Note for Reviewers:

Here is a review version of our paper. The scope of paper changed after we submitted our abstract for review because of the publication recently of a paper referencing our earlier work and covering much of the ground we had proposed to cover ourselves.

A small amount of background information not essential to the main findings remains to be added.

If the reviewers wish to see any of our data or calculations, we would be happy to provide them.

We intend to circulate the draft paper to the chair of the IESO's Wind Power Standing Committee with the intention of presenting our findings to the committee at the upcoming January 28th meeting. We also plan to circulate the draft to a number of industry experts we have consulted with who have expressed an interest in seeing the paper and other interested people.

Tom Adams and Francois Cadieux

DRAFT PAPER
WIND POWER IN ONTARIO:
QUANTIFYING THE BENEFITS OF GEOGRAPHIC DIVERSITY

Review Version – January 18th

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Abstract

Integrating wind power into the Ontario electricity system requires managing its variability. Many studies and proponents of wind power claim that positioning wind farms in geographically diverse locations will mitigate variability and smooth wind power’s contribution to electricity generation. Our study analyzes the actual electricity production of wind farms in Ontario with capacities larger than 40 MW for 32 months (March 2006 to December 2008). Seasonal correlations between wind farm outputs are generated and graphed against the distances separating the wind farms. The effect on overall wind production variability of geographic diversity in the locations of wind output is then investigated. The average absolute hourly change in seasonal output is examined, as is change in standard deviation. Results confirm that correlations between wind farm outputs decay with distance. Distances of approximately 250 km are required to reduce the correlation coefficient between the hourly outputs of two wind farms to 0.5 - a representative limit for strongly synchronous outputs. To illustrate the smoothing potential of distance, the variability of output from a closely located group of wind farms was compared before and after adding the output of a farm located 364 km away from closest other

farm. In this case, the change in standard deviation was only from 23.9% to 21.2% of the aggregate installed wind power capacity. This study's results agree with European studies, but indicate that distance provides less smoothing of output in Ontario than has been found in some European countries. However, results disagree with findings of a study of Ontario's wind potential conducted by General Electric.

1. Introduction

Our study focuses on quantifying the level of output synchronization between wind farms located at different distances from each other in Ontario and New York state, USA. It also aims to quantify the benefits of geographic diversity of wind farms with regard to variability by looking at average hourly output changes.

If the penetration of wind power is low enough, the short run fluctuations associated with wind capacity are comparable to other variations in the supply-demand balance, small load following impacts result, and no accommodations such as an increase in reserve provisions are called for. However, as the penetration of wind power rises, system load following impacts due to wind power intermittency could become significant. As noted below, wind capacity is anticipated to grow significantly in the near future.

Quantifying the benefits of geographic distance between wind farms is necessary if transmission investments are to be compared against other types of generation or demand management options for managing wind variability. The costs of transmission can be significant. Hydro One, Ontario's main transmission utility, is currently building the first major transmission project primarily driven to serve wind generators. The Bruce to Milton transmission line, approved by the OEB September 15, 2008, extends from the Lake Huron shore in south western Ontario into the Greater Toronto Area. The new system will require 180 km of new conductors, of which 173 km is to be double circuit, and will operate at 500 KV. Approximately 58% of the expected incremental generation capacity in the region served by new line is wind power. The line is forecasted to cost $630 million or approximately $3.5 million per km including the cost of related transmission and sub stations.

1.1 Power system context

Grid operators must balance overall load with overall generation. Each generation component is only a piece of an overall and portfolio. Recognizing that the operational characteristics of wind power interact with the capabilities of the rest of the power system in meeting consumer demand, it is useful to survey some of the salient aspects of Ontario's demand/supply mix.

Annually, electricity demand in Ontario generally peaks on the warmest summer days, with lesser peaks during the coldest winter days. The record peak was 27,005 MW in August 2006. In 2008, peak demand was 24,195 MW (June 9) and minimum load was 11,450 MW (October 13). Spring and fall are typified by relatively low demand.

Ontario demand for March '06 – February '07 is approximately described by:

