WIND POWER IN ONTARIO: QUANTIFYING THE BENEFITS OF GEOGRAPHIC DIVERSITY

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Abstract

Using Ontario wind power production data, this study quantifies the benefits of positioning wind farms in geographically diverse locations to mitigate variability and smooth wind power's contribution to electricity generation. Wind farm outputs are cross-correlated and graphed against the distances separating the farms. Results confirm that correlations between wind farm outputs decay with distance, but remain positive. Results agree with European studies but suggest that distance provides less smoothing of output in Ontario than in Europe. However, results disagree with aspects of a study of wind power integration in Ontario conducted by General Electric in 2006.

1. Introduction

Wind power is a new and rapidly expanding source of grid electricity supply in Ontario. Wind power contributed 1.4 TWh of Ontario's supply in 2008, equal to 0.9% of supply. Its output is expected to double by 2010. Observing the patterns of Ontario's developing wind power experience provides critical information for further planning and development of the power system.

Claims that distance between wind farms reduces the variability of overall wind power output have been made by many commentators. The Independent Electricity System Operator (IESO) has remarked that, "The geographic diversity of Ontario wind resources, as more sites are commissioned, should mitigate some of the risk associated with wind speed variability" [1]. The Canadian Wind Energy Association (CanWEA), like most 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 (sic)" [2].

The extent to which distance between wind farms smoothes output significantly impacts power system planning and operations, particularly as reliance on wind grows. 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 operating reserve provisions are called for.

However, as the penetration of wind power rises, system load following impacts due to wind power's intermittency could become significant.

This study focuses on quantifying the level of hourly and daily output synchronization between wind farms located at various distances from each other in Ontario and New York State. Quantifying the benefits of geographic distance between wind farms can help to optimize future wind farm siting, transmission investments, load following generation requirements, and demand management options for managing wind variability.

1.1 Power system context

Grid operators must balance overall load with overall generation continuously, in real time. Each generation component is only a piece of an overall 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 supply and demand mix.

Annually, electricity demand in Ontario generally peaks on the warmest summer weekdays, with lesser peaks during the coldest winter days. The record hourly peak demand was 27,005 MW, reached on August 1, 2006 over the period from 4 to 5 pm.

Average 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 observed in Ontario is very similar to that of wind farms across Canada and throughout central and northern Europe.

By comparison with all other provinces in Canada, Ontario's generation mix includes a high proportion of inflexible baseload generation. In 2008, 53.0% of in-province generation and 11.4 GW of the province's capacity were provided by CANDU nuclear generation [3]. The existing reactor fleet in Ontario has limited ability to accommodate short term changes in output to balance load and other generation.

In 2008, hydroelectric generation provided 7.7 GW of capacity and supplied 24.0% of Ontario's generation, achieving a record high output of 38.3 TWh due to cool temperatures and record precipitation [3]. Most of the hydroelectric capacity in the province lacks long-term storage capacity. During high runoff periods, the short-term generation flexibility of hydroelectric capacity can be limited due to flood control constraints. During periods of low run-off, hydroelectric production is constrained and short-term operational flexibility can be limited by minimum flow requirements. 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 to a short-term, daily cycling operation, shifting energy from off-peak to on-peak hours. 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 [4].

Ontario's coal and gas-fired generators are key generation resources from the perspective of generation flexibility for seasonal and shorter term load balancing. In 2008, coal provided 14.6% of Ontario's generation and 6.4 GW of its capacity. Gas provided 6.9% of Ontario's generation and 3.4 GW of its capacity (not including gas-fired cogeneration) [3]. Coal is being phased out under government mandate and will be eliminated by 2014. Ontario's transmission capacity and interconnections with neighboring jurisdictions have some significant limitations with respect to interregional transfer capability.

1.2 Overview of wind power in Ontario

The Ontario government has identified wind power as a preferred method of power generation and is enacting policies to maximize its use. Ontario currently has 471.1 MW of wind capacity from large wind farms with more than one year of service, 233 MW from large wind farms added in the last year, and 58 MW of total capacity from wind farms under 10 MW in size. A total of 1,952 MW of wind capacity is expected to be installed by the end of 2010 [5]. By 2025, 4685 MW is expected [6].

