Technical Assessment of Small Wind Turbine Power Generation

TECHNICAL BRIEF

Renewable Energy Series

People have harnessed the power from wind for thousands of years for sail boats in the Nile, for water pumping in the Rhine, for grain milling in the Middle East. The large variety of designs and configurations invented for wind power generation has resulted in turbines that operate at the scale of a residential lot to much larger wind farms that can generate power for thousands of homes. To date, the widespread application of wind energy has been hindered by low fossil fuel prices. However, the need for renewable energy is becoming increasingly better understood.

According to the Canadian Wind Energy Association, 2012 marked the first year when more electricity was generated by wind than by coal in Ontario, with more than 2400 MW of installed capacity. This is enough to provide power to a city of nearly 500,000 households.

This study assesses the feasibility and performance of micro-wind turbines installed at different hub heights at the Toronto and Region Conservation's Living City Campus wind field test in Vaughan, Ontario. Power curves were generated based on measured wind speed and power output data for a Bergey 1 kW and Skystream 2.4 kW wind turbines. A Bergey 10 kW power curve was generated based on measured wind speed and manufacturer power output data and compared to historical measured mean monthly power. Results indicate that the Bergey 1 kW and 10 kW power output were both operating at 95% of expected power generation, whereas the Skystream 2.4 kW power output was operating at only 66% of expected power generation. The location of the Skystream turbine close to the Archetype House was thought to have contributed to this turbine's poor performance. Wind measurements at seven different heights showed that turbine power output would have increased by as much as 50% had the turbines been located at roughly twice their current hub heights. Although the Bergey turbines performed as expected, the low wind regime and high start-up cost of the turbines resulted in long payback periods. A 1kW solar panel installation mounted at the same site was found to have a payback of less than one quarter of the wind turbine. Despite a long payback period, the implementation of small wind turbines remains an attractive option for off-grid sites where power line diversions would be cost prohibitive.

INTRODUCTION

Renewable sources of energy are a proven alternative to conventional energy sources. They promote cleaner air and help reduce the emission of greenhouse gases that are driving long term changes in our climate. Electricity generation through renewable sources remains an outranked solution, as current electricity generation in Ontario is dominated by nuclear (59%). Other current sources of power generation in Ontario are hydro (23%), gas (11%), wind (3%), coal (2%), bioenergy (1%) and solar (1%), as per Ontario Power Authority 2013 production reporting. Wind turbines are one of the most common options for renewable energy generation. They are manufactured in a range of dimensions with different power capabilities; small-scale turbines are rated at less than 300 kW, while turbines rated at less than 10 kW are recommended for residential energy generation (CanWEA, 2014). To assess their suitability for different locations based on wind regimes, manufacturers provide power output values for a range of wind speeds. A curve can be fitted to this relationship, and be used to model potential power output by applying measured wind speeds at the proposed installation site, assuming that the turbine performs as rated.

Although manufacturers provide data for power curves, lack of third-party standardization of small wind turbine testing creates uncertainties that limit the potential market for these products in residential settings (Li and Li, 2005). Small wind turbine manufacturers claim that their products perform well in a wind tunnel, but factors such as hub height, changing wind regimes, site characteristics, location and season can only be explored during field testing.

To advance our understanding of how small-scale wind turbines perform in the field, the Toronto and Region Conservation Authority developed a field site for testing and standardization of micro-scale wind turbines at the Kortright Centre for Conservation in the City of Vaughan. The purpose of this study was to characterize conditions at the Kortright field test site in accordance with IEC 61400 standards and to evaluate the field performance of four on-site micro-wind turbines using manufacturer ratings as a basis for comparison. The primary objective of the study focuses on wind speed and direction data collected from a meteorological tower and power generated from two operating turbines. Mean monthly power output was available for a third turbine from a previous study. A fourth turbine was not operational due to damage. A simple cost-analysis of the on-site wind turbines was also developed and compared to solar energy generation based on data from a photovoltaic field test site installed at the same location.

STUDY SITE

Wind turbines require large areas of open space with consistent and strong wind speeds. With 325 hectares of open vegetated land and wind regimes from the southeast and northwest common to the Greater Toronto Area, the Kortright Centre for Conservation provided ample area and a unique opportunity to test small wind turbines at different proximities to surface obstacles and distance from the measured wind speed location. The test site is 188 m above sea level and is situated next to two semi-detached houses (Figure 1). The site is an open, grassy field with low-lying grasses, shrubs and bordering trees. It is approximately 30 km north of the Lake Ontario shoreline and shares similar weather patterns as Toronto. Toronto's climate is relatively mild due to Lake Ontario's moderating effect, with spring and summer temperatures ranging from 15 to 25°C and an average winter daytime temperature of just below freezing, except in January. Annual average (1981-2010) wind speed at the Toronto Pearson International Airport is 4.16 m/s at a height of 10 m.

