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Effect of Cold Climate on Wind Energy Production in Canada (2010 – 2016)

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Executive Summary

A performance assessment was completed on 23 wind farms across eight Canadian provinces with the objective of quantifying the degree to which cold climate operation affects wind energy production in Canada.

For each wind farm in the study group, monthly losses were calculated as the difference between actual energy output, and expected energy output based on a combination of wind conditions and historical performance using the Measure-Correlate-Predict (MCP) approach. Losses were aggregated over summer (May – October) and winter (November – April) periods, and the results compared.

Among the 23 wind farms in the study group, over the six year study period from May 2010 – April 2016, average summer period loss factor was 4.2%, compared to 8.1% for the winter period, resulting in an average cold climate loss factor of 3.9%.

Regionally, wind farms in New Brunswick and Nova Scotia showed the highest cold climate losses on the basis of installed capacity (0.19 GWh/MW). Moderate losses were observed in Prince Edward Island and Newfoundland (0.12 GWh/MW), Québec (0.10 GWh/MW) and Ontario (0.09 GWh/MW), while minor losses were seen in Alberta and Manitoba (0.02 GWh/MW).

Extrapolating from the study group, based on the installed wind capacity as of December 2015, cold climate losses across all Canadian wind farms are estimated to account for annual financial losses of $113 million and annual additional Greenhouse Gas (GHG) emissions of 140 kilotonnes CO_2e.

While the results of the study showed a strong seasonal trend with respect to energy losses, further insight regarding the specific sources of winter season (and summer season) losses was not possible based on the granularity of the available data. Further research is therefore needed to more accurately classify and quantify losses directly attributable to winter weather conditions, as opposed to other non-meteorological sources of losses such as maintenance, outages or curtailment.

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1. Introduction

With 269 operational wind farms and 11,205 MW of installed wind energy capacity as of the end of 2015, Canada continues to develop its wind energy resources. Wind energy was estimated to have supplied 5% of Canada's domestic electricity demand (excluding exports) in 2015 [1]. As the penetration of wind energy in Canada grows, ongoing analysis of operational data at a national level can assist in identifying trends and issues, providing insights that can ultimately help to improve wind farm performance by reducing losses and maximizing availability.

One issue of concern with regards to Canadian wind farm performance is cold climate operations. Operation of wind turbines in cold climates can produce unwanted effects, such as accumulation of ice on turbine blades, cold temperature shutdowns and restricted or challenging access during cold winter months [2], [3]. Both ice accumulation and cold temperature shutdowns can lead to loss of production, which, if more effectively mitigated, would yield benefits for the Canadian wind industry.

This study, involving the performance assessment of 23 wind farms in eight Canadian provinces over a six year period spanning May 2010 to April 2016, forms part of ongoing efforts by Natural Resources Canada (NRCan) to quantify the degree to which Canadian wind farms are adversely affected by cold climate operation. This report builds on a previous assessment released in 2012 [4] of the same wind farms over a two year period from May 2010 to April 2012.

The same 23 wind farms used in the original two year study period from 2010 to 2012 are studied in this latest assessment. These projects were originally selected on the basis of geographic coverage, the availability of monthly production data and local weather data. Selected wind farms are grouped into five regions for reporting purposes: Alberta and Manitoba (AB/MB), Ontario (ON), Québec (QC), New Brunswick and Nova Scotia (NB/NS), and Prince Edward Island and Newfoundland (PE/NL). The number of wind farms assessed in each region ranged from four to six. In order to maintain the confidentiality of individual wind farm production data, all results presented in this report are aggregated by region, by year, or both. The installed wind energy capacity represented by the wind farms in the study group, as well as the total installed capacity for each region as of December 2015 is shown in Table 1. The second from the right column indicates the proportion of installed capacity represented by each region within the study group, while the the right-most column indicates the proportion of the total installed capacity represented by the study group wind farms, for that region.

Table 1: Installed wind capacity represented by wind farms in the study group

Region	Study group installed wind capacity (MW)	Total installed wind capacity as of Dec. 2015 (MW) [5]	Representation within study group	Study representation out of total installed capacity for the region
AB/MB	254	2,468	14.4%	10.3%
ON	688	4,361	38.9%	15.8%
QC	445	3,262	25.2%	13.6%
NS/NB	286	846	16.2%	33.7%
PE/NL	96	259	5.4%	37.1%
Total	1,769	11,196	100%	15.8%

2. Methodology

The methodology used for the current assessment followed the Measure-Correlate-Predict (MCP) approach originally employed in the 2010 – 2012 assessment, with several modifications introduced to improve consistency and accuracy of the results. The MCP approach is commonly used in wind resource assessment; for example the MCP approach can be used to estimate wind speed and wind direction at a target site, using long-term observational data from a separate reference site. A number of different MCP algorithms have been proposed, several of which are reviewed by Rogers et al. [6]. For this study, the linear regression MCP technique was applied in order to predict wind farm energy production based on the historical correlation between energy production and specific meteorological data measured at the reference Environment Canada weather station nearest to the wind farm. This method involves compilation and/or calculation of three values on a monthly basis for each wind farm:

- Actual wind farm production
- Expected production at the weather station
- Forecast production at the wind farm

2.1 Actual production

As a first step in the analysis, monthly wind farm production data submitted under the Wind Power Production Incentive (WPPI) and ecoENERGY for Renewable Power (ecoERP) programs [7], [8] was obtained for each of the 23 wind farms in the study group, over the six year study period from May 2010 to April 2016.

To evaluate the effect of cold climate conditions on wind farm performance, monthly production data was divided into two periods within each year: a summer baseline period from May 1st – Oct 31st, and a winter period from Nov 1st – Apr 30th. The same delineation was used in the 2010 – 2012 assessment. For the present study, the collection of monthly summer baseline production data from 2010 – 2016 for a particular wind farm is referred to as the “learning period”.

2.2 Expected production at weather station

Hourly meteorological data (wind speed, wind direction, temperature and relative humidity) were obtained from the Environment Canada weather station [9] nearest to each wind farm. When more than one option was available, a weather station was selected based on a combination of proximity, data quality, and degree of correlation to the actual wind farm production.

Windographer™ wind resource assessment software was used to convert hourly wind data into monthly predictions of wind turbine generation at each weather station location, using power curve specifications for turbines at the wind farm being studied. Windographer™ allows the user to input specific losses associated with the wind farm (i.e. downtime losses, array losses, icing/soiling losses, etc.). For this study, values of 2% for downtime losses, and 5% for array losses, resulting in a combined loss factor of 6.9%, were applied uniformly to all wind turbines for all wind farms in the study group, regardless of size or location.

2.3 Forecast production at wind farm

Production forecasts were generated through correlation of actual and expected production. Since the wind data used in the study was taken from a weather station located a certain distance from the wind farm, and not at the wind farm itself, the expected turbine output at the weather station needed to be translated into the expected output at the wind farm. This latter value is referred to in this study as the "wind farm forecast".

This translation was accomplished by establishing a linear relationship between the expected production at the weather station location (from Windographer™), and the actual wind farm production (from WPPI/EcoERP). This process is described in greater detail in Appendix A. Monthly forecasts, along with the actual and expected production at the weather station, are presented in Appendix B, aggregated by region.

2.4 Loss factors

Production losses were calculated as the difference between the wind farm actual production and the forecast production values. Losses were calculated on a monthly basis, and for months where the actual production was higher than the forecasted production, the loss for that month was assumed to be zero.

Absolute losses over various time periods were calculated as follows:

- Monthly loss (GWh) = monthly wind farm energy forecast – monthly wind farm actual energy production
- Annual loss (GWh) = sum of monthly losses (May – April)
- Summer loss (GWh) = sum of monthly losses (May – October)
- Winter loss (GWh) = sum of monthly losses (November – April)

The term "cold climate loss" is used in this assessment to indicate the additional losses incurred during the winter period compared to the summer baseline, and were calculated by subtracting the summer losses from the winter losses:

- Cold climate loss (GWh) = winter loss (GWh) – summer loss (GWh)

Loss factors, expressed as a percentage, were then calculated as follows:

- Annual loss factor = annual loss / annual energy forecast × 100%

- Summer loss factor = summer loss / summer forecast × 100%
- Winter loss factor = winter loss / winter forecast × 100%
- Cold climate loss factor = winter loss factor - summer loss factor

where the annual, summer and winter energy forecasts are the sum of the monthly forecasts over the annual, summer and winter periods, respectively.