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

Table 1 – Wind farms considered (Prince Farm I and Prince Farm II are combined in this study into a single unit and considered only from November 19, 2006 onward).

2. Data sources

For the Ontario wind farms, this study analyzes hourly production data for the entire in-service period of each subject wind farm from data made publicly available and updated weekly by the IESO [7]. In addition, a small sample of daily production data at a five-minute resolution was provided by the IESO. For the Maple Ridge wind farm, this study relied on hourly transaction data provided by the FERC Electric Quarterly Reports from January 2007 onward [8].

3. Methodology

The basic units of analysis for this study were both energy output and Capacity Factor, the ratio of actual power produced vs. theoretically perfect production for a particular time period. Only data from after the in-service date of each wind farm was used.

Cross-correlations in output provided in this study are not based on capacity factor but actual energy output. Parametric (Pearson) and non-parametric (Spearman rho) correlation coefficients are reported based on a 95% confidence interval. Because wind power profiles are very different from season to season, the data used in correlations was separated by season. This allows the identification of possible outliers, although no outliers could be identified due to the limited history available. The seasonal correlation factors were then averaged to obtain representative values between all wind farms.

The FERC data for Maple Ridge is separate for the two related reporting entities – Flat Rock and Flat Rock 2 – with respective installed capacities of 231 MW and 90.8 MW. The data for each entity reflects several short gaps in the respective output chronologies. For Q4/07, the data sets for Flat Rock and Flat Rock 2 were assembled into a complete unified chronology and then correlated. The resulting correlation was 96.3%. Based on this result, Flat Rock was used as a surrogate for Maple Ridge for the purposes of calculating correlations with the Ontario wind farms. Hourly output data for Flat Rock 1 was sorted by time and blank rows were inserted where there was no data available. All hours for which Flat Rock data was available were correlated with other wind farm outputs at those times.

Distances between wind farm locations were calculated using the Haversine formula from longitude and latitude position observations. An automation tool using Mathworks' Matlab was developed and used to assist with data analysis.

4. Results: Output smoothing as a function of distance

Correlation coefficients closer to 1 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 (coeff. = zero) would indicate random outputs while a negative correlation (coeff. < 0) 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 put additional stress on the grid.