APPROACH

A 30 m meteorological tower was installed in July 2012, housing eight anemometers, four of which corresponded to the hub heights of turbines installed at the site. They were positioned at 6.1, 10, 12.2 and 15.2 (Skystream 2.4 kW), 17.4 (Bergey 1 kW), 18.3 (Bergey 10 kW), 24.4 and 30.5 (Westwind 5 kW) metres. Two wind vanes were mounted on the tower mast at 15.2 and 30.5 m to characterize the site's wind direction. The specifications for each turbine are presented in Table 1. The Bergey 1 kW and Skystream 2.4 kW turbines functioned throughout the study period. However, the Bergey 10 kW turbine had a blade failure due to fatigue; the blades had been in service for 15 years and when the machine was lowered it was found it had a loose permanent magnet. Data analysis for this turbine was based on historical mean monthly power output data collected from 1993 to 1999. The Westwind 5 kW tower incurred damage from high winds due to the failure of an anchor. The study only considered efficiency of energy transfer at the rotor, not energy loss due to mechanical and electrical specifications of the alternator and inverter, which could vary between models and behave as power reduction factors.

Data collected between November 2012 to May 2013 were used to construct power curves for the Bergey 1 kW and Skystream 2.4 kW turbines. The measured power is a function of the coefficient of performance (Cp, discussed later) of the wind turbine, the blade swept area (A, m^2), air density (ρ, kg/m^3), and wind speed (v, m/s) expressed as:

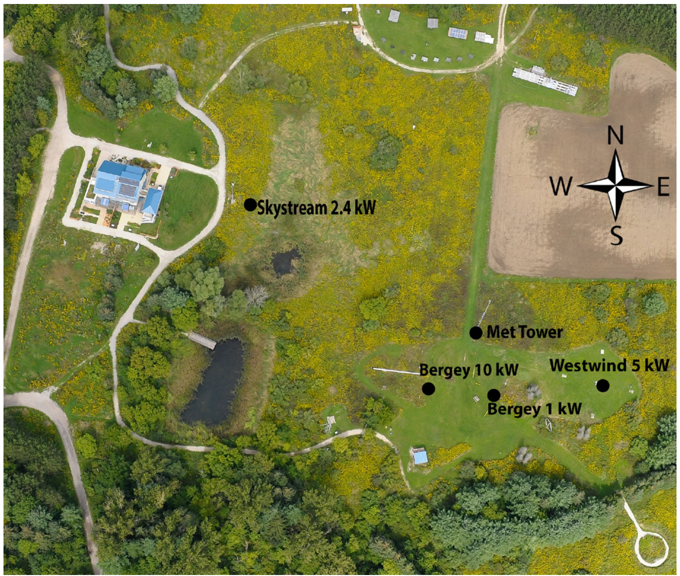

Figure 1. Turbines and meteorological (met) tower positioning at the Kortright Centre for Conservation, Vaughan, ON. The Weswind 5 kW and Bergey 10 kW were not operational at the time of the study. The photovoltaic test site is visible north of the wind turbine test site.

$$P = C_p \frac{1}{2} \rho A \upsilon^3$$

A Sigmoidal Weibull 4 Parameter model was fitted to observed Bergey 1 kW and Skystream 2.4 data and to manufacturer/SWCC power data for the same turbines and the Bergey 10 kW, utilizing observed wind speeds at the site. The manufacturer/SWCC power data have been adjusted for the site's elevation (188 m), turbulence factor (10%), wind shear (0.25), Weibull wind speed distribution (2), average wind speed for each height, and height of each turbine. All regression coefficients were in excess of 0.99 and all p-values were less than 0.01. The resulting models describe observed and potential power output for this site's measured wind speeds. Fitting Weibull distribution models is common for wind power generation due to the distinct skewing of the data, whether it is negatively skewed (power output) or positively skewed (wind speed frequency). The model is presented as:

$$y = a\left[1 - e^{-\left(\frac{x - x_0 + b\ln 2^{\frac{1}{c}}}{b}\right)^{c}}\right]$$

where x represents wind speed (m/s), and the model coefficients of a, b, c and x_0 vary with each fitted power curve.

Table 1. Wind turbine and inverted specifications.

