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WIND ENERGY SCIENCE DISCUSSIONS

Feasibility of small wind turbines in Ontario: Integrating power curves with wind trends.

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Abstract

Micro-scale/small wind turbines, unlike larger utility-scale turbines, produce electricity at a rate of 300 W to 10 kW at their rated wind speed and are typically below 30 m in hub-height. These wind turbines have much more flexibility in their costs, maintenance and siting owing to their size and can provided wind energy in areas much less suited for direct supply to the grid system. The small wind industry has been substantially slow to progress in Ontario, Canada, and there is much debate over their viability in a growing energy dependent economy. In an effort to diversify the energy sector in Canada, it is crucial that some preliminary research be conducted in regards to the relevance of changing winds as they impact small wind turbines; this study seeks to demonstrate the performance of two small wind turbines, and speculate on the potential power output and its trend over Ontario historically over the last 33 years using the North American Regional Reanalysis (NARR) data. We assessed the efficiencies of a Skystream 3.7 (2.4 kW) and a Bergey Excel 1 kW wind turbines at the pre-established Kortright Centre for Conservation wind test site, located north of Toronto. We have found that the small turbine-based wind power around the Great Lakes and eastern James Bay have increased during the seasonal months of winter and fall, contributing as much as about 10% in some regions to the total electricity demand in Ontario.

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KEYWORDS

small wind turbines; NARR dataset; multi-year wind trends; wind turbine power curves; renewable energies

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1 Introduction

Much of the modern wind turbines representing the renewable energy landscape consist of large utility-scale wind turbines which can produce electricity in the magnitudes of MW (megawatts), taking advantage of stronger winds aloft with higher hub-heights and larger rotor diameters. Canadian investment in wind turbines saw a 20% growth in clean wind energy production in 2012, representing over \$2.5 billion in investment, and Canada's current installed capacity is just over 6.5 GW (gigawatts).[1] The province of Ontario has 2.9 GW of installed wind capacity, ~ 30% of Canada's total capacity.[2] The small wind turbine industry however is focused on the installation of wind turbines which produce electricity on an average between 300 W to 10 kW (kilowatts) rated power with hub-heights that are generally below 30 m. Although small-scale wind turbines have been around historically, employed for different functions like grinding grains, they have failed to dominate the wind energy sector owing to increasing doubts about their performance, technological advancements, field-testing and feasibility in a changing climate.

Small wind turbines produce more costly electricity than their utility-scale counterparts, especially in poor wind sites. When tailored to specific wind regimes, and used at optimal conditions through wind site assessment, small wind turbines can be a reliable energy source and socio-economic benefit to regions disconnected from the grid. Seen as a means to increasing electrical supply to small isolated communities in developing countries[3], the small wind industry has been especially hindered in Canada with currently between 2,200 and 2,500 turbines installed, 90% of which fall into the 'mini' wind turbine category (< 1 kW rated power). The total combined capacity of all SWTs (Siemens Wind Turbines) is estimated to be between 1.8

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MW and 4.5 MW, equivalent to the capacity of one to three modern utility-grade wind turbines, with annual output roughly at 7.5 GWh (gigawatt hour) per year, equivalent to an amount of electricity consumed by approximately 750 Canadian homes.[1]

The small wind industry has afforded the renewable energy sector with the benefits of energy independence for the consumer, remote electricity production in regions off-grid and a more diversified energy supply which can be complemented with solar energy and utilized by businesses and households. However, this industry is faced with many challenges, particularly the lack of standardized field testing of these wind turbines, resulting in uncertainty in performance claims by manufacturers. A vast amount of testing done to establish small wind turbine rated power and power curves is done in wind tunnels, focusing on the electrical components of the wind turbines and not realistically assessing turbine performance in the field. As environmental factors such as temperature, radiation and wind variability affect turbine performance, field-testing is essential. Studies assessing the performance of small wind turbines in the field have often focused on the turbine's effect on the local environment or turbulence patterns produced by secondary rotor effects.[4-9] Since there are currently no formal standardized testing regulations for their calibration and power output in the North American wind industry[10], it is difficult to develop a small-scale diversified electrical generation strategy under a changing wind field caused by global warming. Our study is a first step to address this issue in Ontario.

The Kortright Centre for Conservation has been at the forefront of renewable energy initiatives in Toronto, Ontario, being one of two main test sites for standardization of small wind turbines in Canada (second is located in Prince Edward Island). Two leading industry standard turbines were assessed in this study, the Bergey Excel 1 kW and the Skystream 3.7 (2.4 kW) wind turbines with hub-heights of 16.8 m and 15.2 m, respectively. These turbines have varying specifications, as listed in Table 1. Our study seeks to understand the historical (33 year, 1980 - 2012) electrical output potential for small wind turbines using the NARR wind data at 10 m and 30 m over Ontario. We have incorporated highly optimized wind power curves of our two small wind turbines into the NARR data over the 33-year period, finding trends in the electrical output that best demonstrate the potential of this industry, spatially and temporally across Ontario.