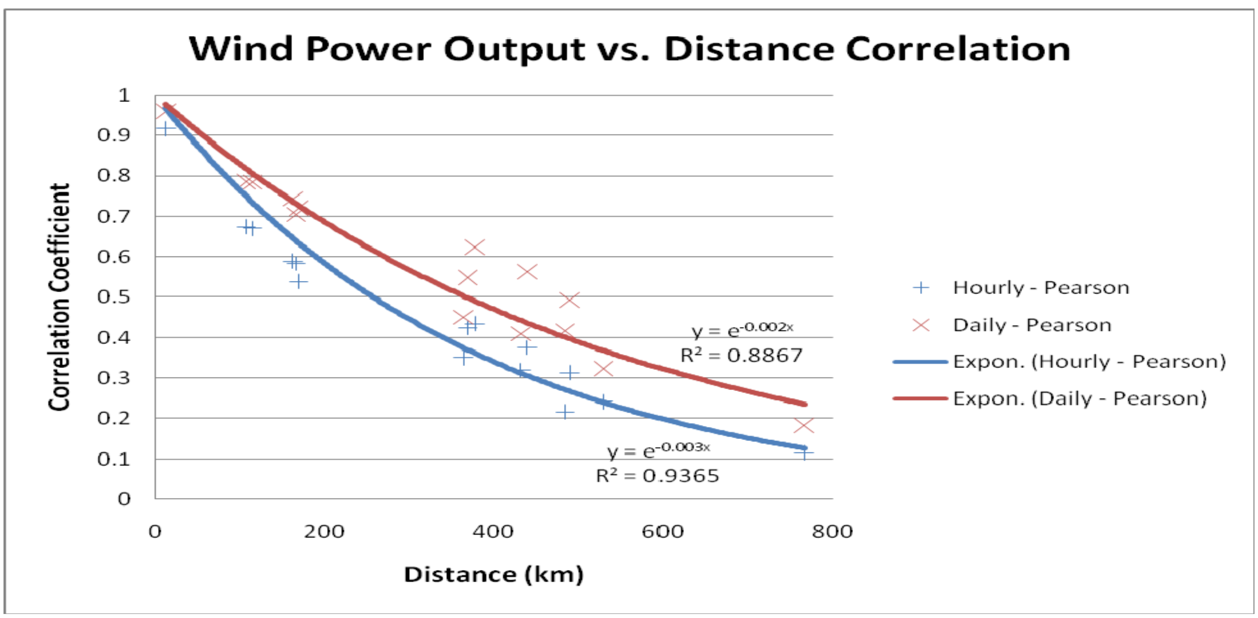

Figure 1: Average seasonal correlation coefficients against distance between wind farms based on hourly and daily outputs

From figure 1, it is apparent that distances of about 250 km are required for the cross correlation coefficients for hourly output to drop from 1 to 0.5. For daily average output, distances of about 350 km are required for cross correlation to drop to 0.5. Distance has an asymptotic effect on correlation that seems to tend towards zero as the distance between the wind farms increase. In the analysis of the distance relationship considering daily time intervals for output rather than hourly, the R^2 is lower than found in the hourly decay relationship but still significant.

Pearson correlation coefficient measures linear correlation and is ideally suited for normally distributed variables. To test robustness, we have chosen a nonparametric correlation metric in the form of Spearman's rho. Table 2 indicates that the two methods yield almost exactly the same structure of exponentially decaying correlation with distance and similar diagnostic results also.

Correlation Method	Hourly output		Daily output	
	Equation	R^2	Equation	R^2
Pearson	$y=e^{-0.003x}$	0.9365	$y=e^{-0.002x}$	0.8867
Spearman rho	$y=e^{-0.003x}$	0.91	$y=e^{-0.002x}$	0.9219

Table 2 – Results of parametric and non-parametric correlation methods

Another way to assess distance benefits is to measure overall fleet output variability for wind farms in southern Ontario with and without the relatively large and distant Prince Farm located near Sault Ste. Marie at the east end of Lake Superior. Amaranth, Kingsbridge, and Port Burwell are all highly correlated and their combined output capacity is almost equal to that of Prince.

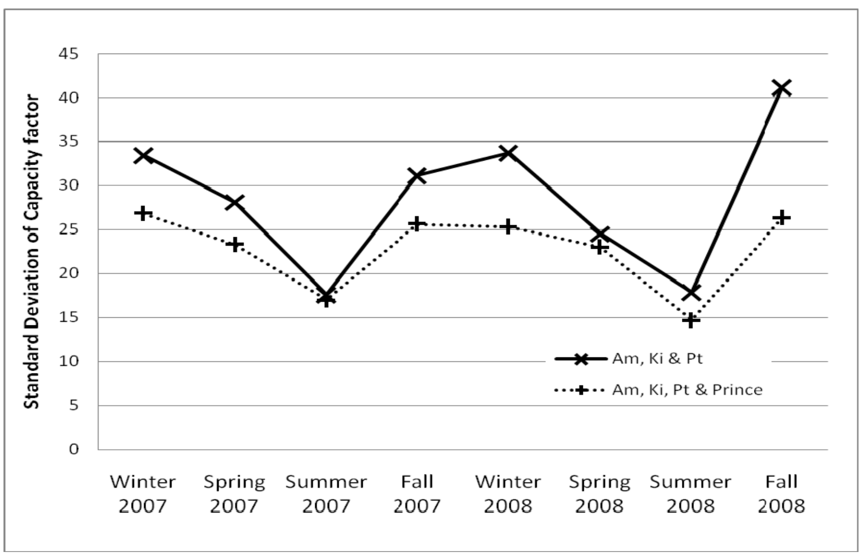

Figure 2: Impact of the addition of Prince Farm to the standard deviation of total capacity factor

Over the two year period starting in January 2007, adding Prince to the three noted southern wind farms reduced the absolute hourly change in capacity factor by 0.41% on average, which corresponds to a reduction in overall standard deviation from 23.9% to 21.2% of the total installed capacity. This is a rather small benefit for a distance of at least 360 km away from all other wind farms, but more importantly, a large distance away from Ontario’s major urban centers, highlighting the tradeoff inherent to wind power between mitigating variability and transmission costs.