3. Results and Discussion

Results are presented in two sub-sections. The first sub-section shows a comparison of production losses for the 23 wind farms in the study group. In the second sub-section, these results are normalized on the basis of installed capacity, and extrapolated to the entire national fleet of wind farms. Greenhouse gas (GHG) emissions and financial losses associated with the production losses resulting from cold climate operation are also estimated.

3.1 Wind farms in the study group

Absolute losses for wind farms in the study group were calculated according to the method described in Section 2.4. Figure 1 shows losses for the summer periods and Figure 2 shows losses for the winter periods. Losses for each year in the study period, as well as the average losses over six years, are provided for each region. The results demonstrate a significant difference between summer and winter period losses. While occasionally summer losses exceeded winter losses for a given region or year, in the majority of cases, winter losses were higher than summer losses. For the six year average, every region except Alberta/Manitoba showed significantly higher winter losses than summer losses.

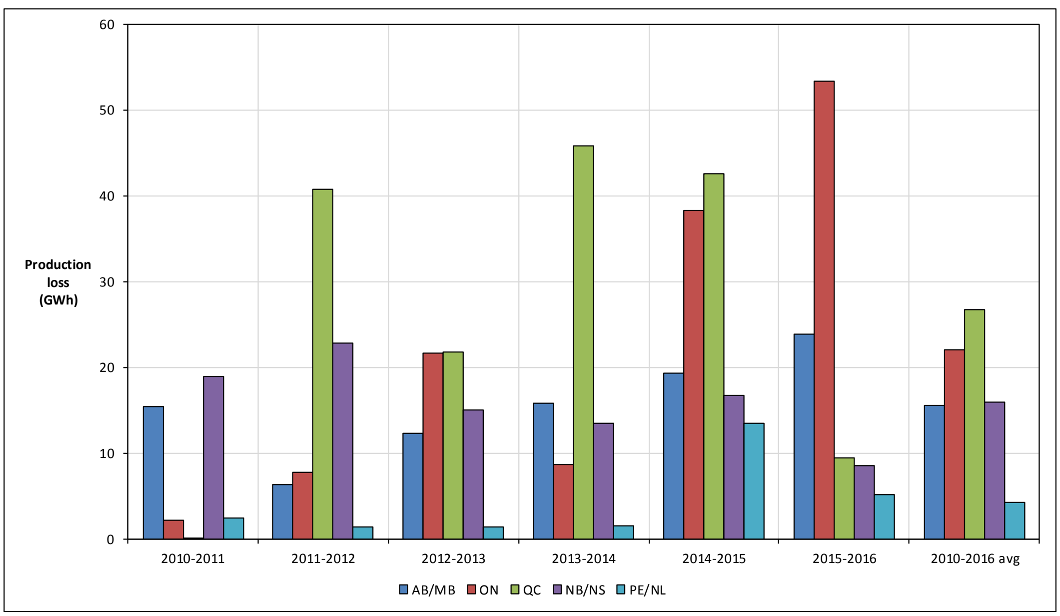

Figure 1: Summer period production losses, in GWh, for wind farms in study group, aggregated by region.

While losses in most regions fluctuated from year to year, a strong upward trend for winter losses was observed in Ontario from 2013 to 2016. Summer losses also trended upward during this period, although to a lesser extent. According to Ontario's Independent Electricity System Operator (IESO), economic dispatch (curtailment) of transmission-connected wind farms in Ontario began in September 2013 [10], which coincides with the start of the period of rising losses observed in Ontario, and observed in Figure 2. This increasing trend in calculated losses likely includes this change in the dispatch of Ontario's transmission connected wind farms, resulting in increased curtailment of wind farms in Ontario, and therefore, higher than expected losses. Despite this observation, further research is required to estimate the relative contribution of losses associated with economic dispatch of Ontario wind farms, versus losses due to cold climate, as well as other sources of lost energy production.

To highlight the difference between winter and summer losses, the cold climate losses are plotted in Figure 3. The cold climate losses represent the additional losses incurred during the winter periods compared to the summer baseline, or put another way, the losses that could be avoided if winter performance was improved to the same level as summer performance.

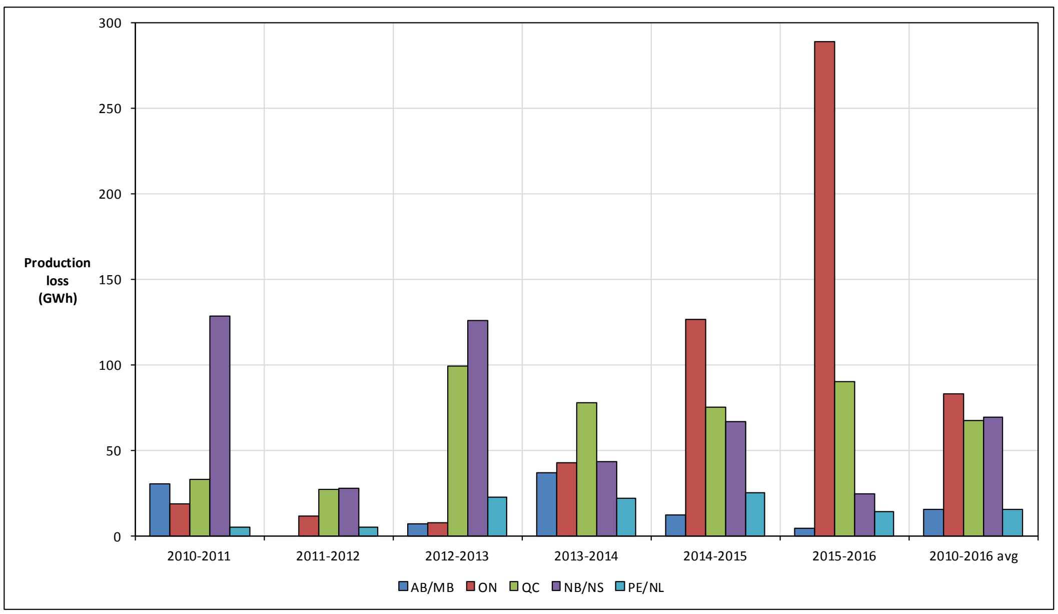

Figure 2: Winter period production losses, in GWh, for wind farms in study group, aggregated by region.

Presenting losses in absolute terms as in Figures 1-3 serves to highlight the magnitude of the differences in energy loss between the winter and summer periods. However, in order to compare losses across regions, which have different quantities of installed wind power capacity represented in the study, it is more appropriate to express results in terms of the loss factors defined in Section 2.4. Figures 4 through 9 present summer, annual and winter loss factors, aggregated by region, for the six one year periods studied, beginning with the period May 2010 – April 2011, expressed in percentages according to the methods described in Section 2.4. While some regions experienced high winter losses in particular years (i.e. NS/NB in 2010-2011 and 2012-2013, PE/NL in 2013-2014, ON in 2015-2016), relatively low winter losses were observed in other years.

The lowest loss factors occurred in study year 2011-2012, in which winter loss factors across the five regions ranged from 0% – 6%. In this same year, four out of five regions yielded summer loss factors that were higher than winter loss factors. This finding suggests that factors such as maintenance, outages or curtailment, had a greater impact on wind farm performance (or higher contribution to losses) during that period than did losses related to cold weather operation. In most other time periods, the winter loss factor was higher than the summer loss factor for each region except Alberta / Manitoba, similar to the results obtained for absolute losses.

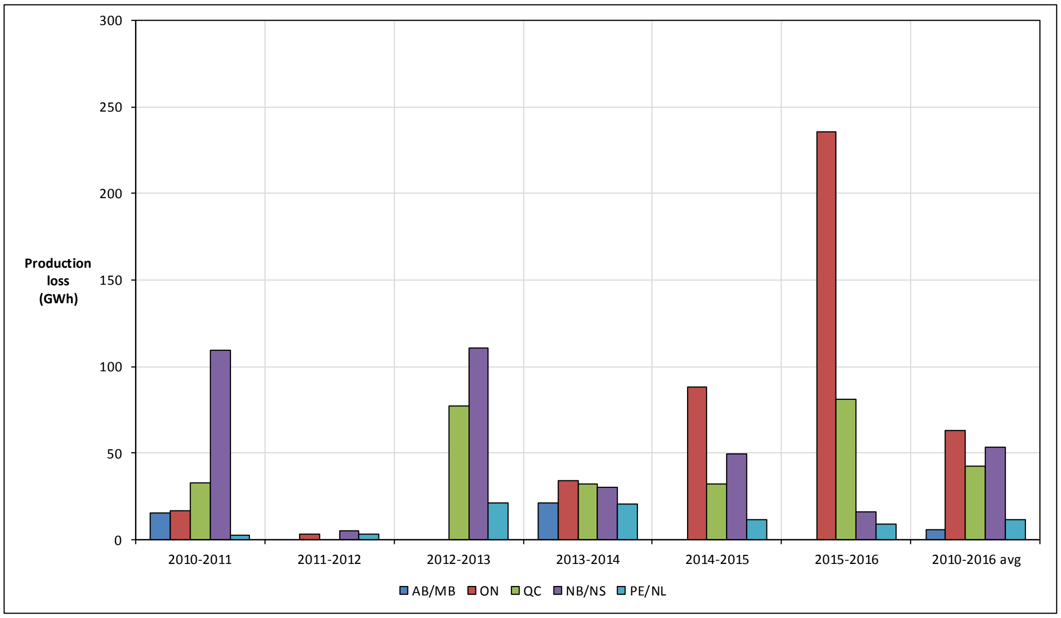

Figure 3: Cold climate losses, in GWh, for 23 wind farms in study group, aggregated by region.