1.1 NARR dataset

The NCEP-NARR is a high-resolution atmospheric and land surface hydrology dataset for the North American domain.[11] At present this dataset comprises of reanalysis data for the period 1979 - present; in the present study, 3-hourly data from 1980 - 2012 were used. The widely known NARR procedure uses the very high resolution NCEP Eta Model (32 km, 45 layers) together with the Regional Data Assimilation System (RDAS).[12-15] NARR is widely known for its successful assimilation of high-quality and detailed precipitation observations into the atmospheric analysis which was previously lacking from many global models. This research focused on the electrical output potential over Ontario for the tropospheric heights of 10 m and 30 m, hub-heights relevant to small wind turbines. However, owing to a preliminary coding error, 43 grid cells along the lower Hudson Bay coastline were found to be incorrect at the 30 m level, due to their low lying elevation (http://www.emc.ncep.noaa.gov/mmb/rreanl/faq.html#zero-30m-winds). However, these grid cells (0.01% of the study area) were found to be non-influential on the neighbouring cells and were omitted from the analysis.

Wind Energ. Sci. Discuss., doi:10.5194/wes-2016-9, 2016
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2 Methods

2.1 Power curves

The Kortright test site is located short distance (~30 km) north of Toronto, with an open fetch, having a predominantly southeast and northwest wind pattern. Meteorological and electrical output data were captured for both turbines between 7 November 2012 and 30 April 2013. These data provided 5-second readings of wind speed at 8 levels above ground, temperature, wind direction and turbine power output for ~ 6 months. Analysis of these data produced performance data through power curve analysis (Fig. 1), demonstrating how the Bergey and Skystream wind turbines performed at differing wind speeds. Applying a best fit curve, 4th order polynomial equations were obtained for each turbine that best described the ability of the turbine to convert wind energy into electrical power (P) in Watts, Eq. (1) and (2):

Bergey 1 kW

$$P = -0.101x^4 + 2.02x^3 - 2.878x^2 - 2.187x + 2.732 \quad (1)$$

Skystream 2.4 kW

$$P = -0.144x^4 + 2.985x^3 - 8.246x^2 + 9.301x - 3.978 \quad (2)$$

where x is the output wind speed.

2.2 Applying power curves to NARR

Using the NARR wind components, u and v, wind speed U (ms^{-1}) at the tropospheric levels of 10 and 30m was calculated using the standard magnitude formula (Eq. 3):

$$U = \sqrt{u^2 + v^2} \tag{3}$$

Wind speeds at 10 and 30 m heights were derived for every 3-hr measurement from the corresponding NARR wind data (1980 – 2012). Monthly mean wind speeds, 33-yr monthly averages and seasonal means were assessed for winter (DJF), spring (MAM), summer (JJA) and fall (SON).

The historical power generating potential for the Bergey and Skystream wind turbines were then calculated by inputting the NARR wind speed data to Eq. 1 and 2, respectively; however, only the data for the Bergey 1 kW wind turbine is presented as it was found that the Skystream 2.4 kW power curve closely represented the Bergey's due to its underperformance. The Bergey turbine power curve demonstrated electrical output for each 3-hr reading from the NARR dataset in megajoules (MJ) and the summed electrical output for each month was averaged based on 33 years of wind speed data. This method was repeated at the 30 m and spatial differences in

Wind Energ. Sci. Discuss., doi:10.5194/wes-2016-9, 2016
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performance between the hub-heights of 10 and 30 m show regions where increases in the hub-height have proven more effective than in other regions.

Trend analysis in the electrical output over Ontario and the Great Lakes from each wind turbine was computed with the OLS (ordinary least squares) method, along with the interannual variability of wind power. Plots of significant trends using *t*-test analysis are reported on a seasonal basis.

3 Results and discussion

3.1 Seasonal variations in turbine power output

Seasonal variations and long-term trends in the NARR wind field from 1980 to 2012 at the 10 and 30 m heights have been described in Ashtine et al. (2016). The spatio-temporal patterns of the turbine energy output correspond well with changes in winds discussed in Ashtine et al. (2016). Power curve produced for the Bergey 1 kW (Fig. 1) wind turbine was in close agreement with the power curves of this turbine from the field testing.[16, 17] The Bergey reaches its maximum power output of 1.1 kW at 13.5 ms^{-1} with a cut-in wind speed of 2.5 ms^{-1}. Turbine power output closely follows patterns in mean wind speeds, with the Great Lakes and James Bay producing the greatest amount of electrical energy for both turbines during the winter and fall seasons (Fig. 2). Significant seasonal variations in the power output are observed over the major water bodies, as a result of the impact on surface winds from melting and formation of ice over water.[18]