4.1 Spot checks of experience at 5-minute intervals

A few days where high cumulative variability in hourly outputs was identified were examined by reviewing performance measured at 5-minute intervals. Insufficient data was available to analyze patterns in the overall wind fleet at a 5-minute resolution. One observation arising from spot checks on 5 minute interval data is the implication of geographically concentrated wind developments.

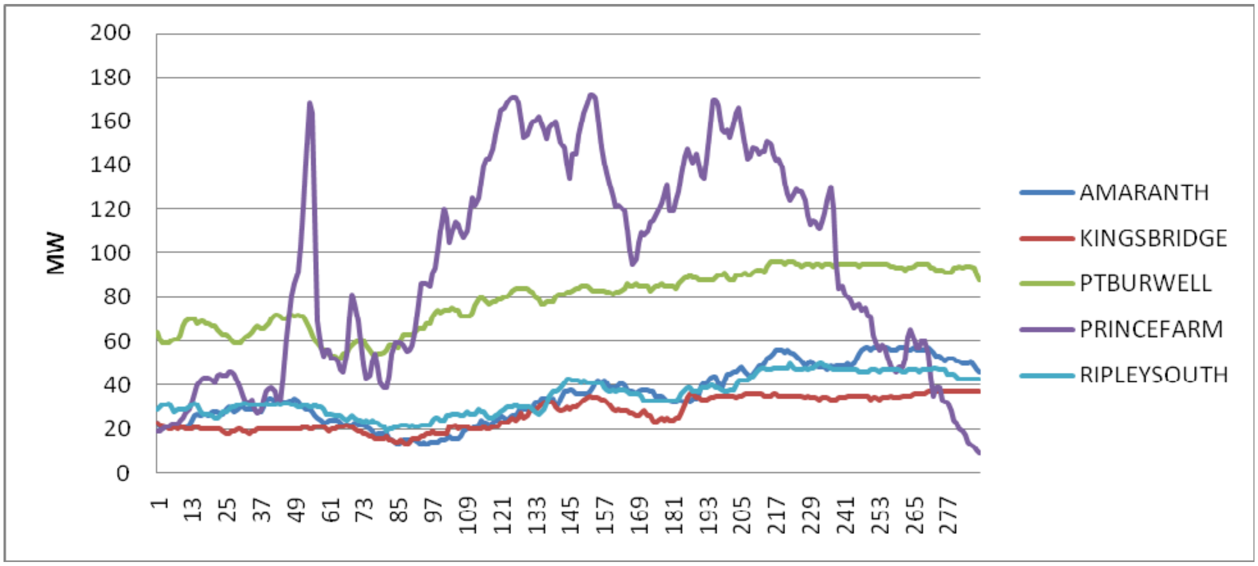

Figure 3: Output by farm at 5 minute intervals for 24 hours (January 6, 2008)

The production results for January 06, 2008 illustrate the significance for variability of having a relatively large portion of the total wind fleet concentrated in one wind farm. The total 10 minute maximum output swing for the Prince farm was a drop of 50.3% capacity factor. For the total Ontario wind fleet, the maximum capacity drop over that period was 21.4% capacity factor.

At present, the market rules in Ontario consider generator contingencies to be limited to prompt generator failures. While simultaneous, synchronized failure of a significant portion of the wind fleet does not appear to be a credible event, Figure 2 illustrates that large output changes are possible over the course of 10 minutes. Rapid ramping of the Ontario wind fleet should be reviewed as a potential contingency.

As governed by the Northeast Power Coordinating Council, Ontario is required to maintain 10 minute operating reserve of extra generation equal to the largest potential single equipment trip on the power system. Typically, this trip or “first contingency” is one of the 881 MW Darlington units. Leaving aside the question of whether ramped output should be considered a contingency, the output change event in Ontario on January 6, 2008 scaled up for a larger wind fleet would imply that wind power would take over Ontario’s first contingency for the purposes of operating reserve from Darlington once wind power surpassed 4.1 GW of installed capacity.