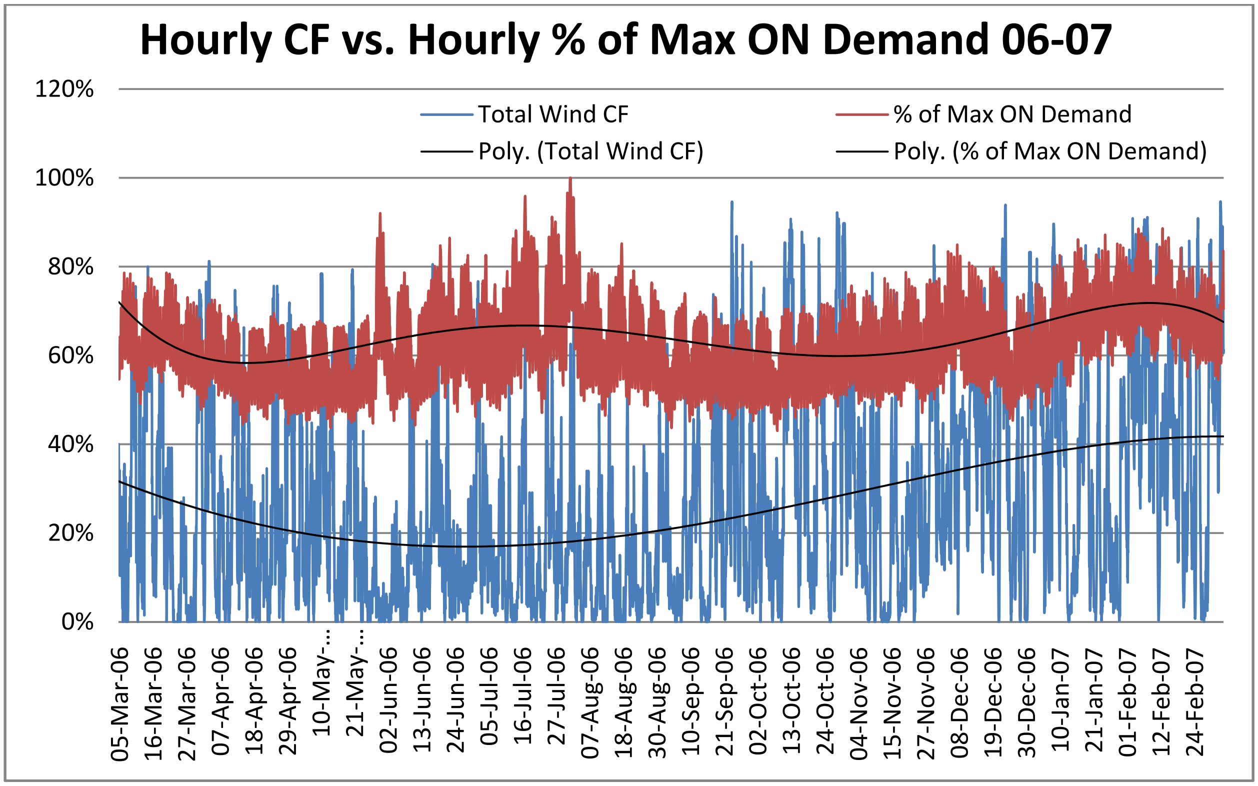
y=27005cos[(pi)*(x-40)/183]

where y is in MWh for one day and x is days

Ontario wind power output is approximately described by:

Wind Output y=390cos[(pi)*(x-50)/365]

Graph 1



As Graph 1 shows, wind output is high in winter and low during the summer, whereas demand is highest in summer. This imbalance represents a key limitation with respect to reliance on wind power in Ontario. The seasonal wind output pattern in Ontario is very similar across Canada and throughout central and northern Europe.

By comparison with all other provinces in Canada, Ontario's generation mix includes a relatively high proportion of inflexible baseload generation. In 2007, 52% of in-province generation and **** MW of the province's capacity was provided by CANDU nuclear generation. The existing reactor fleet in Ontario is unable to accommodate significant short term maneuvering of output to balance load and other generation.

Hydro-electric generation supplied 21% of Ontario's generation and **** MW of capacity in 2007. Most of the hydro-electric capacity in the province lacks long term storage capacity. During high runoff periods, the short term generation flexibility of hydro-electric capacity can be limited due to flood control constraints. The installed base of pumped storage capacity in Ontario is limited to 176 MW of relatively low head storage located at the Niagara Beck complex. Reservoir capacity limits its use primarily to daily peaking application. Economics also constrain the use of the pumped storage system. Over the period from 2005-2007, only about 46% of the energy stored was recovered.

Ontario's coal and gas-fired generators are key generation resources from the perspective of generation flexibility for seasonal and peak load balancing. In 2007, coal provided 18% of Ontario's generation and **** MW of its capacity. Gas provided 8% of Ontario's generation and and **** MW of its capacity. Coal is being phased out under government mandate and will be eliminated by 2014.

Transmission capacity within Ontario and interconnections with neighboring jurisdictions has some significant constraints with respect to interregional transfer capability. Transmission capabilities will be impacted over the near future by ongoing changes in the geographic distribution of loads and generation. Key changes impacting transmission system capability include declining overall load with pockets of load growth in some urban areas of southern Ontario, elimination by 2014 of coal-fired generation, and construction of new transmission assets.

1.2 Overview of wind power in Ontario

Ontario currently has 471.1 MW of wind capacity from large wind farms with over one year of service, 233 MW from large wind farms added in the last year, and many projects of 10 MW or smaller operating or under development. Installed capacity is growing rapidly. The Ontario Power Authority (OPA) is an Ontario government agency responsible for planning Ontario's power future. In that capacity, the OPA has procured under contract all significant wind generation capacity in the province. The OPA's plan for the provincial electricity supply is the Integrated Power System Plan (IPSP). According to the current edition of the IPSP, a total of 2006 MW of wind capacity will be installed by the end of 2010 [1]. By 2025, 4685 MW is expected [2]. Total planned wind capacity for the longer term is now subject to review by the OPA under a directive from the Minister of Energy issued September 17th 2008. (note to reviewers: This paragraph will require updating after March 17, 2009 when Ontario's new official plan is scheduled to be released.)