Description		Bergey 1 kW	Skystream 2.4 kW	Bergey 10 kW
Structural	Hub Height	17.37 m	15.24 m	18.3 m
	Turbine Type	HAWT, upwind	HAWT, downwind rotor with stall regulation control	HAWT, upwind
Manufacturer Rating	Rated Power	1 kW	2.4 kW	10 kW
	Rated Wind Speed	11 m/s	13 m/s	12 m/s
Rotor Specifics	Rotor Diameter	2.5 m	3.72 m	7 m
	Swept Area	4.91 m^2	10.87 m^2	38.48 m^2
	Rotor Speed (RPM)	490	50-330	310
	Blade Material	Pultruded fiberglass	Fiberglass reinforced composite	Pultruded fibereglass
Wind	Cut-in Wind Speed	2.5 m/s	3.5 m/s	2.5 m/s
	Cut-out Wind Speed	None	25 m/s	None
	Max Design Wind Speed	54 m/s	63 m/s	60 m/s
Protection	Furling Wind Speed	13 m/s	No furling	15.6 m/s
	Overspeed Protection	Auto tail furl	Electronic stall regulation	Auto tail furl
Position	Distance from Meteorological Tower	18 m	117 m	20 m

As a secondary analysis of potential wind energy production in Ontario, the Bergey 1 kW power curve equation was inputted into a North American Regional Reanalysis (NARR) modeled dataset for a 33 year period form 1980-2012. It uses a 32 km, 45 layer model developed by NOAA's National Centre for Environmental Prediction in the United States. This NARR model is widely utilized due to its relatively high accuracy of hydrology and land-atmosphere interactions. For this report, the historical wind patterns generated by the model have been utilized to assess Ontario's wind regime as part of a geographical analysis.

FINDINGS

The direction of wind at the field test site was typical of the Greater Toronto Area. Most winds at 15.2 m and 30.5 m were from the northwesterly and southeasterly directions, with very few from the northeast and southwest sectors (Figure 2). This agrees with Environment Canada data that indicate a dominance of northwest winds for most of the year in Toronto. The northeasterly direction is associated with low wind speeds (Figure 3), suggesting that even if a wind turbine's perimeter is obstructed from that direction, the total power output would not be significantly affected. The low wind speed from that direction translates into significantly lower power production when the average wind speed for a given direction is fed through the Weibull model (Figure 4).

There was no evidence that surface obstructions significantly distorted wind profiles near the meteorological tower. The effects of vegetation and built structures can cause turbulence effects, wind profile skewing or wind funneling. However, there was no conclusive evidence to suggest that these factors distorted wind patterns measured at the meteorological tower. The bank of vegetation south of the meteorological tower did not appear to create enough turbulence to distort southerly winds and the open fetch in the northeast sector did not explain the poor wind resource for this bearing. This is confirmed by an almost identical wind rose pattern at the 15.2 and 30.5 m heights for wind direction frequency (Figure 2) and average wind speed (Figure 3), which is expected to increase with increasing height due to reduced drag by surface roughness elements.

There is a higher frequency of low wind speeds than high wind speeds, limiting the potential for wind power generation at this site. The Kortright test site experienced an average wind speed of 3 m/s (12.5 m/s maximum) and 4 m/s (18.5 m/s maximum) at the 15.2 and 30.5 metre hub heights, respectively (Figure 5). The average wind speed at 15.2 m was less than the Toronto annual average provided by Environment Canada for the same period of time, which is 3.8 m/s at the 10 m environmental standard height. This difference may be a reflection of the higher elevation and lack of obstructions at the measurement site of Lester B. Pearson Airport. Since the rated power of wind turbines is assessed at the wind speeds when the power curve ceases to grow (i.e. maximum power generated), it is unlikely that the installed wind turbines will reach their rated power very often. For this reason, it is important to assess the site wind regime for a minimum of one year to provide an ample range of wind speeds during all seasons for site feasibility assessment. The wind speed regime for a site can also be characterized by the shape of the frequency distribution, as represented by the Weibull K parameter. This parameter is generally assumed to be 2 for potential wind power generation calculations as a default value derived from the theoretical distribution. The observed K parameter for the test site varied from 1.4 in July to 2.5 in April for the 30.5 m hub height. Lower K values represent low wind speed regimes with high standard deviation typical for thermally driven winds, while higher K values are typical for the high and steady wind regimes of trade winds. This further highlights the lack of strong winds required for wind power generation at the study site.