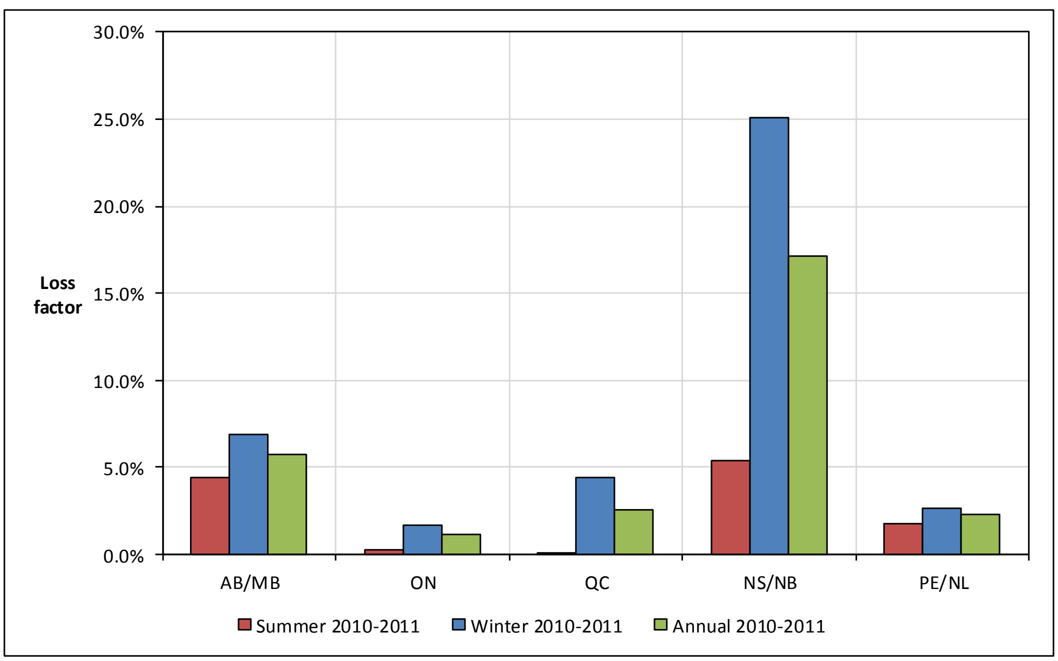

Figure 4. Loss factors aggregated by region, 2010-2011.

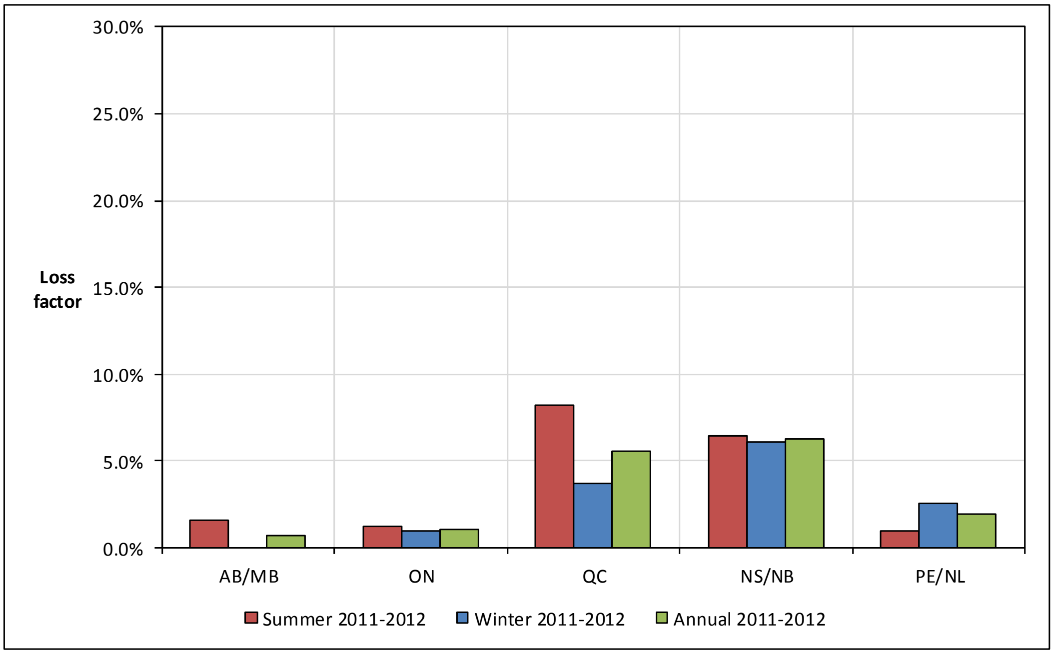

Figure 5. Loss factors aggregated by region, 2011-2012.

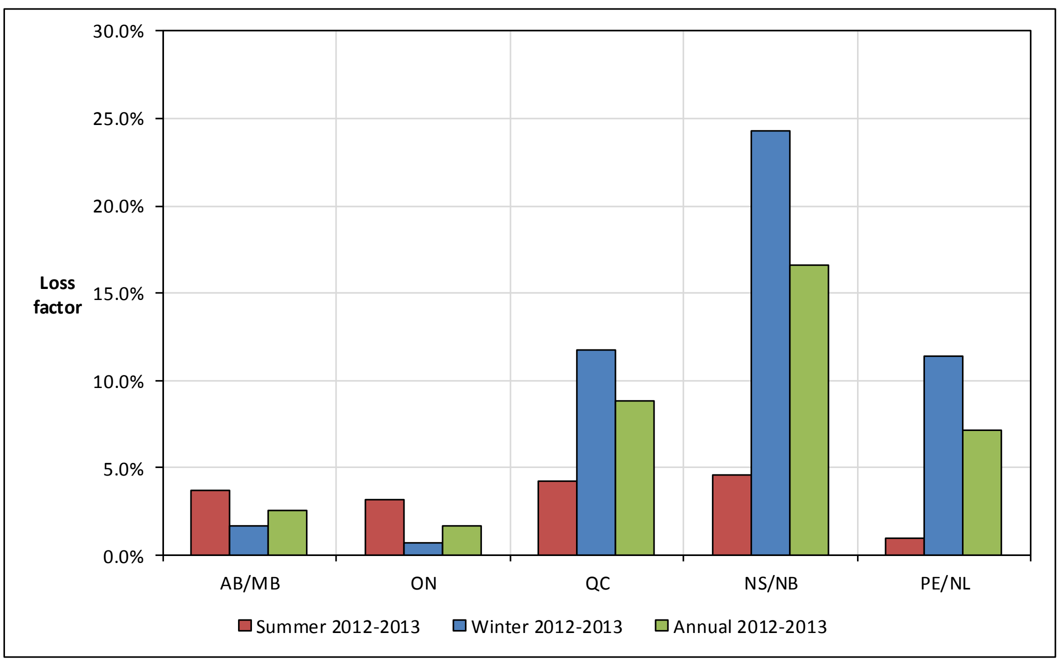

Figure 6. Loss factors aggregated by region, 2012-2013.