Wind Energ. Sci. Discuss., doi:10.5194/wes-2016-9, 2016
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The Bergey turbine produces less electricity around Lakes Erie and Ontario but Lake Ontario shows more promising yields during the winter by approximately 25% more electrical output. Spring values are regionally less pronounced, with electrical production becoming more uniform across the province and the Lakes have reduced output with regions surrounding the lakes producing a mean of 1000-1200 MJ (megajoules). This pattern of more uniform production is further seen during the summer where means have fallen to 800 MJ over most of Ontario, with regions around Lake Superior have the highest yields. Northern Ontario benefits in the summer, with regions producing between 1000 to 1200 MJ. Energy output increases in northern Ontario along the Hudson Bay coastline and western James Bay during the fall, with outputs varying in the range 1500-2000 MJ. The Lakes obtain higher yields in the fall with roughly 1500-2000 MJ produced by the Bergey turbine in surrounding areas and yields are fairly evenly distributed amongst the Lakes with Lake Ontario giving slightly lower output. Electrical output patterns are similar at the 30 m hub-height with total energy production being higher, particularly in the winter and fall seasons (Fig. 3).

Intuitively, trends in the electrical output closely represent wind speed trends with the largest trends occurring in the winter and fall seasons (Fig. 4). Winter can see positive trends in turbine electrical output at 10 m of roughly 7 MJyr^{-1} (5% decadal increase) over regions close to the Lakes and up to 20 MYyr^{-1} along the eastern James Bay coast (20% decadal increase). Fall averages are different with the trends over the Lakes being not as strong (0-5 MJyr^{-1}) whereas regions over the western James Bay coastline can see trends of 25 MJyr^{-1} that translates to a 10% increase over means per decade. Winter trends persist into the spring season but are more limited to Lake Superior and eastern James Bay, whereas summer trends show the highest increases over western James Bay (8 $MJyr^{-1}$) and the lower Hudson Bay coastline. Trends at the 30 m hub-height follow a similar pattern but are not as strong as those at 10 m hub-height. The aforementioned trends seen during the winter and fall around the Lakes and James Bay are highly significant ($p < 0.005$) at both hub-heights.

Increasing the hub-height of the Bergey turbine during the winter gives slightly higher output during the winter than in the fall; up to 100% increase in wind speeds can be experienced over much of Ontario in the winter versus approximately 80% in the fall (Fig. 5). Differences in electrical production are much less near the Lakes, with surrounding regions seeing *ca.* 60% and 20% over the Lakes themselves. Winter means are slightly lower with height over the Lakes than in the fall. Hub-height increase to 30 m can enhance electrical output by 60-80% during the spring with less spatial variability across Ontario. The summer season presents a more spatially heterogeneous distribution of power output, as while much of northern and central Ontario experience increases in output by 80% at 30 m, southern Ontario experiences increases in the range 100-120 %, particularly in areas close to Lake Erie and Ontario.

Annual averages (Fig. 6) remain consistent in patterns of electrical production for the Bergey 1 kW wind turbine, with regions surrounding the Great Lakes having an annual average of total electrical energy production *ca.*1250 kWh, with central, northern and southern Ontario having averages close to 500-1500 kWh at the 10 m hub-height. Energy production is more evenly produced at the 30 m hub-height, with most of Ontario producing between 2000-2500 kWh and regions around the Lakes having higher means in electrical output than regions in central and northern Ontario.

3.2 Seasonal wind trends at hub-height

Wind speed trends in seasonal mean values show greatest change and highest wind speeds in regions surrounding the Great Lakes and James Bay in northern Ontario at both the 10 and 30 m hub-height. Wind patterns change in distribution and speed when transitioning from large water bodies to land as the latter landscapes have very distinct properties (such as greater surface friction) that influence the atmosphere above. Changing dynamics in lake/sea ice cover and their respective breakup and reformation dates can influence atmospheric conditions and stability and these changes can lead to changes in wind speed over the Great Lakes and James Bay region, with a causal link between the observed decline in ice cover over the Great Lakes during the past decades with an increasing wind speed during transition months (winter and fall). [19-21]

3.3 Trends in electrical output

Consistent with the observed spatio-temporal trends in the wind, turbine output is greatest during the winter and fall seasons, with the winter season seeing high yields in regions surrounding the Great Lakes and James Bay. These yields are expected owing to the higher trends in the wind speed seen during these seasons. Summer and spring yields are lower due to weakening wind gradients, with spring having higher output for most of Ontario than in summer. It is evident that the majority of electrical energy produced by the turbine is seasonally and spatially dependent; thus, not all of Ontario will benefit from small wind turbine implementation. We note that the southern Ontario region surrounded by Lakes Erie, Huron and Ontario has the highest concentration of utility-scale wind farms in Ontario due to the existence of favourable wind speeds. Analysis in the Waterloo region (southern Ontario) has shown that the windiest months where wind energy potential is the greatest are from November to May.[10] It is widely noted that an increase in turbine hub-height increases electrical yields, as faster winds are captured at higher hub-heights owing to the reduced effect of wind shear from the terrain.[23] Although the same patterns in electrical output by the analyzed Bergey 1 kW wind turbine at the 10 m hub-height also exist at 30 m, the yield is not always spatially and temporally consistent. Increasing the hub-height in the winter can produce up to 100% increase in wind speeds over much of Ontario versus 80 % in the fall, as wind gradients are slightly steeper in the winter.