Wind speeds were greater during the winter than the summer and increased on average by approximately 50% from hub heights of 6.1 m to 30.5 m above the surface. Observed wind speeds in the test field differed with season and hub height (Figure 6a). The wind speed increases with increasing hub height in accordance with the logarithmic wind profile. Wind speeds are lowest during the summer and range from 0.6 (at 6.1 m) to 2 m/s (at 30.5 m). Winds begin to pick up in the winter and reach their maximum during the stormy spring months, ranging from 2.4 (at 6.1 m) to 4 m/s (at 30.5 m). During the summer, vertical buoyant air movement is more common, which results from intensive heating of the ground surface under high energy regimes and peaks in the afternoons. During the winter, the movement of the jet stream

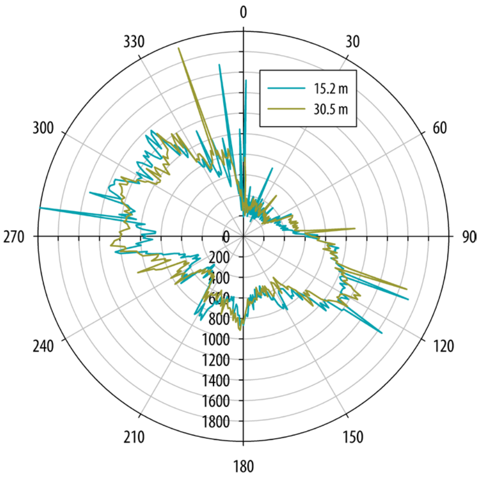

Figure 2. Annual wind direction frequency plot.

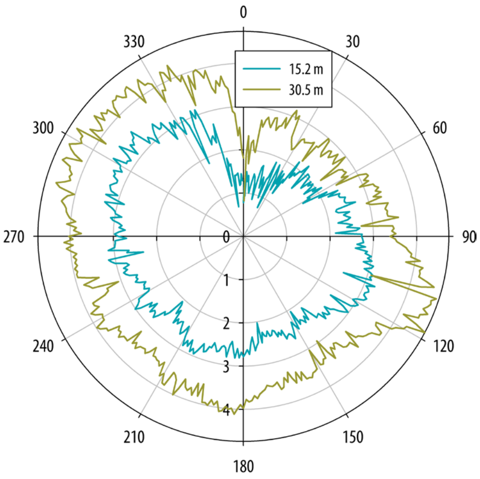

Figure 3. Mean annual wind speed.

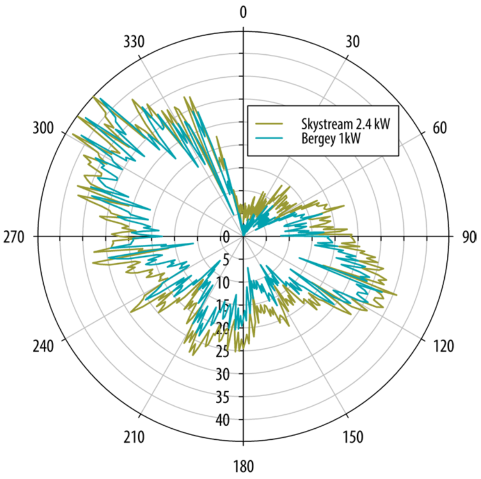

Figure 4. Power generation for observed mean wind speed.

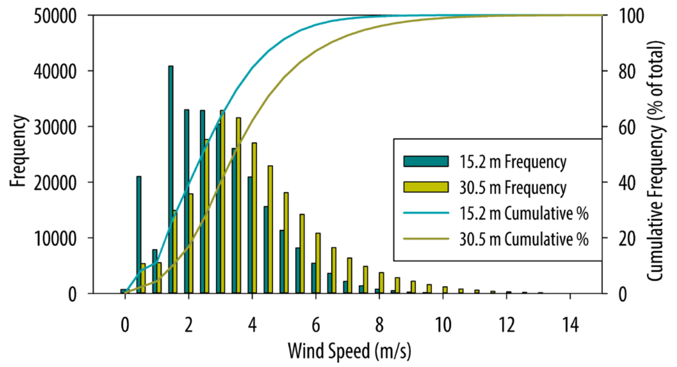

Figure 5. Frequency and cumulative percent frequency for observed wind speeds at the 15.2 and 30.5 anemoemter heights.