Table 1 – Wind farms considered

Name	Location (lat/long)	In-service Date	Unit Size (MW)	Hub Height (m)	Capacity (MW)
Amaranth I	44.100, -80.287	4-Mar-06	1.5	80	67.5
Kingsbridge I	43.934, -81.700	16-Mar-06	1.8	80	39.6
Port Burwell	42.644, -80.771	24-May-06	1.5	80	99
PrinceFarm I	46.584, -84.540	21-Sep-06	1.5	80	99
PrinceFarm II	46.584, -84.540	19-Nov-06	1.5	80	90
Ripley South	44.029, -81.627	21-Dec-07	2.0	79	76
Ontario Total					471.1
Maple Ridge, NY	43.805, -75.585	Nov. 06	1.65	80	321.8

Note that Prince Farm I and Prince Farm II are co-located and share transmission connection facilities. They are therefore combined in this study into a single unit and considered only from 19-Nov-06 forward.

Rowlands and Jernigan have recently published a very useful analysis of some of the performance characteristics of Ontario's developing fleet of wind generation with particular attention to load following issues [3]. Using empirical data, these researchers observe that wind and demand are poorly correlated on an annual basis. The diurnal output pattern for wind power match the pattern of demand best in winter during afternoons, butt matches up poorly with demand during winter mornings. Periods of little wind output are as common during low periods of summer demand as during high periods. Rowlands and Jernigan also conclude that distance between wind farms reduces output correlation but do not quantify the effect.

2. Source data

This study relies on empirical data. For the Ontario wind farms, this study analyzes hourly production using data provided by the Ontario Independent Electricity System Operator (IESO). The analysis uses data starting at or later than the in-service dates of the respective wind farms. For the Maple Ridge wind farm, this study relied on hourly transaction data provided by the FERC Electric Quarterly Reports [add link].

Many available wind studies addressing wind power in Ontario rely on simulated wind turbine output based on wind speed. Wind power models face a number of challenges. Historically, wind speed data was routinely collected from anemometers mounted on 10 m masts, approximately 70 meters below the nacelle of wind turbines. Only in recent years have higher altitude measurements become widely used. Weather stations were often intended to provide data for aviation and agriculture. Since windy locations are unfavourable for airports and make accurate precipitation measurement more difficult, much of the historical data was collected at relatively calm sites. Modeling has therefore been used to estimate winds at locations where measurements are unavailable. Stochastic extreme weather events such as freezing rain and lightning have impacted wind production in Ontario but can be challenging to accurately model.

There is some evidence of an over-estimation bias in the modeled outputs, although there are exceptions. Production for each farm completing at least one full in-service year is indicated in the table below.

Table 2 – Production summary and forecasts (CF) by in-service year

	Yr 1	Yr 2	Developer's forecast	Helimax forecast [4]
Amaranth	27.70%	29.80%	33.00% [5]	
Kingsbridge	31.10%	33.90%	31.40% [6]	28.00%
Port Burwell	28.60%	26.90%		29.00%
Prince	28.20%	28.10%	32.40%[7]	30.00%
Ripley South	32.10%			28.00%
Maple Ridge	25.10%			

Other reports have identified an overly optimistic bias in wind power production forecasts. Boccard indicates that while forecasts of European wind production routinely anticipate production of approximately 35% CF, the mean realized value for fifteen nations in the EU over the period 2003-2007 was 20.8%CF on a weighted average basis [8].

As of March 2008, the cumulative capacity factor for the 18 wind power projects participating in the federal Wind Power Production Incentive program was 36.2%CF and the forecasted output was 39.5%CF, a shortfall of 9.2% [9].

The forecasted capacity factor for Huron Wind was 30%CF whereas for the period 2003-2005 the average actual capacity factor was 24.7%CF [10].

This study avoids potential shortfalls associated with modeled data by relying on actual production data. One drawback with production data is that only a short period of history is available. Relying on actual production data based on less than three years of data also limits the value of any observations about wind power contributions during peak times. Another potential consideration is that stochastic events or mechanical problems can mask our view of the underlying wind resource.

3. Methodology

Traditionally, the basic unit of analysis for similar studies is Capacity Factor (CF), the ratio of actual power produced vs. theoretically perfect production for a particular time period. Reflecting the fact in turbine design productivity and cost optimization considerations can lower (raise) capacity factors while lowering (raising) per unit production, some authors have discussed alternative production measures for wind power, such as kWh/m2 of swept area [11]. This alternative has been examined in an Ontario context [3]. General consistency between capacity factor and yield per unit of swept area has been found, perhaps because of the similar vintage and design of the wind generation units installed in Ontario.