Although the focus of the present study is on small wind turbines and not on offshore production, it is useful to note that the electrical output is increased by 20 % over the lakes at the 30 m hub-height versus up to 60 % in regions surrounding the lakes. Surface roughness causes winds closer to the terrain to lose more momentum than over water bodies. Furthermore, wind profiles are steeper over the land, and so too is the corresponding wind energy potential.[24] Southern Ontario, particularly regions closer to Lakes Erie and Ontario, would most benefit from increases in hub-height to 30 m, as capturing lake winds can raise yields by 100-120 %. These southern regions will benefit more from turbines of a higher hub-height, potentially reducing the need for more turbines in regions where only 60 % increase with hub-height is experienced. With the 10 m hub-height, decadal trends indicate increases in electrical output by approximately 6% over regions close to the lakes and up to 20 % along the eastern James Bay coast in the winter. Ontario will most benefit from James Bay trends in the fall, particularly over the western James Bay coastline

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Published: 18 April 2016

Open Access WIND ENERGY SCIENCE DISCUSSIONS

can see up to 10% increase in mean electrical production per decade. Trends at the 30 m hub-height are not as strong but still suggest growing supply of wind energy through the winter and fall seasons.

Based on the examination of annually-averaged total electrical output for the Bergey 1 kW at the 10 m hub-height, it is evident that regions that will most benefit from small wind turbine investment in Ontario are those surrounding the Great Lakes influenced by lake winds, as well as regions along northern Ontario influenced by strong winds blowing to and from Hudson Bay and James Bay. Based on the NARR wind data, much of Ontario would see an annual power production of 800-1200 kWh at 10 m, while areas surrounding Lake Superior could have high outputs of 1.6 MWh. Power production is more evenly distributed at 30 m, since the influence of surface roughness is reduced at that height, and much of Ontario would see power outputs of approximately 1.5 to 2.3 MWh, with greatest increases in southern Ontario and around the Great Lakes. Using the mean values of 1.5 to 2.3 MWh from much of Ontario at the 30m hub-height and the reported electrical cost of 8.45cents/kWh for Ontario as of May 1st, 2013 (http://www.ontariohydro.com/index.php?page=current_rates), the use of the Bergey 1 kW wind turbine can see an approximate annual saving of $130 to $200 in electrical bills per annum.[25] However, this value is greatly limited by the fluctuating nature of electrical prices and the difference in costs between providers. Having a combination of higher hub-heights and a higher rated output turbine (e.g. 10 kW, 25 kW) will surely increase annual savings, but a cost-effective analysis was not performed in this study.

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The Statistics Board of Canada gives an annual Ontario household consumption of 107 GJ from its last household energy census in 2007. Spatial comparison (10 m hub-height) of the supply of electricity from the Bergey 1 kW wind turbine to the demand of the average Ontarian household shows that the Bergey turbine is most economically viable around the lakes but will only account for up to 6% of annual energy demand (e.g. near Georgian Bay) and approximately 3.5 to 4.5 % in southern Ontario, whereas much of Ontario will see this turbine accounting for 2.5-4 % of energy demands (Fig. 7). These values are increased at the 30 m hub-height with much of Ontario now experiencing between 5 and 7 % of energy demand from the Bergey turbine and regions around Lake Superior can meet energy demands of up to 9-10 % in some regions.

5 Conclusion

Wind speed trends during the winter and fall months are the greatest at both hub-heights of 10 and 30 m, with the summer season giving the lowest means. These trends are spatially highly heterogeneous, occurring frequently over the Great Lakes, lower Hudson Bay and James Bay. Much of Ontario experiences statistically insignificant wind speed trends much lower than surrounding water bodies. It is purported that a strong correlation with decreasing lake/sea ice concentrations and increasing wind speeds exists, where loss of sea ice leads to perturbation in both physical and energy balance near the surface, leading to changes in the stability in the atmospheric boundary. Through turbine analysis, we have postulated that the small wind turbine industry will be most feasible at a higher hub-height of 30 m and utilizing turbines of a higher rated output. Even with a 1 kW wind turbine (< 0.001% of most utility-scale wind turbines), annual savings of \$130-\$200 can be possible for much of Ontario at the 30 m hub-height, contributing to approximately 5 and 7 % of the total provincial energy demand. These statistics however, are derived from general energy usage averages and apply a basic energy demand to Ontario, whereas true estimates are heterogeneous and not spatially even as energy demands are surely higher in southern populated regions. The Bergey turbine is rated at only 1 kW output, while other small turbines with commonly rated outputs of 10 kW and 25 kW an lead to higher turbine output. Limitations in the estimation of turbine electrical power exists as power curves are inherently based on data collected and sample size of such data. However, this study's analysis produced a power curve which was a good representation of the Bergey manufacturer power curve.