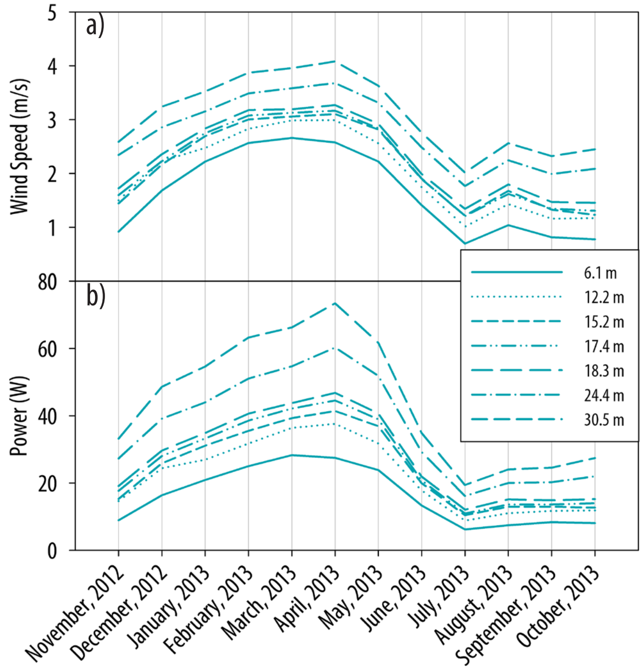

Figure 6. a)Monthly average wind speeds for different anemometer heights over a one year period; b) monthly total power for Bergey 1 kW based on measured power curve.

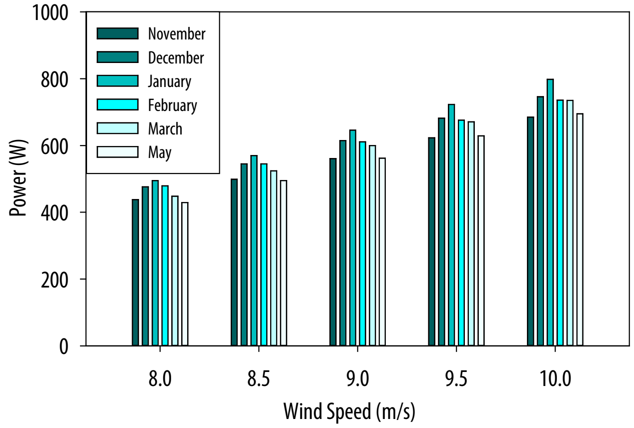

Figure 7. Exerpt of wind speed bins and measured power generation for Bergey 1 kWfor different months, whereby winter months generate more power for the same wind speeds.

that strengthens high and low pressure cells, strong differential land-water heating and suppressed atmosphere, act concurrently to strengthen the advection of horizontal wind. The total monthly power output for the Bergey 1 kW turbine presented in Figure 6b shows that as wind speeds increase, power rises exponentially (see Equation 1).

The state of the atmosphere influences a turbine's ability to generate power. The low solar radiation regime during winter months results in less buoyant vertical mixing of the air, which suppresses the air column. The decrease in air volume results in increased air density, which is able to transfer more momentum to the blades of the wind turbine. Consequently, a wind turbine will generate more power in the winter, even if summer wind speeds are the same. This is shown for the Bergey 1 kW in Figure 7, where the power output in the winter months is higher than in warmer months for the same wind speed bin.

Average winter wind speeds at Kortright were less than half those over Lake Ontario at a 10 m hub height. The wind speed varies geographically, with the greatest wind speeds observed over the Great Lakes, based on the North American Regional Reanalysis (NARR) modeled dataset for all of Ontario. During the winter months at a 10 m hub height, Great Lakes wind speed ranged from 5.5 to 7.5 m/s, while average wind speeds over land for all Ontario over the same period were 4.5 m/s. By comparison, wind speeds at the Kortright test facility remained below 4 m/s even for the highest hub height of 30.5 m and during the winter months. Since the Kortright Centre's proximity to Lake Ontario is approximately 30 km, there exists some advective influence from the Lake due to differential heating and pressure differences that result in the lake-breeze effect. It has been found that Lake Ontario's lake-breeze effect is able to penetrate more than 40 km inland, which characterizes sites closer to the Lake as potentially good wind power generation (Comer and McKendry, 1993). However, the obstructions surrounding the study site may contribute to the lower observed wind speeds, whereas the NARR modeled wind speeds do not take the existing land cover into account. The test site is representative of urban wind speeds that would be encountered under urban wind turbine installation projects, thereby providing a realistic representation of the potential power generation in such areas.