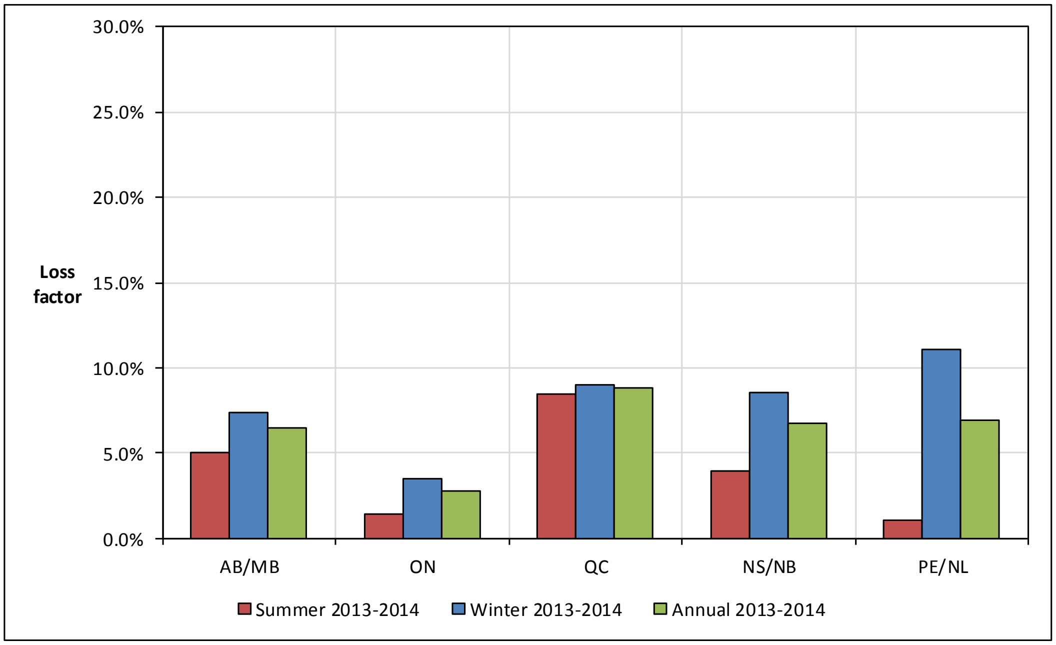

Figure 7. Loss factors aggregated by region, 2013-2014.

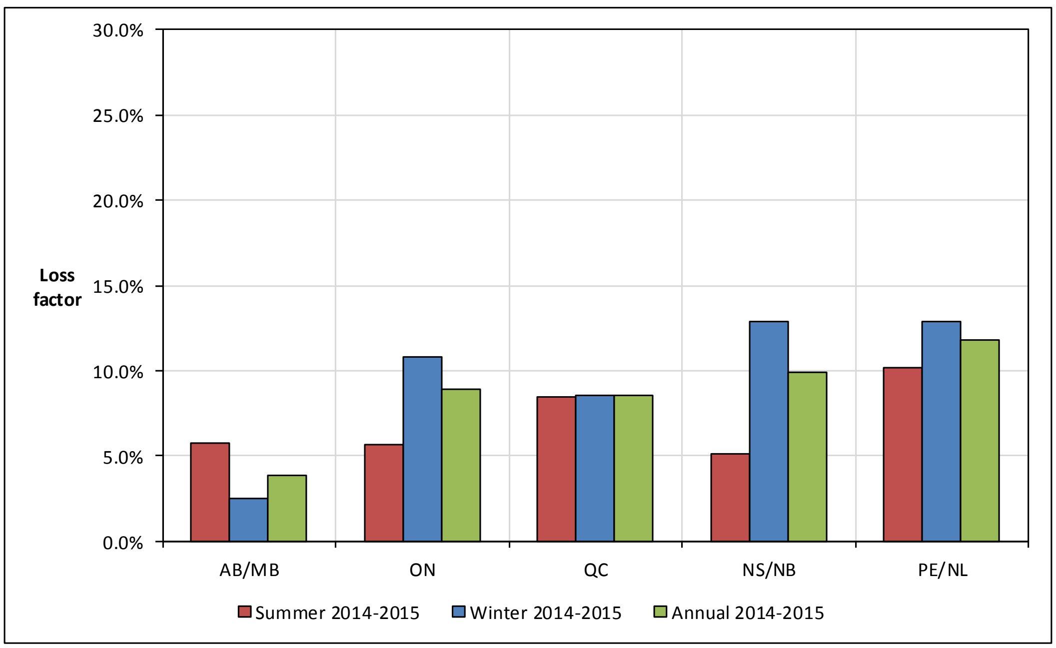

Figure 8. Loss factors aggregated by region, 2014-2015.

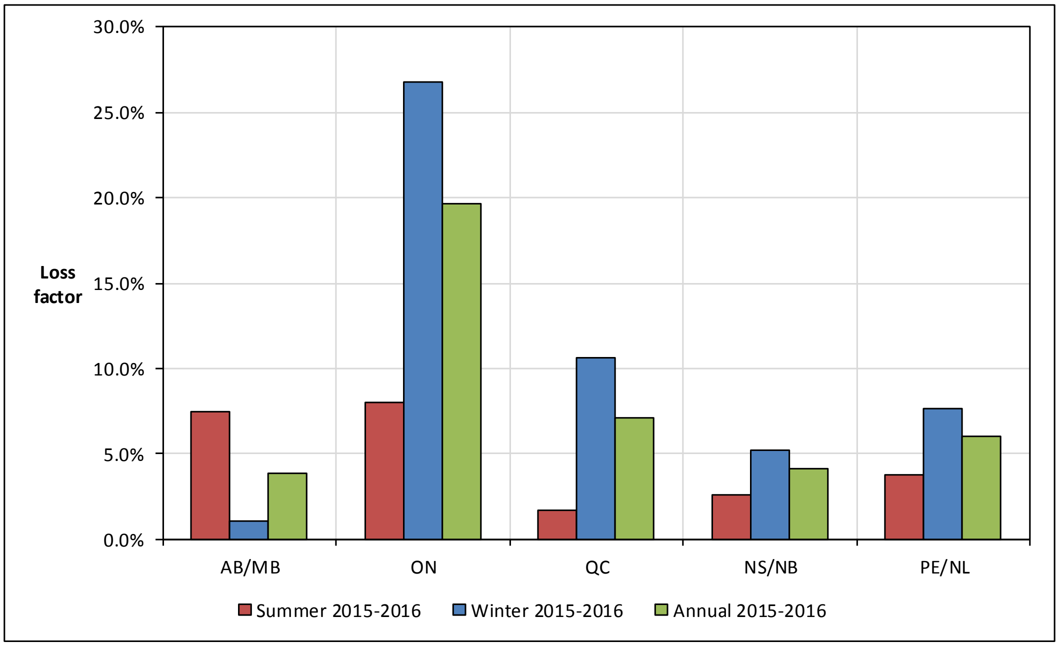

Figure 9. Loss factors aggregated by region, 2015-2016.

A consistent trend emerges when losses are averaged over the six year study, as shown in Figure 10. Over this time frame all regions except Manitoba/Alberta experienced significantly higher losses in winter periods compared to summer periods. The Nova Scotia/New Brunswick region showed the highest average annual winter loss factor (14.0%) and the highest cold climate loss factor (9.3%), defined as the difference between winter and summer loss factors. Prince Edward Island/Newfoundland, Ontario and Québec experienced cold climate loss factors of 5.0%, 4.0% and 3.1%, respectively, while the lowest average cold climate loss factor (-1.3%) was observed in Manitoba/Alberta, indicating that, on average, summer period losses were slightly higher than winter period losses for this region. These results suggest that, on average, wind farms in Eastern and Central Canada tend to experience higher production penalties (or losses) during winter months as compared to summer months.

When losses are presented by year, averaged across all 23 wind farms in the study group (Figure 11), five out of the six years showed higher winter loss factors compared to summer loss factors. The average winter loss factor for all 23 wind farms, averaged across 2010 – 2016, was 8.1%, compared to an average summer loss factor of 4.2%. This indicates that among the 23 wind farms studied, the average cold climate loss factor was 3.9%.