Author contribution

R. Bello and K. Higuchi played an important role in the editing and direction of research for this manuscript.

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Wind Energ. Sci. Discuss., doi:10.5194/wes-2016-9, 2016
Manuscript under review for journal Wind Energ. Sci.
Published: 18 April 2016

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Wind Energ. Sci. Discuss., doi:10.5194/wes-2016-9, 2016
Manuscript under review for journal Wind Energ. Sci.
Published: 18 April 2016

Table 1: Wind turbine specifications for Skystream and Bergey turbine at the Kortright field-testing site. Information obtained from manufacturer description.

		Bergey	Skystream
Structural	Hub-height	17.37 m	15.24 m
	Turbine type	HAWT, upwind	HAWT, downwind rotor with stall regulation control
Manufacturer rating	Rated Power	1 kW	2.4 kW
	Rated Wind Speed	11 ms^{-1}	13 ms^{-1}
Rotor specifics	Rotor Diameter	2.5 m	3.72 m
	Swept Area	4.91 m^2	10.87 m^2
	Rotor Speed (RPM)	490 (rated rotor speed, no range applied)	50 – 330
	Blade Material	Pultruded fiberglass	Fibreglass reinforced composite
Wind	Cut-in Wind Speed	2.5 ms^{-1}	3.5 ms^{-1}
	Cut-out Wind Speed	None	25 ms^{-1}
	Max Design Wind Speed	54 ms^{-1}	63 ms^{-1}
Protection	Furling Wind Speed	13 ms^{-1}	No furling
	Over-speed protection	Auto tail furl, electrical breaking system	Electronic stall regulation

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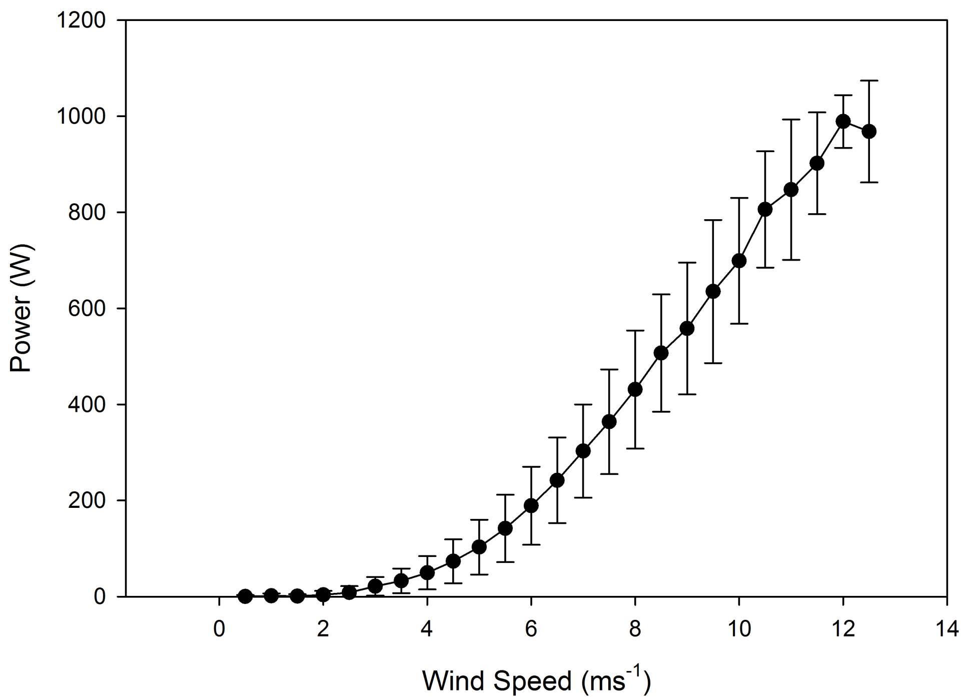

Figure 1: Computed power curve for the Bergey Excel 1 kW small wind turbine. Data were collected between Nov 2012 – April 2013.