The Bergey 1 kW and 10 kW turbines performed only slightly below their manufacturer rating, while the Skystream 2.4 kW turbine showed significant underperformance. The Bergey 1 kW reached its rated wind power of 1 kW at 12.3 m/s

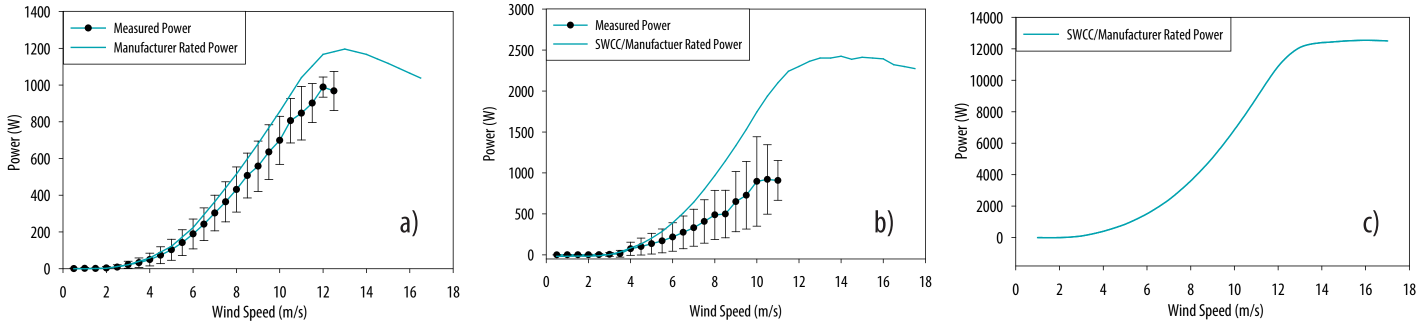

Figure 8. Measured and SWCC/manufacturer power curves. a) Bergey 1 kW; b) Skystream 2.4 kW; c) Bergey 10 kW.

(Figure 8a) and furling occurred at 14 m/s, suggesting that it was not reaching its rated power as quickly as the manufacturer claimed (11 m/s and furling at 13 m/s). However, furling at a later speed allows for the turbine to produce more power, although such high wind speeds were uncommon. The power curve obtained for the Bergey 1 kW closely resembled the manufacturer-produced power curve (no SWCC rating was available for this turbine). As an annual average, the Bergey 1 kW produced 95% of expected manufacturer rated power for the given site conditions and wind regime. This performance varied by ±1% for different heights. This indicated that the position of this turbine and its proximity to the meteorological tower did not negatively affect its performance. Similarly to the Bergey 1 kW, the Bergey 10 kW turbine performed within 95% of its manufacturer rated performance for the location and observed wind regime, which was also positioned close to the meteorological tower.

By contrast, the Skystream 2.4 kW was severely underperforming compared to the SWCC and manufacturer-derived power curve (Figure 8b). The measured rated power was 34% less than its factory certified rating for the site conditions and observed wind regime. The peak power output was 920 W at 10.5 m/s which is 62% less than its rated power of 2.4 kW. The total underestimation is 34% rather than 62% since the two curves diverge at high wind speeds which are not encountered very often at the study site (Figure 8b). Although the installation and maintenance of the turbine conformed to existing standards, it was discovered that there was a balancing issue which prevented the turbine to turn quickly enough with changing wind speeds. This issue was reconciled after the completion of this study. Additionally, the observed underperformance could also be due in part to the larger distance between the turbine and the meteorological tower (117 m), and its proximity to the two semi-detached houses (Figure 1). Another, more important factor, may be the large tare losses that occur when the machine is preparing to start and after it has stopped. This turbine has a cut-in wind speed of 3.5 m/s. Since 73% of the observed wind speeds at the site are below 3.5 m/s, these high cut in speeds could result in significantly lower performance. By contrast, the two Bergey turbines have lower cut-in wind speeds (2.5 m/s) and favourable positions close to the meteorological tower (< 20 m) and away from the Archetype houses. This reinforces the importance of location of a wind turbine within a potentially sensitive wind regime in urban areas with heterogeneous roughness elements.

The Bergey 1kW Coefficient of Performance (Cp) agrees with the manufacturer rating, while the Skystream 2.4 kW Cp is significantly lower. The Cp is the ratio of power produced by the turbine to the energy available in the wind. According to the Betz limit, a wind turbine cannot physically convert more than 59% of the kinetic wind energy to mechanical energy turning the blades of the turbine, for a maximum Cp of 0.59. The Bergey 1 kW Cp was 0.28 (Figure 9), which means that it extracts 47% of the maximum Bertz limit, and 28 % of the available kinetic wind energy. This measured Cp coincides with the SWCC/manufacturer rating of 0.28. The measured Cp value for the Skystream 2.4 kW is 0.16, which means that extracts 23% of the maximum Betz limit and 16% of the available kinetic wind energy. This value is significantly lower than the Cp obtained by SWCC/manufacturer of 0.29, reinforcing the performance results referred to earlier.