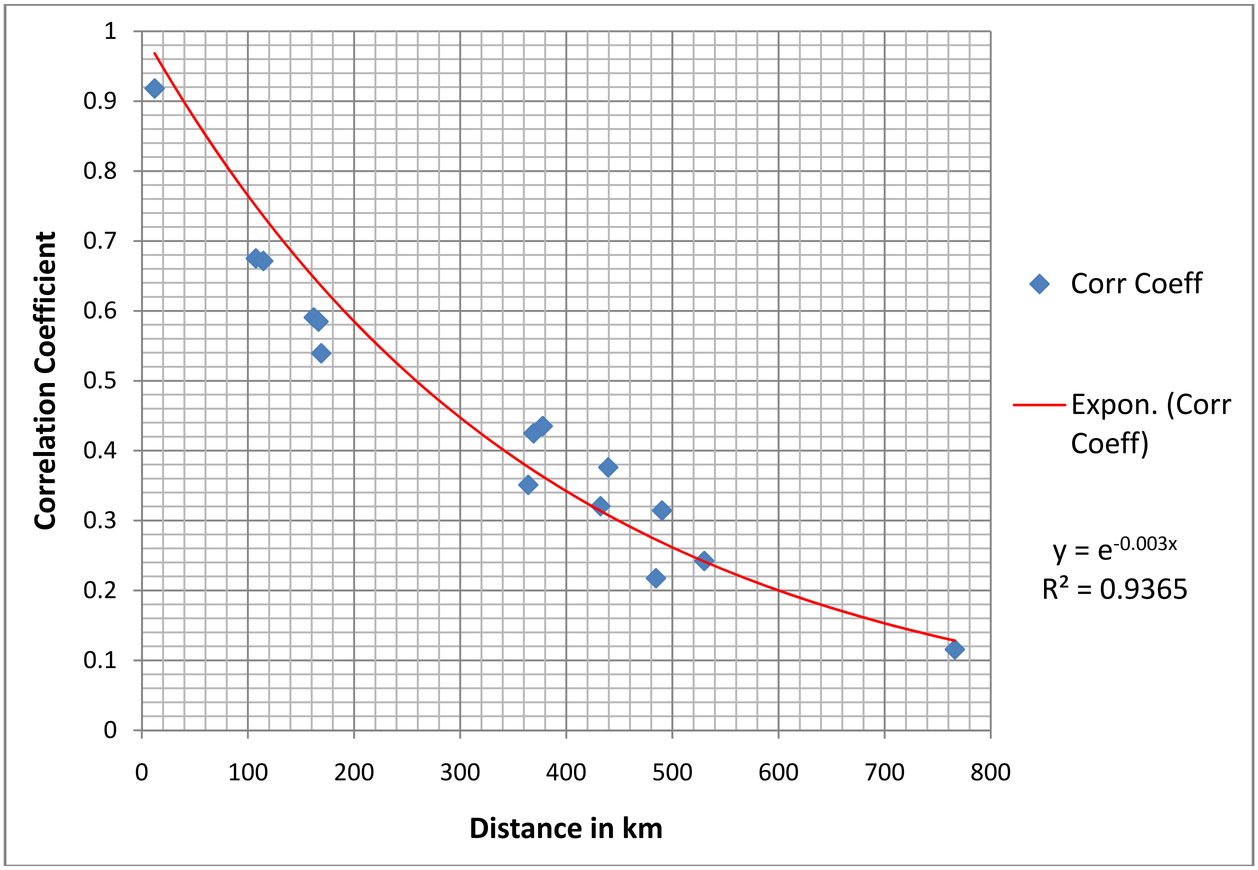
The cross-correlations in output provided in this study are not based on capacity factor but actual energy output. All correlation coefficients reported are based on a 95% confidence interval. Because wind power profiles are very different from season to season, we have divided the data used in correlations into seasons. This provides a more reliable outlook on the correlations and also allows identifying possible outliers. The seasonal correlation factors were then averaged to obtain representative values between all wind farms. Distances between wind farm locations were calculated using the Haversine formula from longitude and latitude position data. An automation tool using Mathworks' Matlab was developed and used to assist with data analysis.

4. Benefits of distance

Many commentators have observed that distance between wind farms tends to reduce the correlation in output, thereby reducing the variability of overall wind power output. The IESO has remarked, "The geographic diversity of Ontario wind resources, as more sites are commissioned, should mitigate some of the risk associated with wind speed variability." [12] The Canadian Wind Energy Association (CanWEA), like perhaps all wind energy advocacy organization, recommends significant investment in transmission. CanWEA remarks, "To provide reliable power, wind generation facilities must be distributed across a wide geographic area. The more broadly distributed they are, the less likely it becomes that poor wind conditions will affect more than a few facilities at the same time." [13]

Correlation coefficients closer to 1 (or 100%) indicate a stronger positive synchronization of energy outputs: when one wind farm's output increases or decreases, the comparator wind farm does the same. Neutral correlation (0%) would indicate random outputs while a negative correlation would indicate one wind farm tending to do the opposite of a comparator wind farm. Higher positive correlation of output between wind farms would tend to putting additional stress on the grid's transmission and load balancing resources.

