Wind Energy Resource Assessment Using Wind Atlas and Meteorological Data for the City of Guelph, Canada

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Abstract
The ability to accurately assess renewable energy resources is an essential prerequisite to integrating renewable energy technologies into the energy supply portfolio of a community. This study investigates the potential for wind energy development in Guelph, a growing mid-size city in Southern Ontario, Canada. Community awareness of energy has led to the development of a Community Energy Plan that includes discussion on the utilization of energy supplied from renewable sources. Wind resources are particularly difficult to evaluate at the community level. A preliminary evaluation of the City of Guelph’s wind energy resource was undertaken to determine the degree to which locally-produced wind energy could supply the city’s current and future energy demand. Wind data for Guelph and the nearby village of Elora was sourced from two wind maps (Environment Canada’s Canadian Wind Energy Atlas and the Wind Resource Atlas published by the Ontario Ministry of Natural Resources), as well as the weather stations at the Guelph Turfgrass Institute and the Elora Research Station. These different data sources produced wind energy estimates all within ±44% of each other for a small wind turbine (10 kW). Community scale generation was estimated through a uniform grid of turbines across the city. Nearly 18,000 small wind turbines generate 139 GWh while 128 utility-scale turbines generate 424 GWh. These utility-scale turbines could potentially deliver 24% of Guelph’s 2005 electrical demand.


Primary Theme: Capacity Building
Secondary Theme: Technology Advancement and Availability

Introduction
Global climate change, poor air quality particularly in urban settings, the ongoing decline of fossil fuel resources and the escalation of fossil fuel energy prices are all driving the pursuit of sustainable energy resources. The wind is one natural resource that is currently underutilized for electricity production. The wind energy market is growing rapidly, with 20 GW of capacity installed globally in 2007 (CANWEA, 2008). During that
year, the installed capacity in Canada grew by 286 MW to a total of 1,846 MW, but there is an expectation that a minimum of 700 MW will be added in 2008 (CANWEA, 2008).

Communities are beginning to examine their local resources for renewable energy potential. The city of Guelph, Ontario (Canada) recently developed a community energy plan in which it acknowledged that wind could help the city in attaining its overall goals (Garforth International LLC, 2007). Through this plan, the city has made commitment to achieving a sustainable energy future, which inherently involves the use of renewable resources.

For this study, the goal was to provide an estimate of the total wind energy resource that could potentially be harnessed within the boundaries of the City of Guelph and to compare the power production potential forecast by various models. The goal relied on several objectives: (1) to obtain wind speed data from local meteorological stations; (2) to utilize that data to obtain wind speed distribution parameters at several heights; (3) to investigate available wind atlases and obtain wind speed distribution parameters from these resource; (4) to apply the wind speed distribution parameters to estimate the potential power output of two wind turbines; (4) to determine the potential power output of an array of these wind turbines based on the footprint necessary to minimize interference between turbines; (5) to rank the wind turbine arrays based on total power output; and (6) to comment on the results obtained.

Methods

An estimation of electricity production from wind turbines has been investigated by utilizing data from meteorological stations and wind maps. The meteorological data was used with two models from which probability distribution parameters of the wind speeds were obtained. The wind atlas data, which included these distribution parameters was used as provided and extra/interpolated using one of the models applied to the meteorological data to fill in voids where data was not provided. Power curves of two wind turbines were then used to determine the power output per unit and for an idealized array of equally spaced units covering the city of Guelph. Finally, comparisons was made to the total energy demand of the city.

Meteorological Station Data

Hourly meteorological data was acquired from the weather stations located at the Guelph Turfgrass Institute (GTI; 43º 33’ N, -80º 13’ W) and the Elora Research Station (ERS; 43º 39’ N, -80º 25’ W) from the Agrometeorology group of the Department of Land Resource Science at the University of Guelph (University of Guelph – LRS, 2007). This study focused on the eleven-year period between 1994 and 2004, as this was the longest consecutive time span available for both sites. Both stations were maintained to Environment Canada standards for weather monitoring stations. The wind speed data at these locations were observed at 10 m above ground level.

Weibull Probability Distribution

For the various sources of data the Weibull probability function was utilized to approximate the probability of the occurrence of wind speeds. The Weibull probability distribution function is
where $p$ is the probability of the wind achieving speed $v$, $c$ is the scale factor, and $k$ is the shape factor (Weibull, 1951).