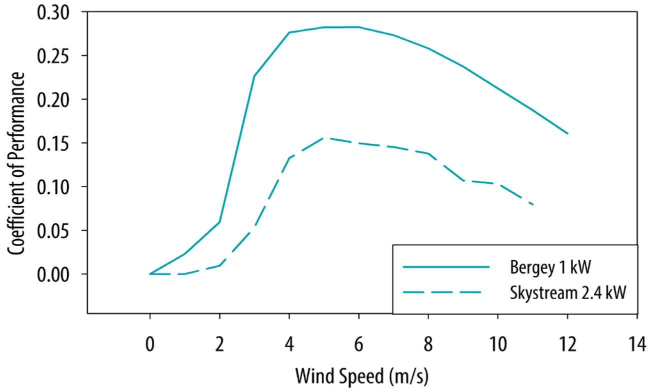

Figure 9. Calculated Coefficients of Performance over varying wind speeds for Bergey 1 kW and Skystream 2.4 kW turbines.

Table 2. Simple payback for tested turbines based on annual yield and at their installed heights.

	Installation Cost ($)	Yield (kWh/year)	FIT Payback Price ($)	Income From Electricity Sales ($)	Simple Payback Years
Solar Panel 1 kW @ $0.40/kWh	3900	1302.04	0.40	515.61	7.56
Solar Penel 1 kW @ $0.12/kWh	3900	1302.04	0.12	156.24	24.96
Bergey 1 kW (Measured)	13285	531.31	0.12	61.10	217.43
Bergey 1 kW (Potential)	13285	556.31	0.12	63.98	207.66
Skystream 2.4 kW (Measured)	27500	529.98	0.12	60.95	451.21
Skystream 2.4 kW (Potential)	27500	820.92	0.12	94.41	291.30
Bergey 10 kW (Measured)	52420	2288.90	0.12	263.22	199.15
Bergey 10 kW (Potential)	52420	3822.58	0.12	439.60	119.25

High start-up costs, low wind speeds and the lack of significant incentives for micro-wind generation make wind turbines an expensive renewable energy option relative to solar photovoltaics. Although Ontario is Canada's leader in wind energy generation with a total of 2,471 MW of installed capacity being generated from 1,328 wind turbines, there is ample potential for further growth (CanWEA, 2014). The Province of Ontario's Feed-in Tariff (FIT) Program was created in 2009 to help encourage renewable energy generation from sources such as biogas, biomass, landfill gas, solar photovoltaic, waterpower and wind. The incentives provided by this program have the potential to be widely adopted by businesses and homeowners if they are provided with sufficient knowledge on each technology's performance and payback period. The FIT payback price is the amount of income a homeowner can generate from selling the produced energy back to the grid, usually in $/kWh.

Table 2 summarizes the payback period for each turbine discussed in this study based on material and initial installation costs, excluding long-term maintenance and replacement. The payback period is compared to a 1 kW solar panel, monitored by the TRCA's Sustainable Technologies Evaluation Program at a solar photovoltaics field test facility adjacent to the wind turbine test site. The proximity of the two test sites allows for direct comparison of these types of renewable energy technologies. Although each technology relies on different atmospheric parameters, information presented in Table 2 highlights the dramatic difference between the two renewable energy generation sources, tested at the same site.

The 1 kW solar panel is the most cost-effective investment and produces 245% of the Bergey 1 kW energy production for 30% of its price. The simple payback period for the solar panel was just over 7.5 years, which increases to 25 years if the FIT price for wind energy was used. By contrast, the wind turbines had payback periods in excess of 100 years, even when power outputs are based on manufacturer/SWCC modeled performance. The long paybacks are a function of the initial cost, relatively low FIT incentive ($0.12/KWh compared to $0.42/kWh for solar), turbine underperformance, and low wind regime at Kortright. Chan et al. (2011) found similarly poor paybacks in Massachusetts, reporting that after 25 years only 12.5% of a Skystream 2.4 kW turbine cost was recovered at $0.15/kWh with adjustments for escalating maintenance, insurance and energy costs. The scale of the installation has an important influence on wind turbine costs. Small wind turbines cost more per kW installed than large wind turbines, but the latter generate more power and are usually installed on wind farms where installation and maintenance is conducted on a mass scale (CanWEA, 2014).

To provide a better perspective on the influence of turbine height on costs, Figure 10 demonstrates the difference in payback for each turbine modeled at different hub heights. The payback period for low heights is particularly extreme, exceeding 1400 years for the underperforming Skystream turbine at 6.1 m. This analysis suggests that the observed wind regime is not suitable for wind power generation in the Greater Toronto Area for obstructed sites and at large distances away from Lake Ontario due to decreasing lake-breeze effect. The observed wind speeds are strongly skewed to speeds under 3.5 m/s, which is also the speed at which some turbines begin to generate power, bypassing the potential energy that low wind speeds could generate.