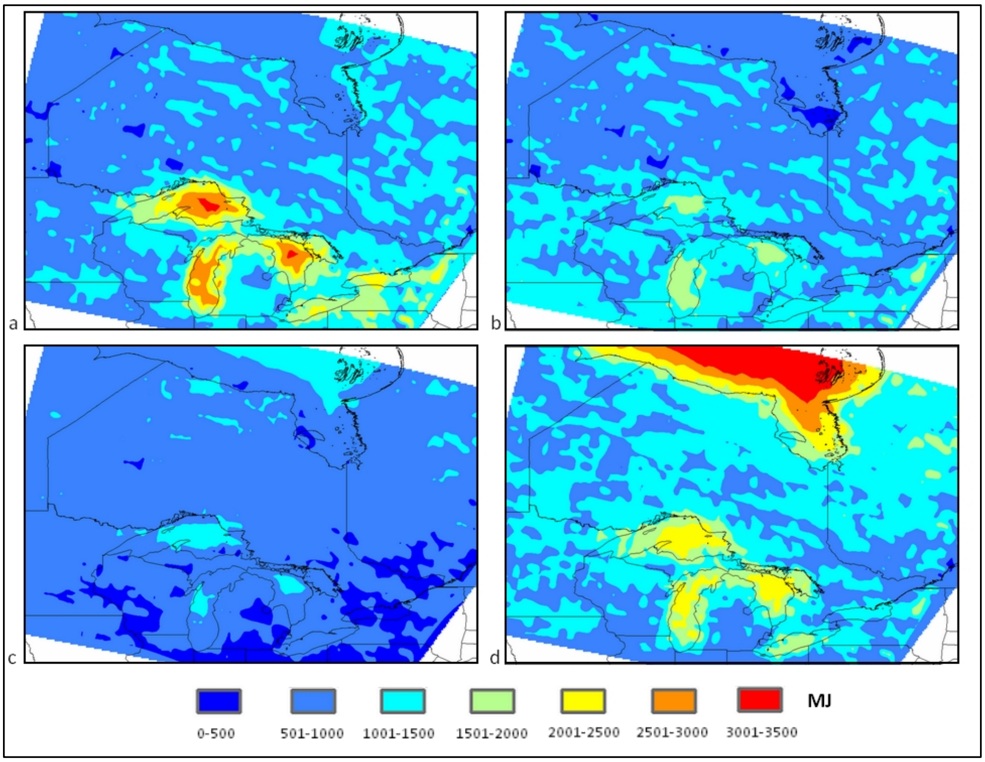

Figure 2: Seasonal total mean turbine energy output (MJ) for the Bergey Excel 1 kW wind turbines for study area at 10 m for (a) winter b) spring c) summer d) fall.

Wind Energ. Sci. Discuss., doi:10.5194/wes-2016-9, 2016
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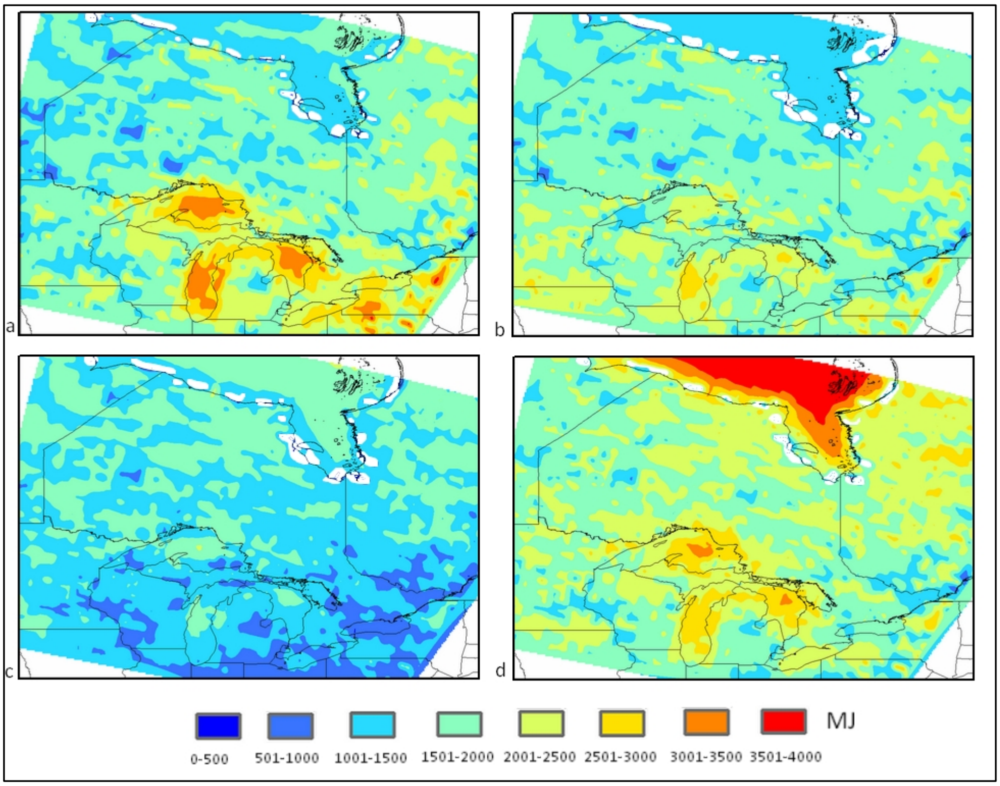

Figure 3: Seasonal total mean turbine energy output (MJ) for the Bergey Excel 1 kW wind turbines for study area at 30 m for (a) winter, (b) spring, (c) summer, (d) fall. *Coastal regions in white have been omitted due to coding error at the 30 m hub height.*