From the weather station data, the Modified Maximum Likelihood Method (Seguro and Lambert, 2000) was used to determine the Weibull wind speed probability distribution parameters $k$ and $c$ at 10 m. In applying this method, the initial value of $k$ was assumed to be 2.0 and $k$ was solved iteratively by

$$k = \left( \frac{\sum_{i=1}^{n} v_i^k \ln(v_i) P(v_i)}{\sum_{i=1}^{n} v_i^k P(v_i)} \right) \left( \frac{\sum_{i=1}^{n} v_i^k \ln(v_i) P(v_i)}{P(v > 0)} \right)^{-1},$$

until the square of the difference between the new and old $k$ was less than $10^{-10}$. Parameter $c$ was subsequently obtained from $k$ by

$$c = \left( \frac{1}{P(v > 0)} \sum_{i=1}^{n} v_i^k P(v_i) \right)^{1/k}.$$

**Adjusting Wind Data for Height**

Two models have been used to adjust wind data for alternate heights.

Justus and Mikhail Model (J&M, 1976) was the first of these models to adjust the Weibull parameters. J&M was applied to determine the wind speed distribution parameters at 30, 50, and 80 m. The equations utilized in this model were:

$$k(z) = k_a \left[ \frac{1 - 0.0881 \ln(z_a/10)}{1 - 0.0881 \ln(z/10)} \right],$$

and

$$c(z) = c_a \left( \frac{z}{z_a} \right)^n,$$

where $n$ is given by

$$n = \frac{[0.37 - 0.0881 \ln c_a]}{[1 - 0.0881 \ln(z_a/10)]}.$$

The second model used was the Power Law model (PL) as defined by,
\[ v(z) = v_0 \left( \frac{z}{z_o} \right)^\alpha, \quad (7) \]

was applied to the velocities from the GTI and ERS sites to obtain the corresponding wind speeds at 30, 50, and 80 m. The power law exponent, \( \alpha \), was determined using (Counihan, 1975):

\[ \alpha = 0.096 \log_{10} \left( \frac{z_o}{\nu} \right) + 0.016 \left( \log_{10} \left( \frac{z_o}{\nu} \right) \right)^2 + 0.24. \quad (8) \]

From the velocities obtained, the Modified Maximum Likelihood Method was utilized to determine the Weibull parameters \( k \) and \( c \) at 30, 50, and 80 m.

**Wind Turbine Power Curves**

Following the attainment of the Weibull distribution parameters, the functions were applied to two power curves to estimate the seasonal and annual power production. The first power curve selected was that of the 10 kW Excel-S of the Bergey Windpower Co. (2006), as shown in Figure 1. The power curve of a 1.65 MW Vestas V82 wind turbine (Vestas, 2008), as shown in Figure 2, was also utilized. The power curves and Weibull probability distributions were evaluated at integer velocities between 0 and 20 m/s. In this way, the potential power output of these wind turbines were obtained (independent of wind direction).

**Community Scale Power Generation**

A simple approach was used to extend the generation from a single turbine to the entire community of Guelph. A uniform grid of turbines has been distributed across the city with a spacing of ten rotor diameters. Generation is based on estimations for the GTI location with a 10% penalty for all of the turbines based on the proximity of the units (Manwell et al., 2002). The Bergey Excel-S has been used with a height of 30 m while the Vestas V82 was with a height of 80 m.

**Wind Maps**

Two wind maps were utilized as part of the investigation into the potential for electricity production from the wind. For each, the latitude and longitude selected were those closest to that of the meteorological stations of interest. For the sites selected wind speed distribution parameters and average wind speed data were available.

The Canadian Wind Energy Atlas (CWEA; Environment Canada, 2003) was utilized to determine Weibull wind speed distribution parameters at 30, 50, and 80 m. Using the navigable atlas, the data were obtained for the latitude and longitude of the GTI (43.537 N and -80.213 W) and the ERS (43.630 N and -80.406 W). Weibull parameters at 30 and 80 m were obtained from the Ontario Wind Resource Atlas (OWRA; Ontario Ministry of Natural Resources, 2006). Using this navigable atlas, the parameters for wind speed distribution were obtained for the latitude and longitude of the GTI (43.54 N and -80.21 W) and the ERS (43.65 N and -80.41 W).
Using the Justus and Mikhail model, the data obtained from the CWEA and OWRA were used to determine $k$ and $c$ at 10 m for comparison with the raw data. For each of these sources, the parameters were obtained from each of the available heights: 30, 50, and 80 m for CWEA and 30 and 80 m for OWRA. For the OWRA data, the parameters for a height of 50 m were also determined in this way. The parameters in each case were applied to the power curves described to obtain corresponding power outputs. These results were then averaged and the standard deviation determined. For comparison, the power outputs from the various heights and models were normalized to that determined from the distribution parameters obtained for the wind speed data for the GTI and ERS sites. As with the meteorological station data for the ERS and GTI, the parameters obtained from the wind map data were applied to determine the power output on a community scale.