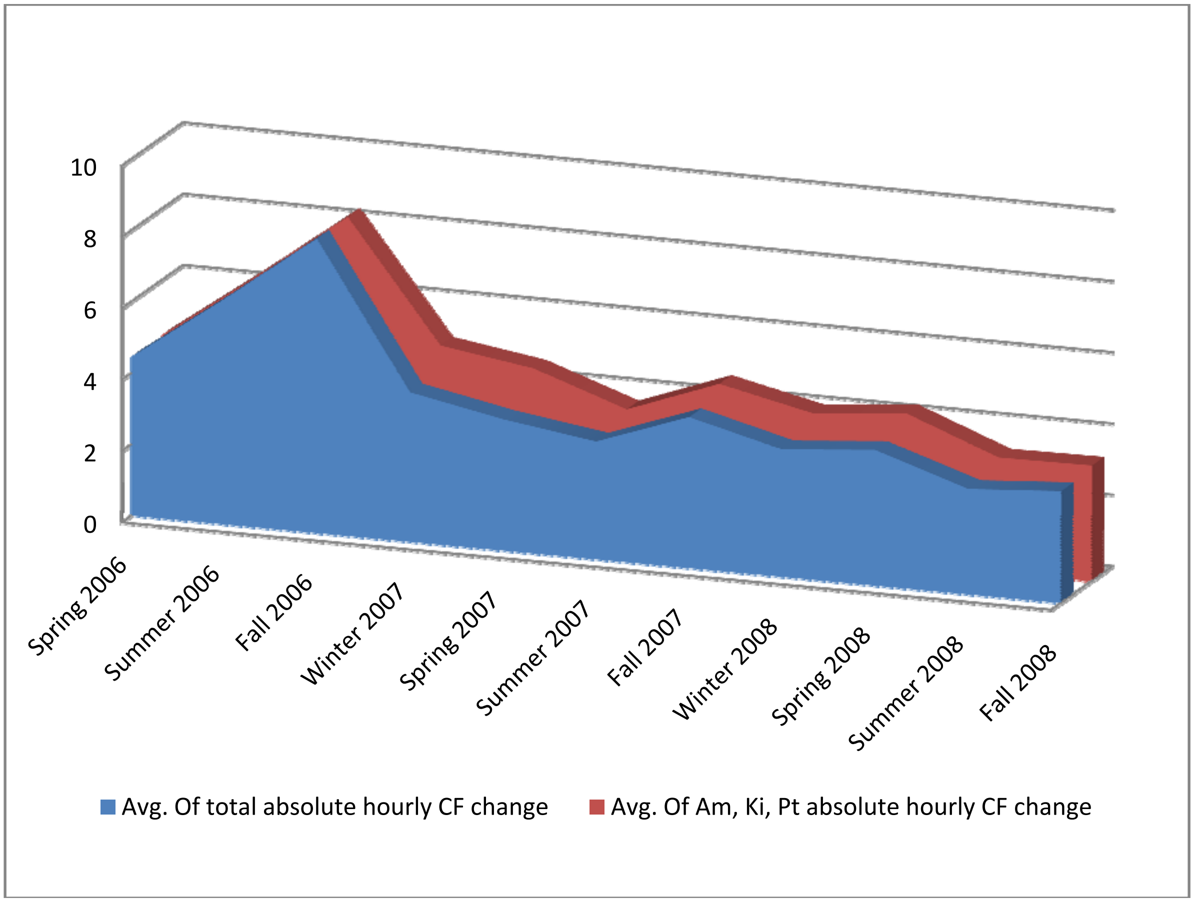
Graph 2 Average seasonal correlation coefficients against distance between wind farms based on hourly outputs



From Graph 2, it is apparent that distances greater than 250 km are required for the cross correlation coefficients to drop below 0.5. With the anticipated high wind penetration in the energy mix in Ontario, wind power capacity should thus be installed far away from other wind farms, and the amount of capacity should be adequately balanced with sufficient generation and load flexibility to deal with the anticipated variability. If large enough aggregate wind capacity is allowed develop within a small radius (in the order of 150 kilometers), its output could dominate that of the other wind generators, and dilute the smoothing effects available from other wind generators. It is also important to note that the challenges for grid reliability and transmission that would arise from concentrating too much wind in a small area do not arise from the number of wind farms but the aggregate capacity of the farms.

From Graph 2 we observe an asymptotic behavior that seems to tend towards zero as the distance between the wind farms increase. However, distances greater than 600 km, comparable to the distance between Toronto and Montreal, are required for the correlation coefficient to drop below 0.2. This indicates that within conceivable distances, wind farms are more likely to operate synchronously than not. In other words, geographic diversity alone cannot eliminate the problem of variability associated with wind power.

