisfy a consumer's need in electric power, allow him/her to save money, and be as least disruptive as possible to the neighbours.

2) The power curve of a wind turbine is its most important characteristic in the theoretical and empirical calculations of turbine power output for different wind speed regimes. From such a curve, particularly if actual estimates of turbine power output are not available, two important characteristics of a wind turbine can be derived: Capacity factor (C_f) and Coefficient of performance (C_p).

3) The capacity factor does not demonstrate what is the overall performance of a wind turbine, but rather represents a measure of productivity of a wind turbine at a particular location. The capacity factor of the same wind turbine may differ significantly from site to site.

4) Wind power output estimation can be done using Equation 3.8, which includes both standard and variable air density, for locations with significant variations in air density due to broad variations in air temperature from season to season or due to high elevation above sea level, where atmospheric air pressure differs significantly from standard atmospheric pressure.

5) The WPD and power output vary at different sites located on a relatively small area of Greater Victoria depending on terrain conditions. In open or slightly elevated areas with limited obstructions such as those where the Lansdowne, South Park and Vic High weather stations are located; there is a moderate level of wind power suitable for utilization.

6) The feasibility assessment can be based on such factors as the level of wind power resource and the total cost of a turbine system. In case the turbine power output is known, measured or estimated; the feasibility assessment can be based on the turbine capacity factor.

7) Since the power output calculation for small turbines was based on wind data without height extrapolation of wind speeds to the hub height of a turbine, the power output of these turbines is underestimated. The local wind speed data should be extrapolated with height to estimate the wind power resource available for small and larger wind energy conversion systems.

Chapter 4

Conclusions

With the anthropogenic influence on our environment rapidly increasing, there is a growing need for alternate sources of renewable energy. One such source is wind energy. In several industrial countries, such as Denmark, Spain and Germany, wind power accounts for a significant fraction of their electricity use. Canada is not on this list yet. Canada's installed capacity by the end of 2007 is equivalent to 0.75% of the total electricity demand, whereas its wind energy potential is enough to meet 20% of the nation's electricity needs (*CanWEA* 2007b). According to *EER* (2007), the Canadian wind power market will see unprecedented growth over the next decade. This will require, among others, an extensive province by province analysis of the available wind power resources and suitable wind turbines. It is therefore timely to make a preliminary assessment of such a wind energy potential for residential use here in Victoria, British Columbia.

Using the wind speed measurements collected at the University of Victoria School-based Weather Station Network since 2002 (*Weaver and Wiebe* 2006), I have:

1) performed a statistical description of the local near-surface winds;

2) made a preliminary assessment of the wind power available locally for residential use;

3) provided an assessment of wind turbines suitable for local wind resources;

4) given some specific recommendations as to the local spatial, seasonal and diurnal wind energy utilization;

5) provided some practical recommendations on how these estimates of the local wind power outputs could be further improved.

I found that while the local winds are characterized by relatively small mean values, being mostly within 1.5-2.5 m/s, their spatial variability is relatively large. The examination of wind characteristics at 32 stations in the network revealed areas with wind energy potential of 1.5-2.3 times larger than that at the UVic location, which represents a site with average wind power potential. The station with the highest potential was found to be Lansdowne. Annual and diurnal variability is also significant, with winds being stronger on average during winter compared to summer, and during daytime compared to nighttime, so that the wind power density also follows this variability. Depending on the location, the deviation of seasonally-averaged wind power densities from the annually averaged density ranges from 20% to 40%. This confirms the conclusion of *Khan and Iqbal* (2004) regarding the importance of creating micro-scale maps of wind energy potential which would indicate the classes of wind power better.

The probability distribution of the local winds was reasonably well described by the Weibull function. However, it is recommended that in order for the procedure of computing the Weibull fitting parameters – the scale parameter and the shape parameter – to provide the best fit to the original data the seasonal variability of local winds should be taken into consideration. The estimates for the fitting parameters, based on the standard Least Square technique, were computed for 32 meteorological stations and for both seasons of the year (Table 2.1). They show significant space-time variability, which is then taken into consideration when generating the local (micro-scale) maps of wind power density distribution. In addition, because of its dependence on the cubed wind speed, the wind power density is found to be strong function of wind variability, whereas its dependence on variations in air density can be neglected.