Wind Energ. Sci. Discuss., doi:10.5194/wes-2016-9, 2016
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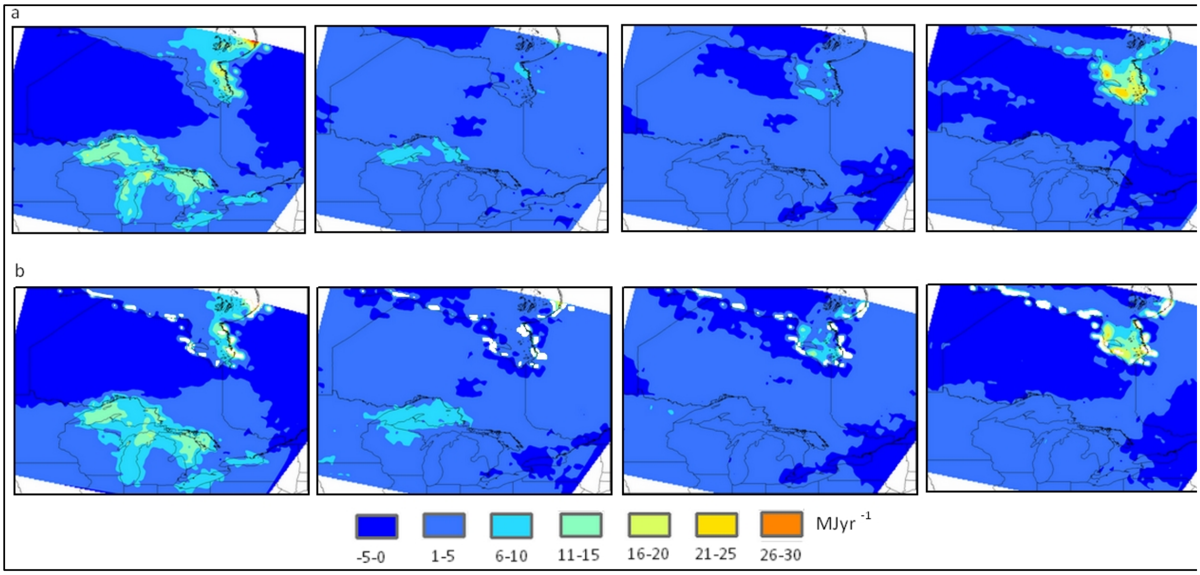

Figure 4: Multi-year trends in seasonal total mean turbine energy output (MJ) for the Bergey Excel 1 kW wind turbines for study area at (a) 10 m and (b) 30 m for winter, spring, summer, fall from left to right respectively. *Coastal regions in white have been omitted due to coding error at the 30 m hub height.*

535

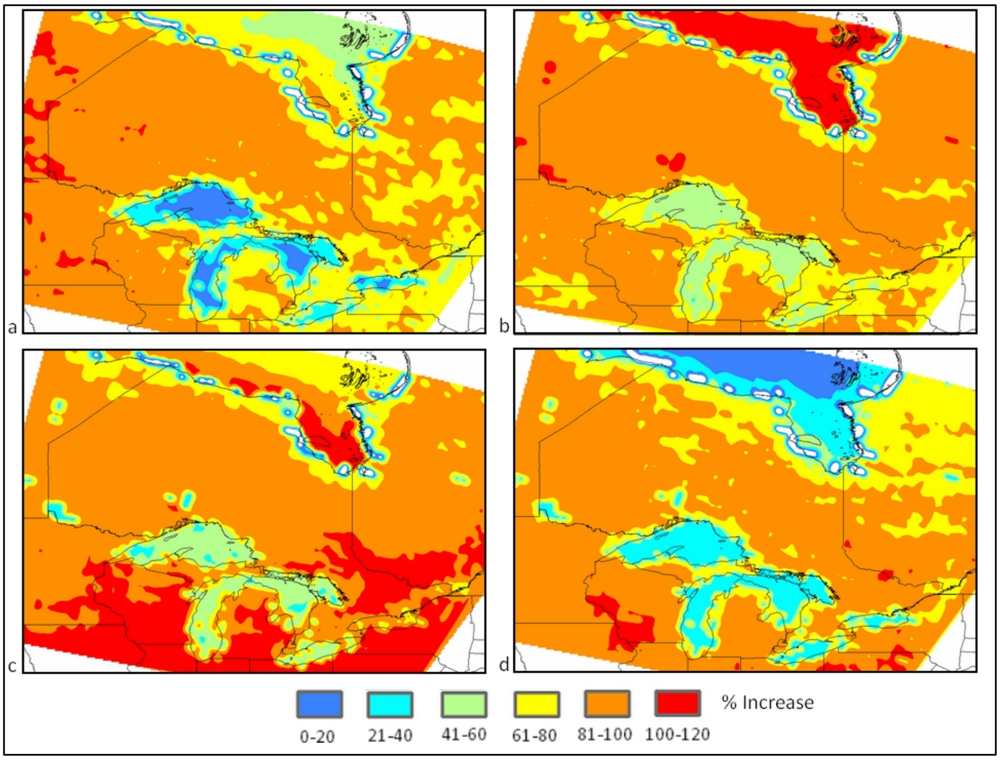

Figure 5: Seasonal differences in turbine electrical output for the Bergey Excel 1 kW wind turbine between the 10 m and 30 m height for (a) winter, (b) spring, (c) summer, (d) fall. Values express the percent increase in turbine output as hub height increases to 30 m. *Coastal regions in white have been omitted due to coding error at the 30 m hub height.*