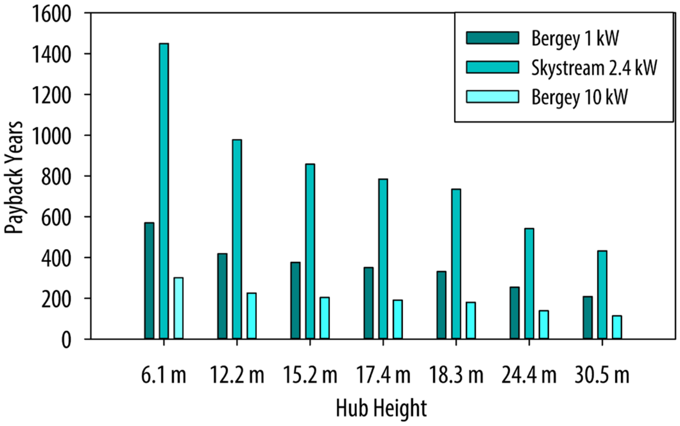

Figure 10. Payback years for different hub heights for each turbine.

CONCLUSIONS

Although the study site experienced wind speeds that were less than the Environment Canada average for Ontario, the site provided a suitable test area that is representative of wind conditions in the Greater Toronto Area and partially subject to typical urban surface obstacles, such as houses and trees. During the field testing period, the observed wind distribution was skewed toward lower wind speeds, resulting in lower than expected yield for average wind speed, calculated assuming a typically Weibull distribution. The yielded power is therefore site dependent, as it would increase significantly at a windier site. The potential for wind power also varies seasonally with higher wind speeds in the winter and with height above the surface.

The Bergey 1 kW and 10 kW turbines performed similarly to their manufacturer and SWCC power curve for the given site conditions, and the Bergey 1 kW met its specified Coefficient of Performance. The Skystream 2.4 kW significantly underperformed, as a result of a mechanical balancing issue, and possibly due in part to its position away from the meteorological tower and proximity to the Archetype houses, placing it under a different wind regime than was measured by the anemometers. High cut-in wind speeds may also have contributed to poor performance, as wind speeds at the test site were often very low. Prior to purchasing a small wind turbine, buyers should request regional field performance data to verify that the actual performance of the turbine under field conditions matches the manufacturer rated performance. A year-long wind test should also be conducted at the proposed hub height in order to assess whether the site's wind regime produces speeds that are able to yield reasonable power and payback period. Once installed, a commissioning process can also help ensure that small defects in the turbine or installation are identified and rectified early on in the process.

A 1 kW solar panel installation was shown to produce 245% of the power produced by a 1 kW Bergey turbine for 30% of its price. Since the solar panel also consumes considerably less space and is easier and cheaper to install, solar power could be a more attractive and feasible option for the observed weather and climate of the GTA with peak power generation in the spring and summer. Wind power generation is greatest in the winter, when the solar resource is weakest, making solar and wind complimentary sources of energy in a future green energy economy. This hybrid setup is favourable for off-grid locations, where each system provides energy at different times of the year, ensuring an even supply of power throughout the year. Although wind energy costs are relatively steep, continuing technical advances will likely result in cost reductions that will help make small wind power more economically feasible.

REFERENCES

Ashtine, Masaō (2013) Feasability of micro-scale wind turbines in Ontario. Master of Science Thesis, York University.

CanWEA - Canadian Wind Energy Association. (2014) Canadian Wind Energy Markets: Ontario. Retrieved from < http://canwea.ca/wind-energy/ontario/>.

Chan C, Silva P, Zhang C (2011) Danehy Park Wind Turbine Project Preliminary Assessment Report. Danehy Park Project Group, Wind Energy Projects in Action, Massachusetts Institute of Technology, prepared for the city of Cambridge.

Comer NT, McKendry I (1993) Observations and numerical modelling of Lake Ontario breezes. *Atmospheres-Ocean*, **31**, 481-499.

Li M, Li X (2005) Investigation of wind characteristics and assessment of wind energy potential for Waterloo region, Canada. *Energy Conservation and Management*, **64**, 3014-3033.

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This technical brief was prepared by the Toronto and Region Conservation Authority's Sustainable Technologies Evaluation Program (STEP) based in part on an M.SC thesis completed by Masaō I. Ashtine in 2013, under the supervision of Dr. Rick Bello at York University's Geography Department. The research was conducted collaboratively between York University and STEP, with funding support from the MITACS Accelerate Program Region of Peel, York Region and the City of Toronto. For more information about this project, please contact STEP@trca.on.ca.