The theoretical and statistical analysis of the local winds performed in chapter 2 of the thesis is then used to provide an assessment of the turbine power output and to make some specific recommendations for its residential use (chapter 3). Two most important characteristics of wind turbine, the capacity factor and the coefficient of performance, can be derived from the turbine's power curve. Rather than designing new turbines which would be most suitable for the local wind regimes, I have assessed the performance of different wind turbines that already exist on the market. As the first step, considering several horizontal-axis turbines and vertical-axis turbines, I illustrated that the power coefficient varied significantly with wind speed. This information was then utilized when making a preliminary assessment of which turbine may extract the greater proportion of the power in the wind compared with the other turbines, given the computed local wind speed distributions. For five different locations in Victoria, the wind power output and its dependence on wind power density have been obtained (see Table 3.2; Figure 3.8). Several specific examples illustrating the importance of swept area were presented. For example, for the micro turbines considered, when comparing two turbines of the same rated power such as *SeaHawk* and *WS-2B*, I concluded that the larger swept area of *WS-2B* and its much lower cut-in speed can compensate for the lower available wind power at Campus View compared to UVicISC. Furthermore, for the small turbines considered, I found that those rated at 10kW would produce different amounts of power at different locations, with *ARE10kW* being the best turbine. Overall, the largest amount of power can be produced from the wind at Lansdowne during winter where, among the micro and small turbines I have considered, the *FD2.5-300* and *ARE10kW*, respectively, would produce the most power.

Finally, it is important to point out that for a specific turbine, more accurate estimates of the power output would require either additional measurements of wind speeds at the height of rotors, or some extrapolation using typical vertical wind profiles for the area. Wind speed typically increases with height, and the preliminary analysis presented indicates that the wind power density estimates may increase by up to a factor of two, if the wind speed estimates were done at the heights of rotors. The wind turbine industry is currently at its early, developing state. Nevertheless, sometimes even seemingly small differences in the estimates of the potentially-available wind energy could be of great economical and, importantly, environmental benefit. Even with its seemingly limited wind power resources, it is hoped that the rapidly developing new technologies will soon bring the wind power industry to the Victoria area on a larger scale.

Bibliography

AGBOM (2008), Tropical Cyclone Intensity and Impacts [website]. (Australian Government. Bureau of Meteorology), available at http://www.bom.gov.au/weather/cyclone/about/tropical−cyclone−intensity.shtml. Last accessed: February 7, 2008.

Ahmed, M., F. Ahmad, and M. Akhrar (2006), Assessment of Wind Power Potential for Coastal Areas of Pakistan, *Turk J Phys*, *30*, 1–9.

Akpinar, E., and S. Akpinar (2005), An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics, *Energy Conversion and Management*, *46*, 1848–1867.

Anahua, E., S. Barth, and J. Peinke (2007), *Wind Energy.*, chap. Characterisation of the Power Curve for Wind Turbines by Stochastic Modelling, pp. 173–177, Springer Berlin Heidelberg, doi:10.1007/978-3-540-33866-6.

Archer, C. L., and M. Z. Jacobson (2005), Evaluation of global wind power, *Journal of Geophysical Research*, *110*, 1848–1867, doi:10.1029/2004JD005462.

ARE (2007), Abundant Renewable Energy. Harness the Wind. ARE Wind Turbines, http://www.abundantre.com/ARE Power Curves_121405.pdf. Last accessed: November 12, 2007.

AWEA (2007a), Wind Web Tutorial. Wind Energy Basics [website]. (Americal Wind

Energy Assossiation), available at http://www.awea.org/faq/wwt_basics.html. Last accessed: October 31, 2007.

AWEA (2007b), Wind Energy FAQ. Basic Principles of Wind Resource Evaluation [website]. (Americal Wind Energy Assossiation), available at http://www.awea.org/faq/basicwr.html. Last accessed: October 31, 2007.

AWEA (2007c), Small Wind Turbine Global Market Study 2007, available at http://www.awea.org/smallwind/documents/AWEASmallWindMarketStudy2007.pdf. Last accessed: November 12, 2007.

AWEA (2007d), Wind Energy FAQ. What are Vertical-Axis Wind Turbines(VAWTs)? [website]. (Americal Wind Energy Assossiation), available at http://www.awea.org/faq/vawt.html. Last accessed: December 17, 2007.

AWEA (2008), Wind Energy and Climate Change: A Proposal for a Strategic Initiative [website]. (Americal Wind Energy Assossiation, policy), available at http://www.awea.org/policy/ccwp.html. Last accessed: February 7, 2008.