Graph 3 Absolute hourly CF change: Amaranth, Kingsbridge and Pt Burwell alone vs. Amaranth, Kingsbridge, Pt Burwell and Prince

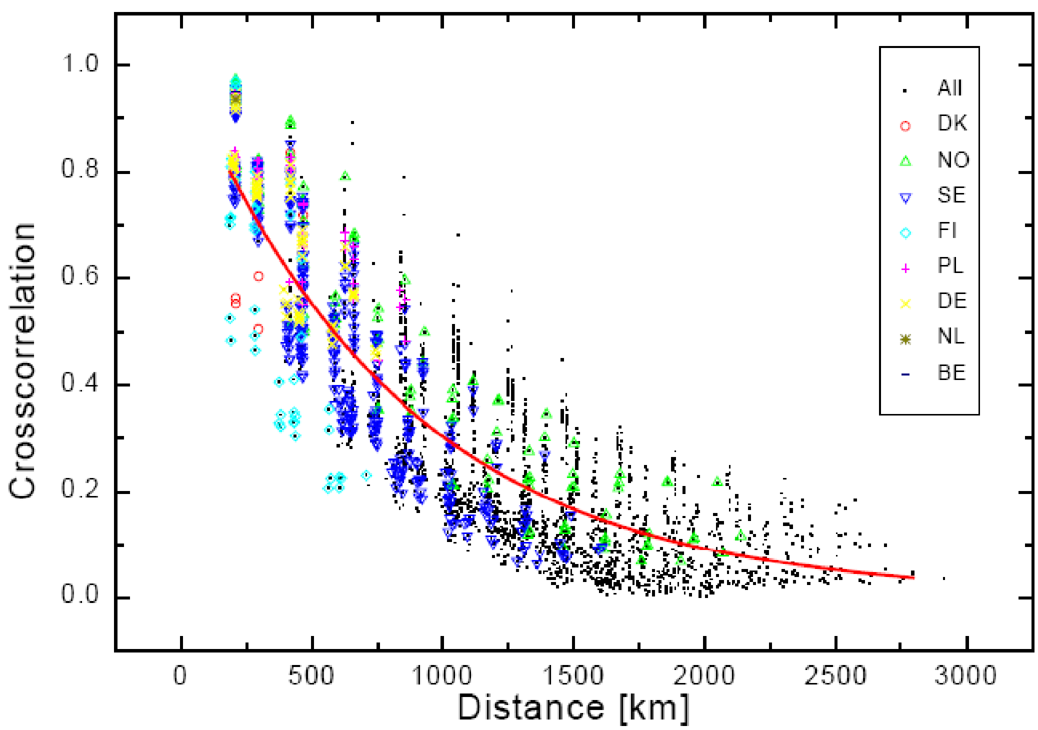


Looking more directly at variability, Graph 3 quantifies the drop in absolute hourly changes in CF for the aggregated outputs of Amaranth, Kingsbridge, and Port Burwell, and those three plus Prince. The combined output of Amaranth, Kingsbridge, and Port Burwell is approximately equal to that of Prince. The first curve indicates the total aggregated CF, while the second omits Prince, the farthest and least correlated wind farm. Graph 3 thus shows how a geographically remote wind farm coming online in winter 2007 helps diminish the average hourly changes in CF, a good indicator of variability. Indeed, the presence of Prince in the wind farm population reduces the absolute hourly change in CF by 0.41% on average, which corresponds to a reduction of 11% in overall standard deviation from 23.9 to 21.2% of the total installed capacity (471.1 MW). This is a rather small benefit for a distance of at least 364.1 km away from all other wind farms, but more importantly, a large distance away from all Ontario urban centers, highlighting the tradeoff inherent to wind power between mitigating variability and transmission costs.

5. Discussion and comparison with other studies

Some researchers have quantified the effect of distance on the output correlations between wind farms in other jurisdictions. Giebel considered the smoothing effect of distance between wind farms located across the Nordic countries and those on the southern coast of the Baltic and North Sea [14]. That study relied on simulated wind output modeled from 34 years of meteorological data collected at 10 m height. When adjusting for the expected 80 m hub height of turbines, such low capacity factors were calculated for Poland and Germany that the height assumption was adjusted to 100 m and orthographic effects were assumed. No significant differences in correlations by season were identified. In breaking down the data by country, significant differences in decay rates were identified. However, Giebel did not provide mathematical descriptions of the decay curves and so the different decay rates are only compared graphically.

Graph 4 Cross-correlation versus distance between grid points [Giebel]



The full line is a fit of an exponential decay function matching the shape we found, however Giebel does not indicate the time interval associated with this curve.

In another study, Ernst, Wan and Kirby consider electric system load following and regulation impacts of wind power [15]. This study reviewed the effect of distance on output correlation using German data. Considering data averaged over 5 minutes, 30 minutes, 1 hour, 4 hours, and 12 hours, exponential decay curves described the effect of distance. This study indicates that distance has a far greater effect in Germany than in Ontario. In Ontario's hourly correlations, separating the farms by 200 km drops the correlation to 50%. In the German case, Ernst et. al. found that the impact of 200 km separation is to drop the correlation to about 10%. In Germany, the correlation decline with distance was described by an asymptotic decay curve however, Ernst et. al. did not provide specifications of the best fit function.

A study by Oswald et.al. considered wind generation variability at the time of winter peak demand in the UK. [16] The effects and continent-spanning size of meteorological factors that drive winds are considered. Oswald et. al. compare modeled UK wind output with wind outputs measured in Ireland and Germany. Although no cross correlations are provided, the graphical correspondence in output during worst case conditions was so strong that Oswald et.al question whether interjurisdictional transmission investments would provide useful smoothing for northern European wind power.