Although distance is expected to be much more effective at lowering cross-correlation over short time intervals as compared with longer time intervals, as identified by Ernst et al. from German data [9], one instance of high cross-correlation over short time intervals was identified.

	Amaranth	Kingsbridge	Port Burwell	Prince F.
Kingsbridge	94%			
Port Burwell	-13%	2%		
Prince Farm	73%	82%	31%	
Ripley South	85%	93%	13%	90%

Table 3 – Cross-correlations for 5-minute data (Feb 1/08)

Table 3 presents the correlation results for February 1, 2008 where, with the exception of Port Burwell in Southern Ontario on the shore of Lake Erie, the output of all the wind farms, including Prince Farm located near the eastern outlet of Lake Superior, were highly correlated when measured using data with a 5 minute resolution. This result suggests that, although highly coordinated output at 5 minute intervals may not be the average experience, it must be considered when evaluating the potential impacts of wind power operations on requirements for grid reliability services such as operating reserve and automatic generation control. Note that a more systematic study of short run changes in wind power output is likely to identify more significant events than are presented here.

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 [10]. That study relied on simulated wind output modeled from 34 years of meteorological data collected at a 10 m height. 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 can only be compared graphically.

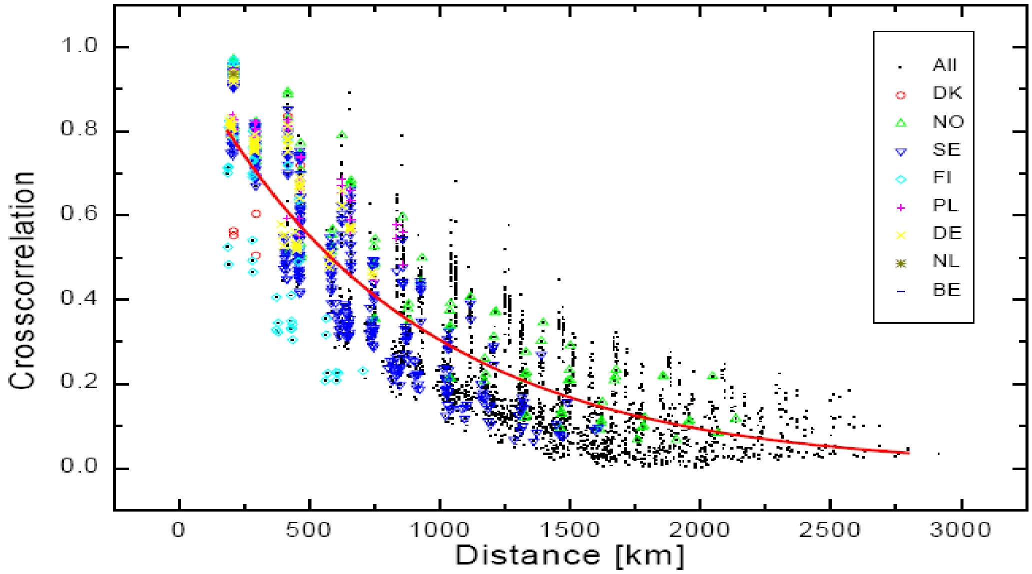

Figure 4: Cross-correlation versus distance between grid points in Northern and Central Europe [Giebel]

The full line is a fit of an exponential decay function and matches the shape we found to describe the Ontario data. However Giebel does not indicate the time interval for the cross correlations associated with this curve. In another study, Ernst et al. consider electric system load following and regulation impacts of wind power in Germany [11].