CanREN (2007), CanREN. Glossary [website]. (Natural Resources Canada), available at http://www.canren.gc.ca/glossary/result.asp?letter=all. Last accessed: December 12, 2007.

CanWEA (2007a), CanWEA Small Wind Energy site: Glossary [website]. (Canadian Wind Energy Assossiation), available at http://www.smallwindenergy.ca/en/Resources/Glossary.html. Last accessed: October 31, 2007.

CanWEA (2007b), Wind Energy Industry. Most commonly asked questions about wind energy [website]. (Canadian Wind Energy Assossiation), available at http://www.canwea.ca/frequently_asked_questions_wind_energy.cfm. Last accessed: December 12, 2007.

CanWEA (2007c), Wind Energy Industry. Canadian Wind Farms [website]. (Canadian Wind Energy Assossiation), available at http://www.canwea.ca/canadian_wind_farms.cfm. Last accessed: December 12, 2007.

Chang, T.-J., Y.-T. Wu, H.-Y. Hsu, C.-R. Chu, and C.-M. Liao (2003), Assessment of wind characteristics and wind turbine characteristics in Taiwan, *Renewable Energy*, *28*, 851–871.

Clarke, S. (2003), Electricity generation using small wind turbines at your home or farm. FACTSHEET [webpage]. (Ontario. Ministry of Agriculture, Food and Rural Affairs), available at http://www.omafra.gov.on.ca/english/engineer/facts/03-047.htm. Last accessed: November 7, 2007.

CWEA (2005), Overall Map [website]. (Canadaian Wind Energy Atlas), available at http://www.windatlas.ca/en/maps.php. Last accessed: November 7, 2007.

Deaves, D., and I. Lines (1997), On the fitting of low mean wind speed data to the Weibull distribution., *Journal of Wind Engineering and Industrial Aerodynamics*, *85*, 75–84.

Dwinnell, J. H. (1949), *Principles of Aerodynamics.*, 391 pp., McGraw-Hill, New York.

EER (2007), Global Wind Energy. Market Studies. Canada Wind Power Markets and Strategies, 2007-2015 [website]. (emerging energy research), available at http://www.emerging-energy.com. Last accessed: December 3, 2007.

Elliot, D., and M. Schwartz (1993), Wind energy potential in the Unides States., *Tech. Rep. PNL-SA–23109*, Pacific Northwest Lab., Richland, WA (United States).

ESRL (2007), Earth System Research Laboratory. Physical Science Division, http://www.cdc.noaa.gov/HistData/. Last accessed: November 7, 2007.

Farrugia, R. (2003), The wind shear exponent in a Mediterranian island climate, *Renewable Energy*, *28*, 647–653.

Gipe, P. (1999), *Wind Energy Basics. A Guide to Small and Micro Wind Systems*, 122 pp., Chelsea Green Publishing Co., White River Junction, USA.

Hartmann, D. (1994), *Global Physical Climatology.*, 411 pp., Academic Press, Burlington, MA, USA.

IPCC (2007), Working Group I: The Physical Science Basis on Climate Change [website]. (Intergovernmental Panel on Climate Change), available at http://ipcc-wg1.ucar.edu/index.html. Last accessed: November 7, 2007.

Johnson, G. (1985), *Wind Energy Systems.*, 360 pp., Prentice Hall, Upper Saddle River, New Jersey.

Justus, C., W. Hargraves, and A. Yalcin (1976), Nationalwide assessment of potential output from wind powered generators., *Journal of Wind Engineering and Industrial Aerodynamics*, *85*, 75–84.

Khan, M., and M. Iqbal (2004), Wind energy resource map of Newfoundland, *Renewable Energy*, *29*, 1211–1221.

Li, M., and X. Li (2005), Investigation of wind characteristics and assessment of wind energy potential for Waterloo region, Canada, *Energy Conversion and Management*, *46*, 3014–3033.

Lu, L., H. Yang, and J. Burnett (2002), Investigation on wind power potential on Hong Kong islands - an analysis of wind power and wind turbine characteristics, *Renewable Energy*, *27*, 1–12.

Mulugetta, Y., and F. Drake (1996), Assessment of Solar and Wind Energy Resources in Ethiopia. II. Wind Energy., *Solar Energy*, *57*(4), 323–334.