Results and Discussion

Table 1 provides an overview of the average wind speeds for the ERS and GTI sites as measured at a height of 10 m. It is immediately obvious that the wind speeds are low at Elora and even lower at GTI, where a good wind resource corresponds to $\sim 8.7$ m/s (400 W/m$^2$), a great wind resource to greater than 10.5 m/s (700 W/m$^2$) and a poor resource as that less than 5.5 m/s$^2$ (100 W/m$^2$) (Manwell et al., 2002).

Figure 3 provides the seasonal variation in the generation of a Bergey turbine for the two locations based on the measured wind speeds at a height of 10 m. For this seasonal analysis, the seasons were broken up into three-month segments with the winter beginning in December, the spring March, the summer in June, and the fall (autumn) in September. As shown here, the ERS and GTI sites, have the highest electricity production in the winter and spring season. Approximately two-thirds of the estimated total electricity production would occur in the winter and spring seasons (approximately one-third each season), followed by a drop to one-ninth of that in the summer, and a recovery to one-fifth of the electricity production in the fall.

The total annual generation corresponds to 3640 kWh (13.1 GJ) at the GTI and 6680 kWh (24.0 GJ) at the ERS. Although the two locations are only about 20 km apart, the difference in generation is a factor of about 1.8.

Figures 4 and 5 provide the relative power generation for each location at the four heights as obtained with the Bergey Excel-S power curve. The results have been normalized with respect to the estimated power output at 10 m for each location. As expected for both sites, the projected power output increases with the height of the wind turbine with an increase of a factor between 2.9 and 4.2 from the 10 m to the 80 m.

Figures 4 and 5 clearly indicate that the models are all in good agreement. For the estimates based on the meteorological data, the two models are within a factor of 1.33 of each other at all elevations. For the ERS, the J&M is higher than the power law model while the reverse is true for the GTI. It is likely that this relative performance difference is largely attributable to the chosen surface roughness in the power law model for the two locations.
The wind map based estimates are generally in good agreement with the meteorological data based estimates. The difference ranges from a factor of 1.09 to a maximum of 1.44. The two map based estimates differ but at most by a factor of 1.23.

Overall the general agreement among the four estimates permits a first estimation of the wind resource with reasonable confidence. For the locations observed, the specific location and height appear to be much more significant factors than the wind data source.

The final step in this analysis has been to estimate the generation potential at the community scale. Table 2 summarizes the results of this estimation. Uniform spacing of Bergey turbines on squares of 70 m x 70 m (ten times the rotor diameter) led to 17,697 turbines. Mounting these at a height of 30 m with their individual generation based on that of the GTI result (less 10%) leads to a total generation of 139 GWh (500 TJ). Correspondingly, 128 Vestas at a height of 80 m led to 424 GWh (1,530 TJ). This estimation is admittedly simplistic as it neglects many site specific factors that would preclude uniform spacing through out the City as well as local terrain, building and foliage effects. However, it does provide an optimistic estimate for local generation potential. These estimates will prove useful as the community continues its energy planning efforts.

In 2005, the city’s population was 115,000 with a corresponding total energy demand of 21 PJ/y, 27% of which was electrical energy (Garforth International LLC, 2007). Under the assumed regime, the installation of Bergey Excel-S wind turbines represents 2.4% of the total energy demand and 8.8% of the electrical energy demand, while the Vestas V82 turbines could provide 7.3% of the total demand and 27% of the electrical demand.

A comparison of the power output between these two arrays lead to a 3-fold increase in power production by the Vestas units, which were at a height of 80m compared to 30 m for the Bergey units. Placing both units at 80 m leads to the Vestas still producing 1.7 times as much power (data not shown). The ratio of swept areas for the Bergey and Vestas units is essentially one and therefore power output differences are not caused by swept area effects. The superior performance of the Vestas ultimately results from the greater efficiency achieved with larger turbines. Thus it is apparent that even with the relatively low wind speeds of Guelph, the best alternative for developing for wide scale wind energy usage is to apply the larger wind turbines to take advantage of the installed height and turbine efficiency.

Conclusions
1. The estimation of electricity production from wind for the City of Guelph has been accomplished by utilizing two models which were applied to meteorological station data and the parameters obtained from two wind maps. All of these estimations are within ± 44.2% for two locations at the four elevations modeled.

   a. Based on these results, there is confidence in these data sources as a basis for estimating the potential for electricity production in this region.
b. The estimated wind resource differed most significantly by elevation (up to a factor of approximately 5) and then location (by a factor of up to 2) for the two locations which are 20 km apart.

c. The wind map based estimates are generally in good agreement with the meteorological data based estimates resulting in a difference ranging from a factor of 1.09 to a maximum of 1.44.

d. The two wind map estimates differ at most by a factor of 1.23.