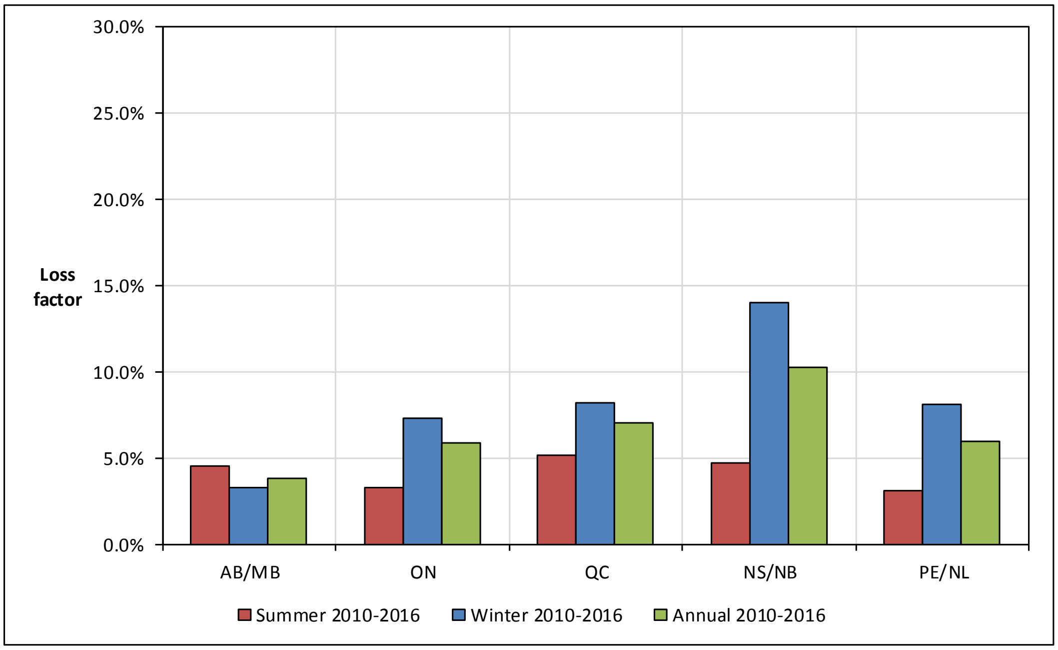

Figure 10. Loss factors aggregated by region, 2010-2016 average.

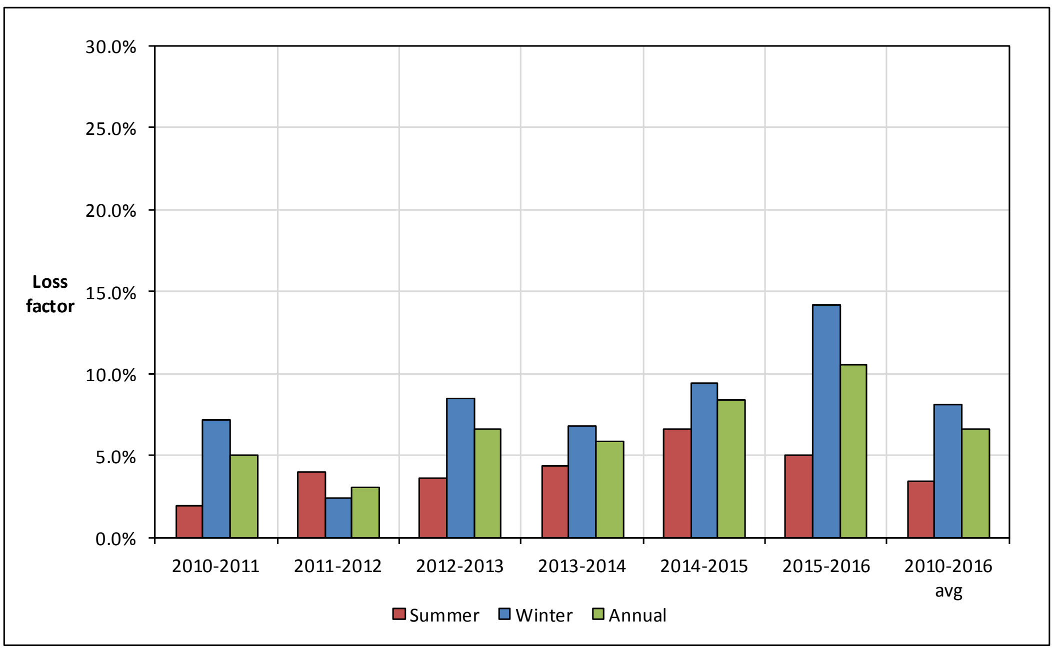

Figure 11. Loss factors by year, all wind farms in study group.

3.2 Extrapolation of study results to the Canadian wind fleet

Another means of comparing losses across regions involves normalizing the cold climate losses for study group wind farms by the installed wind energy capacity represented by that group (see Table 1). This approach is also a convenient way to account for changing installed capacity during the study period, given that across Canada, installed capacity increased by 174% from 2010 to 2016, as shown in Appendix C.

Using the normalized result, assuming that losses in the study group wind farms are representative of other wind farms in the region, losses can then be estimated for the entire country based on the total installed capacity for a given region. In the following sections, normalized and extrapolated results are presented for energy losses, GHG emissions and financial losses associated with cold climate operation.

3.2.1 Energy losses

Normalized energy losses for study group wind farms are shown in Figure 12. Averaged over 2010–2016, normalized losses were highest in NB/NS (0.19 GWh/MW), while the lowest normalized losses were observed in AB/MB (0.024 GWh/MW). The weighted average by installed capacity for all regions was 0.10 GWh/MW. These values are shown in Table 2.

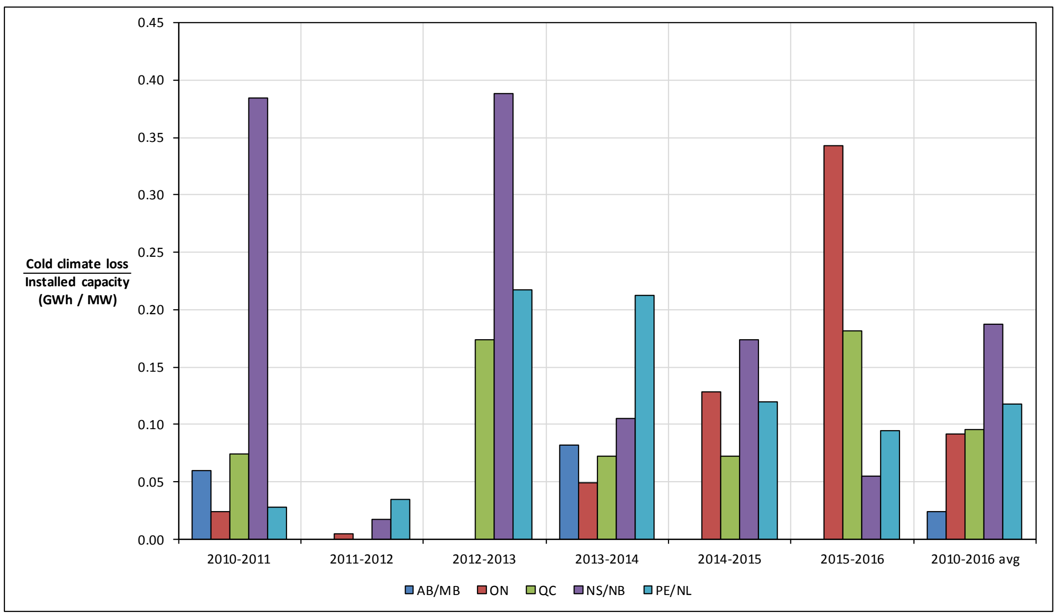

Figure 12. Cold climate energy losses, normalized by the installed wind energy capacity for each region in the study group.

A rough estimate of annual cold-climate losses for the entire country was then obtained by multiplying the time-averaged, normalized energy losses by the total installed capacity for each region as of December 2015 (see Table 1). These results are shown in the right-most column of Table 2. The average annual energy loss due to cold climate operation across Canada is estimated to be roughly 959 GWh. Ontario and Québec, with the highest installed capacities, showed the largest estimated annual losses among regions, at 399 and 312 GWh, respectively.

Wind farms in the 10 provinces in operation as of December 2015, representing roughly 11,196 MW, were included in the extrapolation. Planned wind farms or those under construction were not included. British Columbia and Saskatchewan, while having no representation in the study group, were combined with Alberta and Manitoba for the extrapolation. While it is recognized that BC in particular may have a different operating climate than the three prairie provinces, it was assumed for convenience that BC would experience the same proportion of cold climate losses as those three provinces.

Integrating data from BC wind farms into this work is anticipated in future phases of the cold climate performance assessment study. Wind farms in the Territories were not included in the extrapolation as together they represent only a total installed capacity of 10 MW, are not transmission connected, and face very different operational environments as compared to those in the southern regions of Canada.

The extrapolation relies on the assumption that the losses observed in the study wind farms are representative of the region as a whole. This assumption has not been thoroughly validated, and doing so is beyond the scope of this study; therefore the results in this section should not be viewed as an accurate prediction of losses, but rather as an estimation of the magnitude of the additional penalties associated with winter operation. It should not be viewed as an estimation of icing losses, per se, since losses arise due to a number of reasons, and not necessarily due solely to cold weather.