NCDIA (2007), National Climate Data and Information Archive (NCDIA). Canadian Climate Normals or Averages 1971-2000. Victoria Gonzales HTS, British Columbia [website]. (Environment of Canada. Climatology), available at http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html. Last accessed: October 31, 2007.

NRL (2007), Tropical Cyclone Forecaster Reference Guide [website]. (Naval Research Laboratory), available at http://www.nrlmry.navy.mil/ chu/chap6/se200.htm. Last accessed: February 7, 2008.

Peixoto, J. P., and A. H. Oort (1992), *Physics of Climate*, 520 pp., American Institute of Physics, Melville, New York.

Pitt, L., G. C. van Kooten, M. Love, and N. Djilali (2005), Utility-scale wind power: Impacts of increased penetration, *Working Papers 2005-01*, University of Victoria, Department of Economics, Resource Economics and Policy Analysis Research Group, available at http://ideas.repec.org/p/rep/wpaper/2005-01.html. Last accessed: May 25, 2006.

Seguro, J., and T. Lambert (2000), Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis., *Journal of Wind Engineering and Industrial Aerodynamics*, *85*, 75–84.

Stevens, M. J. M., and P. T. Smulders (1979), The estimation of the parameters of the weibull wind speed distribution for wind energy utilization purposes, *Wind Engineering*, *3*(2), 132–145.

Stull, R. (2000), *Meteorology for Scientists and Engineers. Second Edition*, 528 pp., Thomson Brooks/Cole, Pacific Grove, USA.

van Lieshout, P. (2004), Predicting wind output Time dependent energy calculations, *Refocus*, *5*(3), 40–43.

Weaver, A., and E. Wiebe (2006), Micrometeorological network in Greater Victoria schools: www.victoriaweather.ca., *CMOS Bulletin*, *34*(4), 184–190.

WebMET.com (2007), WebMET.com - The Meteorological Resource Center. Siting and Exposure [website]. (Met Monitoring Guide), available at http://www.webmet.com/met_monitoring/3.html. Last accessed: November 7, 2007.

Weisser, D. (2003), A wind energy analysis of Grenada: an estimation using the "Weibull" density function, *Renewable Energy*, *28*, 1803–1812.

WWEA (2007), New World Record in Wind Power Capacity: 14.9GW added in 2006 - Worlwide Capacity at 73.9GW [website].(World Wind Energy Assossiation), available at http://www.wwindea.org/home/index.php. Last accessed: October 31, 2007.

WWO (2003), Testing the Power Curves of Small Wind Turbines: by Paul Gipe [website].(Wind-Works.org), available at http://www.wind-works.org/articles/PowerCurves.html. Last accessed: February 7, 2008.

ZAP (2007), Zephyr Alternative Power Inc. FAQ [website].(Zephyr Alternative Power Inc.), available at http://www.zephyrpower.com/faq.html. Last accessed: December 17, 2007.

Appendix A

List of Wind Turbines and Manufacturers

Turbine models	webpage address
AirX400	http://www.windenergy.com/air_x.htm
Lite Breeze	http://www.windbluepower.com/
FD2.5/300LH	http://www.wsetech.com/windturbinegenerator.php
FD200	http://www.wsetech.com/windturbinegenerator.php
FD300	http://www.wsetech.com/windturbinegenerator.php
FD500	http://www.wsetech.com/windturbinegenerator.php
FD1kW	http://www.wsetech.com/windturbinegenerator.php
FD3kW	http://www.wsetech.com/windturbinegenerator.php
FD10kW	http://www.wsetech.com/windturbinegenerator.php
ARE10kW	http://www.abundantre.com/ARE_Wind_Turbines.htm
BergeyXL.10	http://www.bergey.com/
Whisper100	http://www.windenergy.com/whisper_100.htm
Whisper200	http://www.windenergy.com/whisper_200.htm
Whisper500	http://www.windenergy.com/whisper_500.htm
AWP3.6	http://www.abundantre.com/AWP-3.6.htm
BergeyXL.1	http://www.bergey.com/
Skystream3.7	http://www.skystreamenergy.com/skystream/
SeaHawk	http://www.pacwind.net/
WS-2B	http://www.windside.com/products.html
WS-4C	http://www.windside.com/products.html
WPU2500	http://www.wind-sail.com/products.html
CFE3500	http://www.cleanfieldenergy.com/wind_download.php

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January 28, 2008