2. Dividing the City of Guelph into equal parcels and distributing turbines throughout led to an estimated production capacity of 139 GWh for the Bergey units at a height of 30 m and 424 GWh for the Vestas units at a height of 80 m.

   a. Of the 21 PJ of energy demand for the city of Guelph in 2005, 2.4% of this demand could be met with the idealized array of Bergey Excel-S wind turbines and 7.3% with the Vestas V82 wind turbines.

Acknowledgement
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References


Counihan, J. Adiabatic atmospheric boundary layers: A review and analysis of data from the period 1880–1972, Atmos. Env. 9:10 (1975) 871-905.


Captions
Figure 1. The power curve of a 10 kW Bergey Excel-S wind turbine which has a 7-meter rotor diameter [Bergey Wind Co., 2006].

Figure 2. The power curve of a 1.65 MW Vestas V82 wind turbine which has an 82-meter rotor diameter [Vestas, 2008].

Figure 3. The seasonal variation in potential power output of a Bergey Excel-S wind turbine at 10 m where seasons are in 3-month intervals and winter begins in December (etc.).

Figure 4. The annual relative power output at the Elora Research Station where 1.0 corresponds to 6680 kWh and asterisks mark values obtained via extra/interpolation with the Justus and Mikhail (1976) model with resulting in error bars.

Figure 5. The annual relative power output at the Guelph Turfgrass Institute where 1.0 corresponds to 3640 kWh and the asterisks mark values obtained via extra/interpolation with the Justus and Mikhail (1976) model with resulting in error bars.

Tables
Table 1. Parameters describing the wind speed for the data (at 10 m) obtained from the ERS and GTI meteorological stations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Season</th>
<th>( k ) (m/s)</th>
<th>( c ) (m/s)</th>
<th>Mean (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS</td>
<td>All</td>
<td>1.76</td>
<td>4.49</td>
<td>3.97</td>
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<tr>
<td></td>
<td>Winter</td>
<td>1.91</td>
<td>5.28</td>
<td>4.67</td>
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<td></td>
<td>Spring</td>
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<td>5.00</td>
<td>4.42</td>
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<td></td>
<td>Summer</td>
<td>1.83</td>
<td>3.48</td>
<td>3.07</td>
<td>1.79</td>
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<tr>
<td></td>
<td>Fall</td>
<td>1.76</td>
<td>4.23</td>
<td>3.74</td>
<td>2.25</td>
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<tr>
<td>GTI</td>
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<td>3.69</td>
<td>3.28</td>
<td>1.99</td>
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<td>4.23</td>
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<tr>
<td></td>
<td>Summer</td>
<td>1.79</td>
<td>2.88</td>
<td>2.42</td>
<td>1.64</td>
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<tr>
<td></td>
<td>Fall</td>
<td>1.81</td>
<td>3.45</td>
<td>2.98</td>
<td>1.86</td>
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Table 2. Community scale electricity generation

<table>
<thead>
<tr>
<th></th>
<th>Bergey ExcelS - 10 kW</th>
<th>Vestas V82 - 1.65 MW</th>
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<tr>
<td>Rotor Diameter (m)</td>
<td>7</td>
<td>82</td>
</tr>
<tr>
<td>Hub Height (m)</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>Area per Turbine (km²)</td>
<td>0.0049</td>
<td>0.67</td>
</tr>
<tr>
<td>Number of Turbines</td>
<td>17,697</td>
<td>128</td>
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<tr>
<td>Generation per Turbine (MWh)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J&amp;M</td>
<td>8.39</td>
<td>3,480</td>
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<tr>
<td>PL</td>
<td>7.56</td>
<td>3,210</td>
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<td>CWEA</td>
<td>9.13</td>
<td>4,210</td>
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<td>OWRA</td>
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<tr>
<td>Average</td>
<td>8.73</td>
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<tr>
<td>Standard Deviation</td>
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<td>Total Generation (GWh)</td>
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<td>J&amp;M</td>
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<td>Standard Deviation</td>
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Guelph

|                                      |                       |                      |
| 2005 Total Energy Demand (PJ)        | 21                    | 21                   |
| Electricity Demand (27%; PJ)         | 5.67                  | 5.67                 |

Portion of Demand Captured

|                                      |                       |                      |
| Total Energy Demand (%)              | 2.38%                 | 7.27%                |
| Electrical Energy Demand (%)         | 8.83%                 | 26.9%                |
Figures

Figure 1

Figure 2.
Figure 3.

Figure 4.
Figure 5.