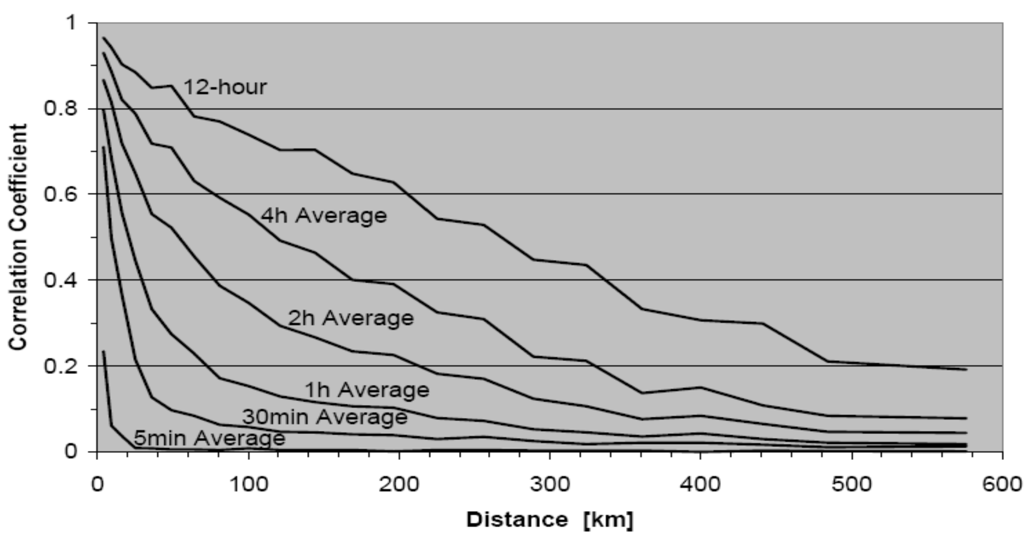

Figure 5: Cross-correlation versus distance for Germany for different time intervals [Ernst et. al.]

This study reviewed the effect of distance on output correlations using wind speed 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 250 km drops the correlation to 50%. In the German case, Ernst et al. found that the impact of 250 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 functions. Different decay rates in Ontario and Germany may be due to local topographical and siting of the wind farms. Whereas most Ontario wind farms are located close to lake shores, many German wind farms are located inland.

A study by Oswald et al. considered wind generation variability at the time of winter peak demand in the UK [12]. 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. If the economic benefits of interjurisdictional transmission are primarily oriented to wind smoothing, the argument that Oswald et al. offer appears sensible, although it is possible that any interconnectors might be used to provide other benefits as well, which may tip the balance in favor of the investment.

5.1 Comments on GE wind study

The IESO has reviewed the operability of Ontario's official Integrated Power System Plan [13]. To consider the implications of the wind elements of the IPSP, the IESO relied on a 2006 GE study [14]. The IESO's major conclusion is that the IPSP "provides sufficient flexibility to meet future system needs. Current market mechanisms and control actions will allow the IESO to reliably operate the system described in the IPSP."

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 intervals. Two of GE's conclusions raise concerns about this element of its assessment.

Figure 5.34 of the GE report shows a provincial map with a series of ten ovals representing "wind groups" -- the locations of anticipated wind power development regions. Correlation coefficients between selected pairs of wind groups are also provided. The correlations calculated by GE, along with approximate distances measured from the centre of the ovals presented in the original diagram are graphed here.