Table 2. Cold climate energy losses

Region	Study group average annual cold climate energy loss normalized by installed capacity (GWh / MW)	Canada-wide average annual cold climate energy loss using 2015 installed capacity (GWh)
BC/AB/SK/MB	0.024	58
ON	0.092	399
QC	0.096	312
NS/NB	0.19	158
PE/NL	0.12	31
Weighted avg.	0.10	–
Total	–	959

3.2.2 GHG emissions

An estimation of the GHG emissions associated with cold climate losses was performed by multiplying the cold climate energy losses in Figure 3 by the respective provincial grid emission factors. These values were then normalized by the installed capacity of the study farms in each region, and the results presented in Figure 13. Averaged over the 2010–2016 period, normalized emissions were highest in New Brunswick/Nova Scotia (87.1 tonnes CO_2e / MW), followed by Alberta/Manitoba (18.8 tonnes CO_2e / MW). Québec, having a very low grid emission factor, also had a very low GHG estimate as expected. The weighted average by installed capacity for all regions was 18.6 tonnes CO_2e / MW. These values are presented in Table 3.

The same set of grid emission factors, using the latest available data from 2014, was used for each year shown in Figure 13, despite the grid factor for some provinces changing during the study period. In this way a comparison between regions of GHG emissions resulting from cold climate losses can be drawn without introducing another variable. Further description on the selected grid emission factors is presented in Appendix C.

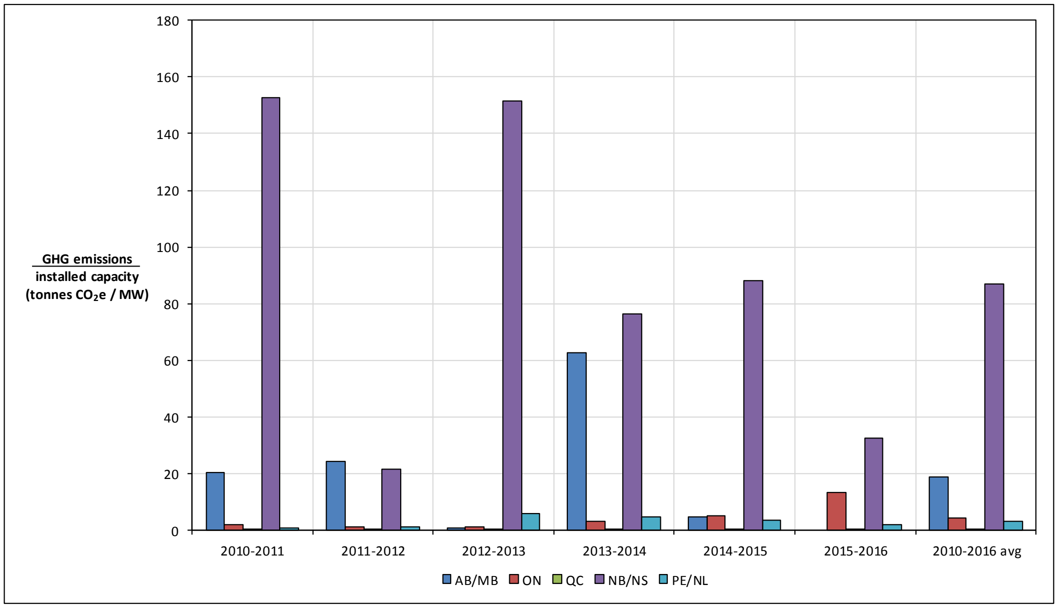

Figure 13. GHG emissions resulting from cold climate losses, normalized by the installed capacity for a given region and year.

The normalized emissions were then extrapolated to the entire country based on total installed capacity in each region. These values, shown in the right-most column of Table 3, represent the GHG emissions that could be avoided across the country if winter performance of wind farms was improved to the point where losses during the winter periods matched those of the summer periods.

The results show that cold climate losses across the country account for an estimated 140 kt CO_2e of GHG emissions annually. This is equivalent to the annual emissions generated by approximately 32,000 average Canadian passenger vehicles [11]. The bulk of these emissions (73.6 kt) are located in New Brunswick/Nova Scotia, as a result of high winter losses and moderately high GHG grid intensity factors. Annual GHG emissions for the western provinces (BC/AB/SK/MB) and Ontario are estimated to be 46.4 and 18.6 kt CO2e, respectively. Due to the very low emission factor in Québec, and the relatively low quantity of wind energy generation in PEI/Newfoundland, the estimated GHG emissions associated with winter production losses in these regions is, as expected, small.

Table 3. GHG emissions due to cold climate losses

Region	Study group average annual GHG emissions normalized by installed capacity (tonnes CO_2e / MW)	Canada-wide average annual GHG emissions from cold climate losses using 2014 grid emission factors (kilotonnes CO_2e)
BC/AB/SK/MB	18.8	46.4
ON	4.3	18.6
QC	0.3	0.8
NS/NB	87.1	73.6
PE/NL	3.0	0.8
Weighted avg.	18.6	–
Total	–	140.2

The GHG emission estimation relies on the assumption that the increase in wind energy generation can be accommodated by the regional electrical grid, and furthermore that this additional generation has an emissions intensity of zero and displaces an equivalent amount of existing generation with a GHG emission intensity equal to the average GHG grid intensity for the province in which the new wind generation is located. Validation of these assumptions would require a detailed analysis of various regional electricity grids, and the economic and security constrained dispatch of different generation sources based on hourly (or sub-hourly) load, marginal/wholesale market prices, transmission constraints, exports and other factors that collectively determine the generation dispatch stack, and therefore the emissions profile, for each case. Due to the complexity involved, this exercise was not completed as part of this assessment, and as such the results are intended only to provide some insight into the effect of cold climate losses in terms of GHG emission reduction potential.

3.2.3 Financial losses

Financial losses resulting from cold climate losses were calculated by multiplying the cold climate energy losses in Figure 3 by the amount paid to wind farm owners per unit of electricity sold. These rates, established through power purchase agreements (PPAs), vary by province, and often differ within the same province, as wind farms have been connected to the grid in different years under different PPAs. For this assessment, a range of estimates for financial losses was established by applying a nominal, high and low rate for each province. A summary of the various rates used in this assessment, along with a description of how the rates were determined is included in Appendix C.

Figure 14 shows the estimated financial losses due to cold climate losses, normalized by installed capacity, by region and by year. These losses represent the additional revenue that could have been earned by wind farm owners across the country if winter period losses were reduced to the same level as summer period losses. The columns are used to show the estimate determined using the nominal rates, while the high and low error bars indicate the results using the high and low rates, respectively.

Averaged over 2010–2016 , the highest normalized financial losses due to cold climate operation among the study group were observed in New Brunswick/Nova Scotia ($20,000 / MW). Average financial losses for Ontario, Québec and PEI/Newfoundland were all in the $10,000 – $13,000 / MW range. The weighted average by installed capacity for all regions was $11,500 / MW. The 2010–2016 average financial loss values are included in Table 4.

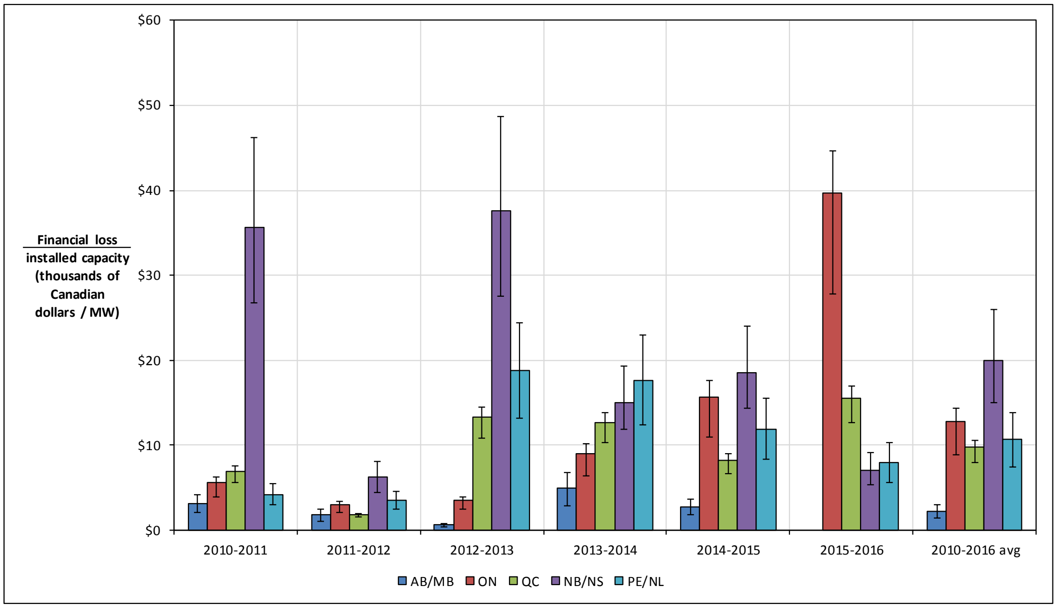

Figure 14. Financial losses resulting from cold climate losses, normalized by the installed capacity for a given region and year.