Gross et. al. analyze load following aspect of intermittent generation in the UK and observe that "wide geographical dispersion and a diversity of renewable sources tends to decrease system balancing costs. Interconnection between regions can further decrease costs. Conversely, geographical concentration will increase cost, and it may be that wind developments tend to cluster in regions with the best resource." [17]

5.1 Difference with GE wind study

The IESO reviewed the operability of the IPSP. To consider the implications of the wind elements of the IPSP, the IESO relied on a 2006 GE study [18]. One of the IESO's conclusion was that 5GW of wind capacity could be reliably accommodated on the Ontario grid assuming that adequate ramping and transmission was available.

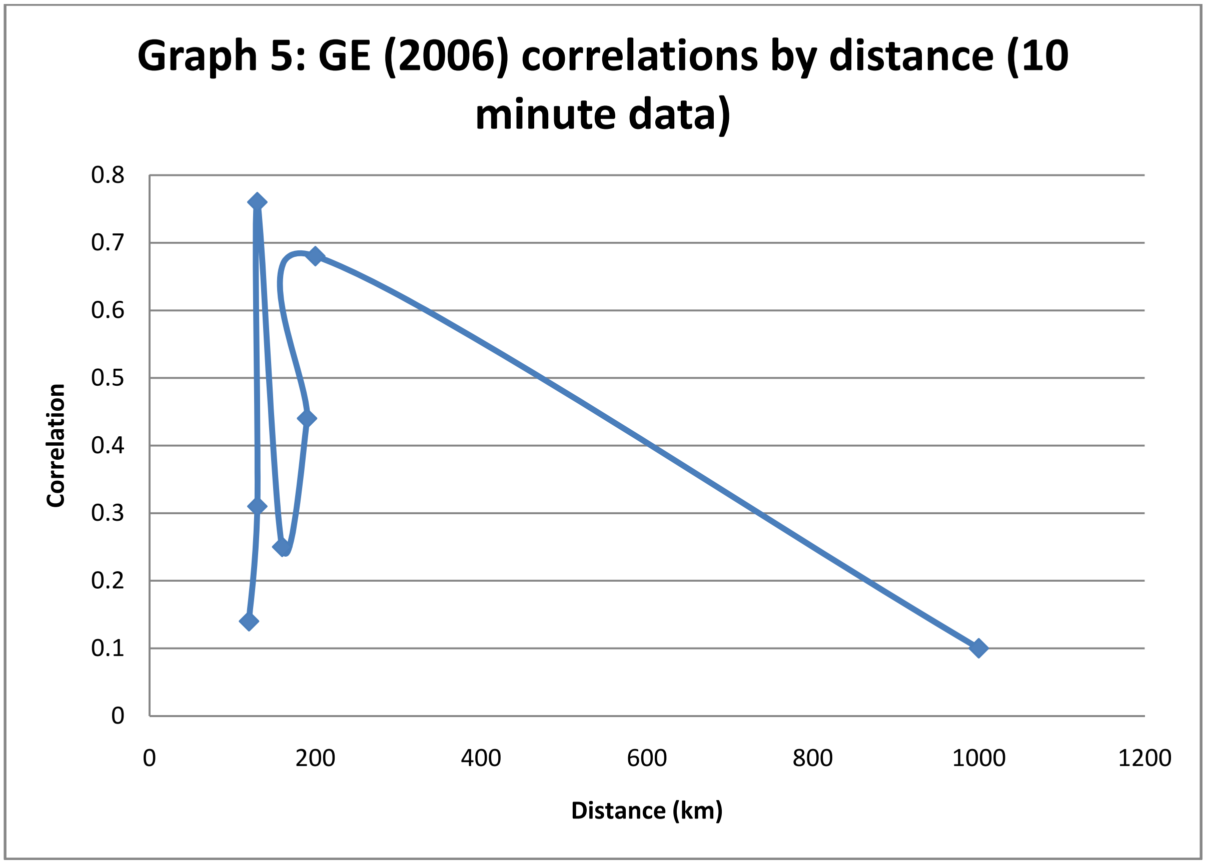
The GE study considered a simulated data set for a one year period. The data was collected from tall masts at 32 locations around the province. GE assessed cross correlations between wind development regions based on data at 10 minute increments.. Two of GE's conclusions raise concerns about this element of its assessment.

Figure 5.34 of the GE report shows the location of the ten wind groups and the correlation coefficient between selected pairs of wind groups. Those correlations, along with approximate distances are provided in Table 3.

Table 3: Output correlations in GE study (10 minute data)

groups	Distance (km)	correl
3&4	120	0.14
4&5	130	0.31
6&7	130	0.76
9&10	160	0.25
7&8	190	0.44
1&2	200	0.68
2&8	1000	0.1

This data does not present the expected asymptotic decay shape seen in our results and other studies considering wind power output cross-correlations.



The results presented in Graph 5 suggest some anomaly, perhaps that the simulated data GE relied upon may not be reflective of real world performance.