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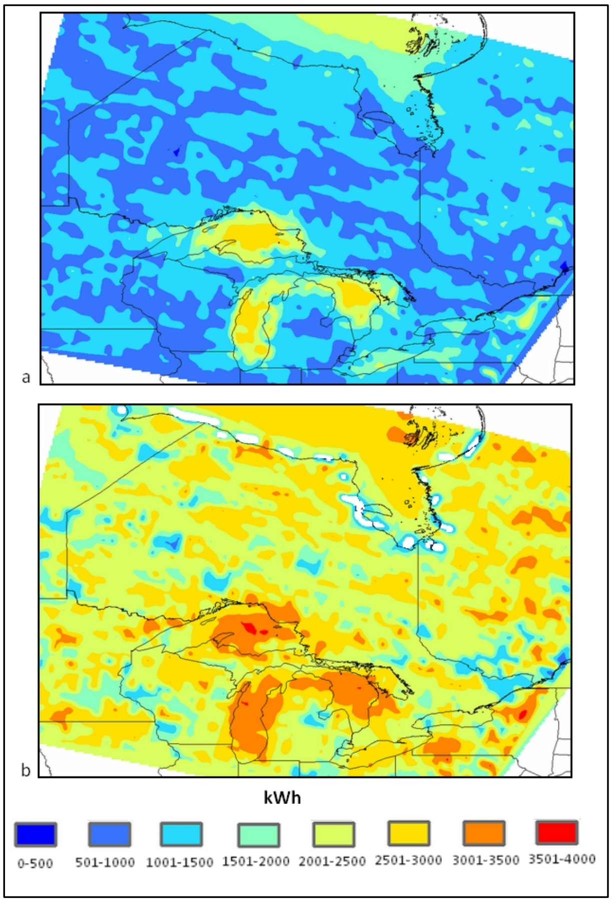

Figure 6: Annual total mean turbine energy output (kWh) for the Bergey Excel 1 kW wind turbine for (a) 10 m and (b) 30 m hub heights. *Coastal regions in white have been omitted due to coding error at the 30 m hub height.*

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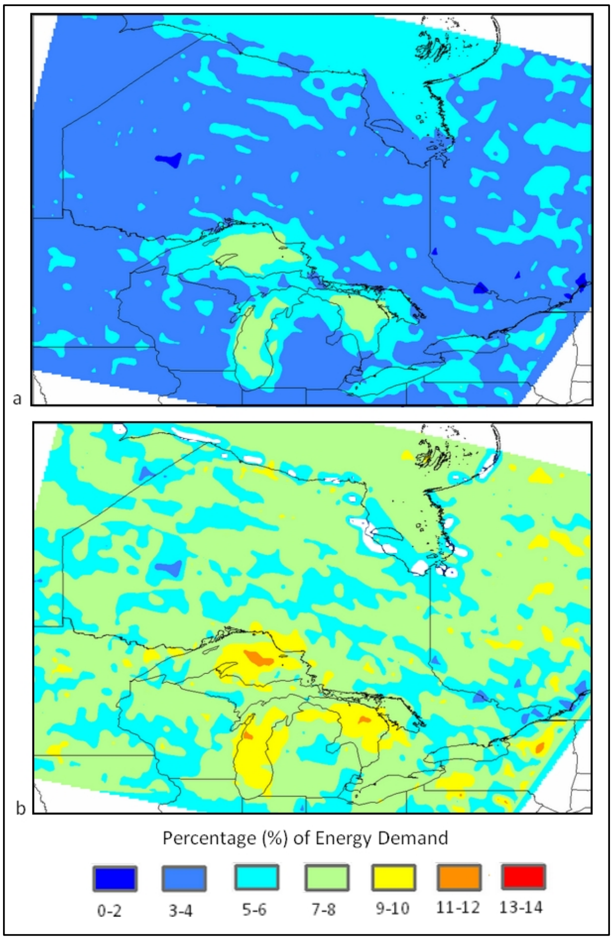

Figure 7: Annual percentage of energy demands met for an average Ontarian household by the Bergey Excel 1 kW wind turbine for (a) 10 m and (b) 30 m hub heights. The average annual energy demand for a household in Toronto is reported as 107 GJ (Statistics Canada, 2007). *Coastal regions in white have been omitted due to coding error at the 30 m hub height.*