The financial losses shown are strictly estimates, and no guarantee of accuracy can be made, particulary given that the details of many PPAs are not released publicly. The error bars are intended to provide a range of possibilities based on the known information. The financial loss calculation relies on the assumption that all additional energy generated is sold to the grid at the rates listed in Appendix C. Furthermore, energy losses were entirely converted to financial losses at a fixed rate, regardless of the source of the loss. For example, it is common for wind farm operators to be compensated by the electricity system operator in instances of curtailment due to centralized dispatch requirements. However, these amounts are not readily available and were thus not applied in this assessment. Further work is required to break out the various sources of losses, including curtailment.

Extrapolating the results of the study group based on installed capacity at the end of 2015, using the nominal rate for each province, produced an estimate of annual financial losses attributed to cold climate operation across the country of roughly $113 milion. The bulk of the losses occurred in Ontario ($56 million) and Québec ($32 million), followed by New Brunswick/Nova Scotia ($17 million). Losses in the prairies and PEI/Newfoundland amounted to approximately $8 million combined. The extrapolated results are shown in the right-most column of Table 4.

Table 4. Annual financial losses due to cold climate losses, nominal estimate

Region	Study group average annual financial loss normalized by installed capacity ($ thousand CAD / MW)	Canada-wide average annual financial loss, nominal estimate ($ million CAD)
BC/AB/SK/MB	2.2	5.5
ON	12.7	55.6
QC	9.7	31.8
NB/NS	20.0	16.9
PE/NL	10.7	2.8
Weighted avg.	11.5	–
Total	–	113

4. Conclusions

An assessment of wind power production was undertaken on 23 wind farms located across Canada over the period 2010 to 2016. Wind power production losses were estimated based on the difference between actual wind farm production reported by wind farm owners as part of the NRCan WPPI and ecoERP programs, and forecasted wind power production estimated using local wind data from proximate Environment Canada weather stations and wind turbine-specific power curves.

While production losses varied from year to year and from region to region, when averaged over the six year study period, a strong seasonal effect on wind farm energy production was observed. In four of the five regions studied, the production loss factor during winter months was significantly higher than during summer months.

Over the six year period spanning May 2010 to April 2016, the cold climate loss factor, i.e the average additional production penalty for winter operation compared to the summer baseline, for the 23 wind farms in the study group, was 3.9%. The New Brunswick/Nova Scotia region experienced the highest cold climate loss factor among the five regions (9.3%),while Alberta/Manitoba experienced the lowest (-1.3%). Ontario, Québec, and PEI/Newfoundland each experienced moderate losses of 4.0%, 3.1% and 5.0% respectively.

On a normalized basis, the weighted average of cold climate energy losses for the study farms across the five regions and the the six year study period was 0.10 GWh per MW of installed capacity. The highest normalized loss was observed in New Brunswick/Nova Scotia (0.19 GWh/MW).

Extrapolating the results from the study group wind farms to the entire Canadian wind fleet, based on installed capacity at the end of 2015, produced an average annual estimated energy loss of 959 GWh attributed to cold climate operation. Improving the reliability of wind turbine energy output during winter months will help to reduce the need for other more carbon-intensive sources of electricity. GHG emissions associated with the cold climate losses of Canadian wind farms are estimated to be 140 kt CO_2e annually, or 18.6 tonnes of CO_2e per MW of installed capacity.

Improved energy production would also translate to additional revenue generation. By reducing losses in winter months, additional revenue could be recouped that is otherwise lost to wind turbine underperformance or downtime. The average annual financial loss incurred by Canadian wind farm operators as a result of cold climate energy losses, was estimated to be roughly $113 million annually, with roughly half of this loss occurring in Ontario. Normalized annual financial losses across the five regions amounted to $11,500 per MW of installed capacity, with the New Brunswick / Nova Scotia region losing $20,000/MW each year. This indicates the strong potential for cost-effective, regionally-focused energy loss mitigation programs.

4.1 Limitations

The main limitation of this study is the inability to determine precisely the relative contribution of various factors associated with production losses. Other limitations include:

- Missing geographic representation: wind farms from some provinces including British Columbia and Saskatchewan were not included in the study.
- Small sample size: Only 23 out of 269 wind farms in Canada were included in the study, representing 1,769 MW out of an installed capacity of 11,205 MW (16%). This serves to limit the extent to which results of the study can be broadly applied to the entire country.
- A lack of knowledge about which wind turbines in the study already have cold weather packages installed. For these turbines, further significant improvements to performance during winter months may not be achievable.
- The age of the turbines was not taken into account. Wind turbine performance is known to decline with age. For example, one study estimated turbine output losses to be 1.6 ± 0.2% per year [12].
- The degree of correlation between actual production and expected production based on weather station data from Environment Canada ranged significantly between wind farms – wind speed data taken at the wind farm itself would be preferred, but was not available for each site at the time of this study.
- An inherent lack of precision in wind farm production data, which was only available from WPPI and ecoERP on a monthly basis.

4.2 Future work

Based on the above, further investigation is recommended in order to better understand the relative contributions of different sources of production losses. Future research aims to obtain site-specific meteorological data, increase the number of wind farms studied, and undertaking interviews with wind farm operators to account for other potential areas of production loss. This could include, for example, planned and unplanned maintenance, force majeure events, forced outages, or curtailment due to centralized dispatch, or bat mitigation requirements.

5. References

[1] International Energy Agency. IEA Wind Technology Collaboration Programme 2015 Annual Report, 2016.

[2] Hochart, C., Fortin, G., Perron J., and Ilinca, A. Wind turbine performance under icing conditions. Wind Energy 11:319–333, 2008.

[3] Lamraoui, F., Fortin, G., Benoit, R., Perron, J., and Masson, C. Atmospheric icing impact on wind turbine production. Cold Regions Science and Technology 100:36–49, 2014.

[4] Lacroix, A. and Tan, M. Assessment of Wind Energy Penalties due to Cold Climate in Canada. CanmetENERGY, 2012.

[5] Canwea. Installed Capacity (as of December 2015). Retrieved from: http://canwea.ca/wind-energy/installed-capacity/ (accessed Nov. 2016).

[6] Rogers, A.L., Rogers J.W., and Manwell, J.F. Comparison of the performance of four measure–correlate–predict algorithms. Journal of Wind Engineering and Industrial Aerodynamics, 93:243–264, 2005.

[7] Natural Resources Canada. ecoENERGY for Renewable Power. 2016. Retrieved from: http://www.nrcan.gc.ca/ecoaction/14145 (accessed Nov. 2016).

[8] Natural Resources Canada. Wind Power Production Incentive Contribution Program. 2016. Retrieved from: http://www.nrcan.gc.ca/plans-performance-reports/rpp/2015-16/17057 (accessed Nov. 2016).

[9] Government of Canada. Historical Data. 2016. Retrieved from: http://climate.weather.gc.ca/historical_data/search_historic_data_e.html (accessed Nov. 2016).

[10] Personal communication with analyst at Independent Electricity System Operator (IESO), November 10, 2016.

[11] Natural Resources Canada. Emission impacts resulting from vehicle idling. Retrieved from: http://www.nrcan.gc.ca/energy/efficiency/communities-infrastructure/transportation/cars-light-trucks/idling/4415 (accessed Nov. 2016).

[12] Stafell, I., and Green, R. How does wind farm performance decline with age? Renewable Energy 66:775–786, 2014.

[13] Canadian Industrial End use Data and Analysis Centre. Canadian Renewables Database. http://edb.rem.sfu.ca/DB_renew_new/ (accessed Nov. 2016).

[14] Environment and Climate Change Canada. National Inventory Report 1990-2014: Greenhouse Gas Sources and Sinks in Canada, Part 3. 2016.

6. Appendix A

6.1 Generation of wind farm energy forecasts

To generate monthly values of forecast production at the wind farm location using the MCP approach, a scatter plot of actual wind farm production (from WPPI/EcoERP) vs. expected production at the proximate weather station location (generated using Windographer™) was created for each wind farm in the study group. For these plots, only the monthly data from the summer learning period was used, thus creating a baseline against which winter production could be measured.

Linear regression was used to produce a line of best fit, thus yielding a linear relationship between expected and actual production. In this way, for a given set of environmental data at a proximate weather station, together with the specific turbine power curves, a monthly forecast was generated for the wind farm based on its historical performance.