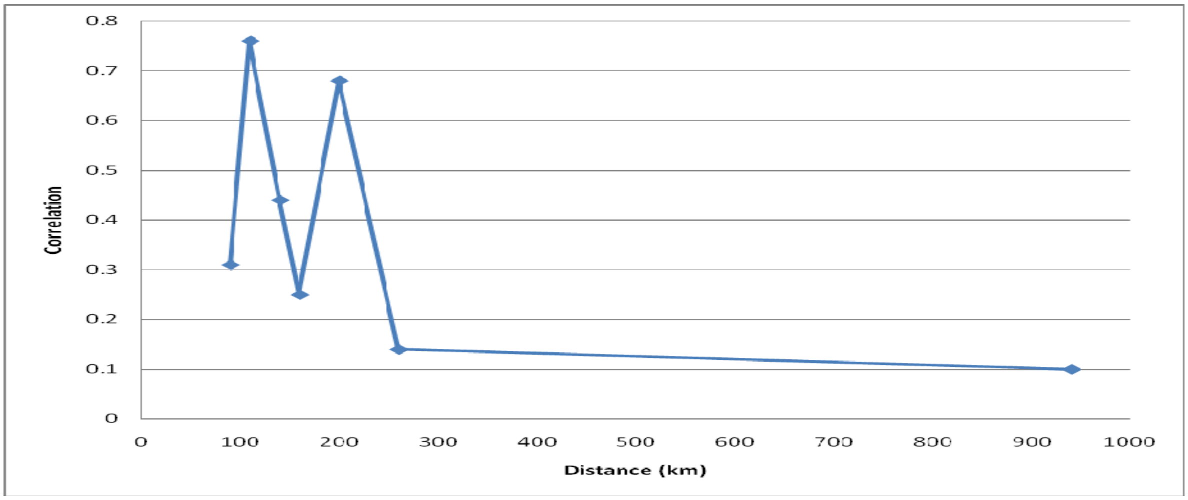

Figure 6: GE (2006) correlations by distance (10 minute data)

The results presented in Figure 5 suggest some anomaly, perhaps that the simulated data GE relied upon may not be reflective of real world performance. GE's data does not present the expected asymptotic decay shape seen in our results and other studies considering wind power output cross-correlations by distance.

An additional concern suggesting a problem 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. 5.47) The international experience presented in the literature and results presented in this study of hourly versus daily correlations support the contrary view that cross-correlations coefficients tend to decline as the time interval between measurements contract.

An additional concern relates to variability analysis within the 10 minute time frame. Based on its analysis of variability within a complete year of simulated data considered at the resolution of a 10 minute time frame, GE claims that wind power does not breach the current operating reserve threshold, which is equal to the capacity of one Darlington unit, until 6 GW of wind power is installed. (p. 5.29) As noted in discussing Figure 2, based only on spot checks, our analysis suggests that wind power would breach the current operating reserve threshold at 4.1 GW.

6. Conclusions

Measurements presented here based on wind outputs from major wind developments in and near Ontario indicate that distances over 250 km between wind farms are required for hourly output correlations to drop to 50%, and distances over 350 km are required for daily correlations to drop to 50%. Moreover, the results presented here suggest that correlation coefficients will be positive over distances greater than 800 km and are not likely to be negative over conceivable distances within the province. The modest benefit of diversifying locations is illustrated when one large wind farm located more than 360 km away from another group of nearly equal capacity was added: the standard deviation in output decreased by only 2.7% of installed capacity. Other studies present similar results for Europe, although distance appears to be less effective in mitigating variability in Ontario than in Europe.

From these results we conclude that spatial diversity does mitigate variability for a given fleet of wind generation. Thus, to meet the policy objective of maximizing wind's penetration of Ontario's electricity generation mix while minimizing grid impacts, any new wind power capacity should thus be installed far away from other wind farms. Conversely, allowing concentrated wind development, either by co-locating wind farms or building relatively large farms, reduces the total wind capacity the system can accommodate within a given level of load balancing expenditure.

Although adding a distant wind farm to an existing fleet fills the valleys of average output and drops the standard deviation of output by a small fraction, it also increases the magnitude of overall output swings. Large overall wind output swings are inevitable because wind farms within the province are statistically more prone to increase and decrease generation synchronously due to the nature and size of the meteorological fronts that largely drive wind speeds. In other words, if wind power output swings or peaks challenge the load balancing capacity of the power system, distance between wind farms does not help.

As wind capacity increases, it will be necessary to ensure that adequate flexible generation capacity is available at all times, potentially supported by short-term power storage options or load management programs. As a practical matter, substantial fossil fuel generation, with its attendant consumer and environmental costs, appears to be required to provide adequate generation flexibility. The scale and spatial distribution of Ontario's wind program will have important implications for future gas demand, gas-fired generation equipment specifications, and the location of future gas-fired generation.

Ontario has made a policy commitment to encourage extensive wind power development supported by only a preliminary understanding of the potential power system impacts of a large wind power fleet. Wind power's consumer impacts – incremental transmission, energy storage, ramping generation requirements, and grid reliability service costs such as automatic generation control and operating reserve – may be insignificant at low wind penetration of the overall electricity supply but will rise as wind capacity rises and may become significant. Additional research on the output variability of wind power, grid reliability mitigation measures, and the load carrying capacity of wind power is thus necessary.

7. References

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