An additional concern suggesting problems with its underlying simulation-based input data is GE's claims that it found from its analysis that "correlation coefficients are noticeably higher over one minute than over ten minutes." (P. 80) The international experience presented in the literature and common sense supports the contrary view that cross-correlations coefficients tend to decline as the time interval between measurements contract because local factors and input lag come into play.

6. Conclusions

Geographic diversity mitigates wind power's overall short run variability, providing a smoother overall output. However, distances over 250 km between wind farms are required for hourly output correlations to drop below 50%. Moreover, the results presented here suggest that correlation coefficients will be positive even at large distances and not likely to be negative over conceivable distances. The variability of output measured by standard deviation decreased by only 11% when one wind farm located remotely from another group by 350 km was added. Other studies present similar results in Europe.

Distance mitigates but does not solve any challenges that might arise from wind power variability. We can conclude that adding any wind capacity, even at great distances, increases the requirements for load following by other generation resources or demand adjustments.

Future planning must take into account the geographic location and installed capacity of wind development to achieve targeted levels of smoothing. It should also take into account the overall costs of transmission associated with the wind generation capacity required.

Even if transmission constraints can be substantially eliminated, large wind power production swings cannot be avoided. Wind farms within the province are statistically prone to increase and decrease generation synchronously due to the nature and size of the meteorological fronts that largely govern wind speeds. European experience is consistent with this observation.

As wind capacity increases, it will be necessary to ensure that adequate flexible generation capacity is available, potentially supported by short term power storage options or load management programs. Hypothetically, short to medium term storage capacity could allow higher wind penetrations, however costs and potentially other environmental and social factors may rule out this option. As a practical matter, substantial fossil fuel generation, with its attendant consumer and environmental costs, appears to be required to provide adequate ramping and summer seasonal generation.

References [Needs to be cleaned up]

[1] OPA Presentation to the Ontario Energy Board, Case: EB 2007-0707 Exhibit K1.1 Slide #60, September 8, 2008.

[2] OPA Presentation to the Ontario Energy Board, Case: EB 2007-0707 Exhibit D, Tab 5, Schedule 1 p. 4.

[3] Rowland, I.H. and Jernigan, C, Wind power in Ontario: Its contribution to the electricity grid, *Bulletin of Science, Technology & Society*, Vol. 28, Number 6, December 2008.

[4] Helimax Energy Inc., “Analysis of future wind farm development in Ontario, March 2006” (Study performed for the OPA) IPSP Exhibit D5/1 Attachment 1. Note that the nearest geographic locations are reported here.

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[16] Oswald, J., Raine, M., Hezlin, A.-B.,. "Will British weather provide reliable electricity?" *Energy Policy* 36 (3212-3225), 20 June 2008.

[17] Gross et. al., http://www.ukerc.ac.uk/ResearchProgrammes/TechnologyandPolicyAssessment/TPAProjectIntermittency.aspx

[18] GE Energy Report on Ontario Wind Integration Study, October 6, 2006, http://www.powerauthority.on.ca/Storage/50/4536_D-5-1_Att_2.pdf

Appendix

Correlation Coeff. Over time

Season	Am-Ki	Am-Pt	Ki-Pt	Am-Pr	Ki-Pr	Pt-Pr	Am-MR	Ki-MR	Pt-MR	Pr-MR	To-MR	Am-Ri	Ki-Ri	Pt-Ri	Pr-Ri	Ri-MR
Winter 2007	0.7682	0.7141	0.6907	0.3769	0.4389	0.3415	0.4865	0.358	0.3958	0.0863	0.3408					
Spring 2007	0.7469	0.6551	0.6385	0.3647	0.4676	0.2957	0.5044	0.3799	0.4508	0.2176	0.4327					
Summer 2007	0.6345	0.5127	0.4406	0.3355	0.4217	0.1825	0.42	0.2761	0.1996	0.1335	0.2736					
Fall 2007	0.7749	0.6935	0.6902	0.3736	0.471	0.3537	0.537	0.4849	0.4876	0.1665	0.4291					
Winter 2008	0.7586	0.6487	0.7038	0.3067	0.4383	0.1974	0.4418	0.4727	0.5249	0.1004	0.4289	0.7535	0.92	0.6778	0.3792	0.3967
Spring 2008	0.5839	0.4656	0.4873	0.4026	0.591	0.3244	0.2959	0.0892	0.2624	0.067	0.1835	0.5946	0.9082	0.4422	0.5488	0.097
Summer 2008	0.5933	0.4753	0.4259	0.2481	0.29	0.113	0.3603	0.1396	0.3115	0.0374	0.241	0.6127	0.9084	0.4114	0.246	0.1584
Fall 2008	0.7313	0.6335	0.6333	0.1559	0.2806	0.1286						0.7396	0.9364	0.6256	0.23	

<u>Legend</u>
Am – Amaranth
Ki – Kingsbridge
Pt – PtBurwell
Pr – Princefarm
MR – Maple Ridge
Ri – Ripley South
To – Ontario Total