An example of a regression fit applied to learning period data for a sample wind farm, with the equation of the line of best fit indicated, is shown in Figure 15. Statistically, the data can be described as a sample of n ordered pairs (x_i, y_i), where x_i represents monthly expected production at the weather station, and y_i represents monthly wind farm actual production. Monthly forecast values $\hat{y}_i$ were calculated using the slope m and y-intercept b of the line of best fit:

$$\hat{y}_i = mx_i + b \tag{1}$$

In order to provide an accurate representation of monthly predictions, a need was identified to remove a small number of extreme value data points (outliers) which, if left alone, could significantly skew the equation of the line of best fit and produce a less accurate forecast. Outliers for a sample wind farm are indicated in Figure 15. These outliers were generally observed to result from either atypically low production relative to the same month in other years, or abnormally low wind speeds resulting in very high actual production relative to expected production. While these outliers are likely the result of a legitimate issue (i.e. maintenance events or faults in meteorological equipment), until more information regarding the accuracy of the outliers is obtained, it was concluded that they be removed from the analysis. A consistent approach to outlier identification was applied to each dataset. Monthly regression residuals e_i were calculated as:

$$e_i = y_i - \hat{y}_i \tag{2}$$

Standard error $s_{y/x}$ was then calculated for each dataset as:

$$s_{y/x} = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-2}} \quad (3)$$

The residual value as a fraction of standard error of the dataset $e_i/s_{y/x}$ was calculated for each month and values of $|e_i/s_{y/x}| > 2$ were flagged as outliers and removed from the analysis. The slope, y-intercept and standard error were then recalculated using the remaining data points. This process was repeated for three iterations or until all outliers were removed. A sample plot of $e_i/s_{y/x}$vs. expected production at the weather station, with outlying data points indicated, is shown in Figure 16.

For each dataset, the Pearson R value was computed, which measures the degree of correlation between the actual and expected production. The R-values were generally relatively high, indicating a strong linear relationship between the two variables, with the removal of outliers further improving the degree of correlation. After removal of outliers, 21 of 23 wind farms had R values greater than 0.80.

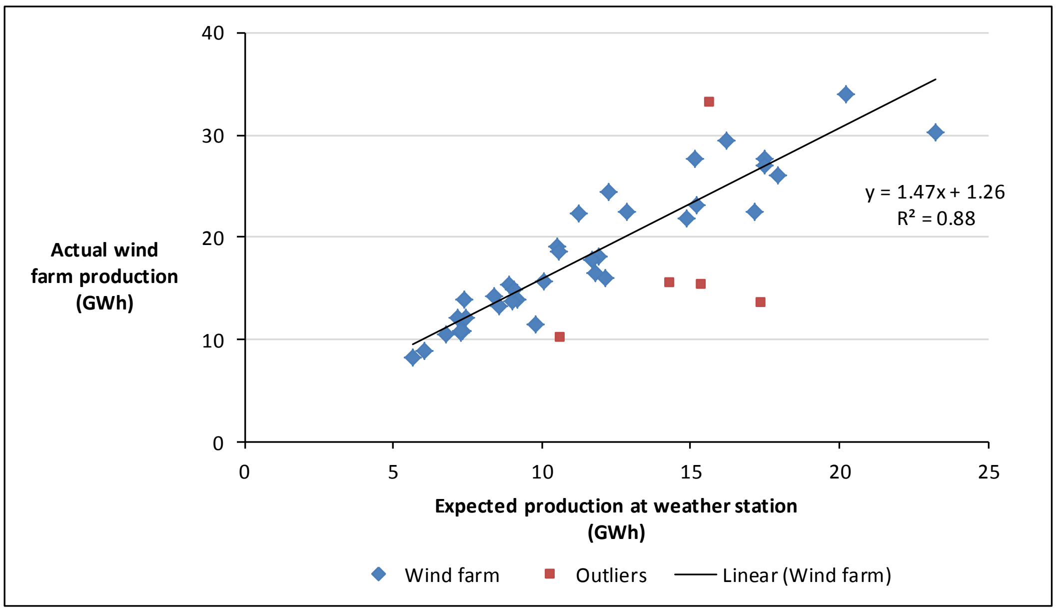

Figure 15. Actual production (from WPPI/EcoERP) vs. expected production at weather station for a sample wind farm, monthly data.

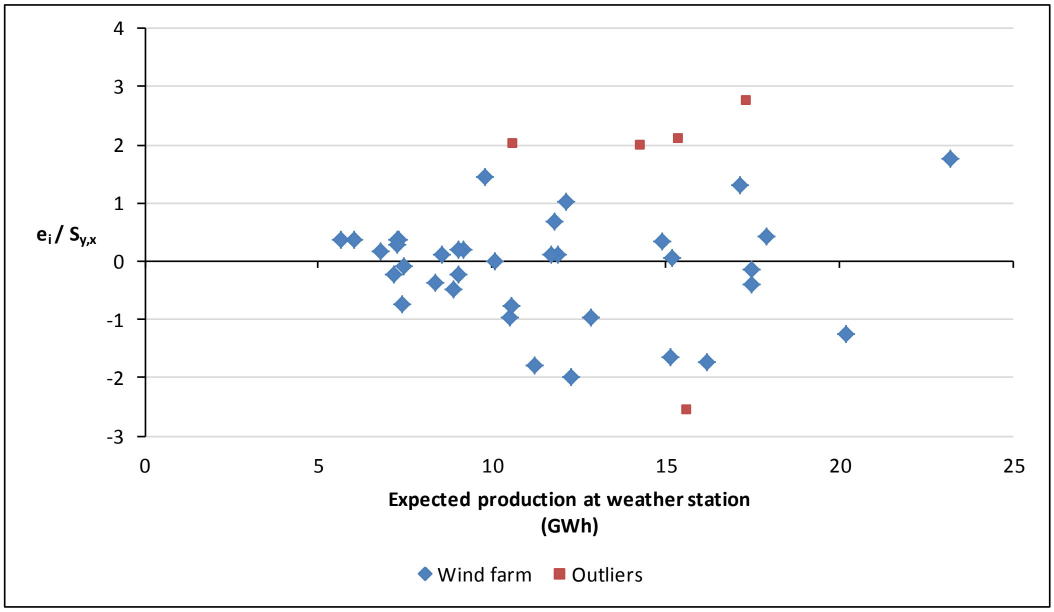

Figure 16. Standard error from regression analysis of monthly production data for a sample wind farm.

7. Appendix B

7.1 Monthly aggregated wind farm production

Figures 17 through 21 show monthly values for actual production (blue), forecast production (red), and loss factor (green), for each of the five study regions.

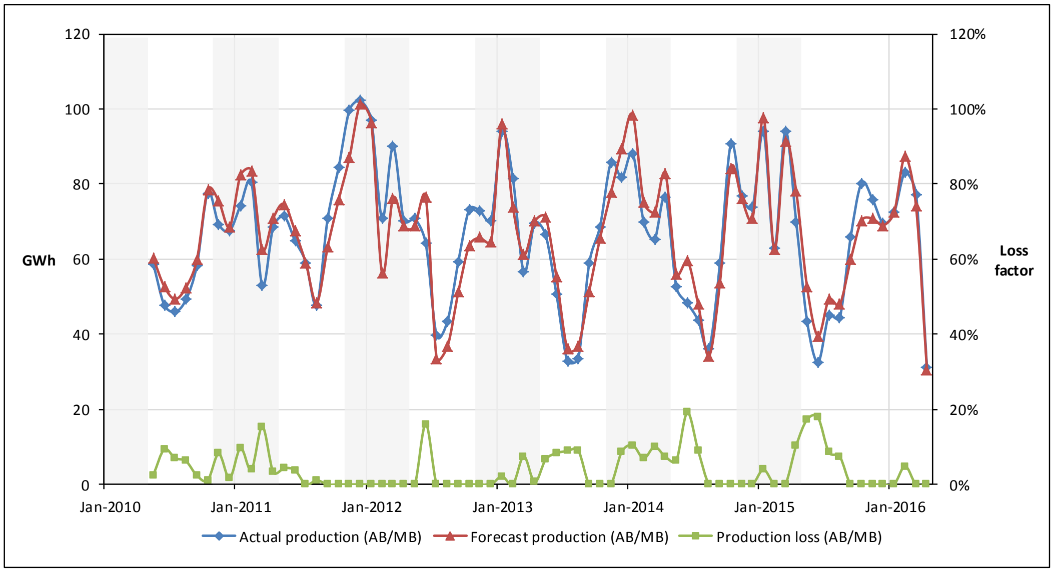

Figure 17. Monthly actual and forecast energy production in GWh (left axis) and production loss as percentage (right axis), aggregated for wind farms in Alberta and Manitoba.

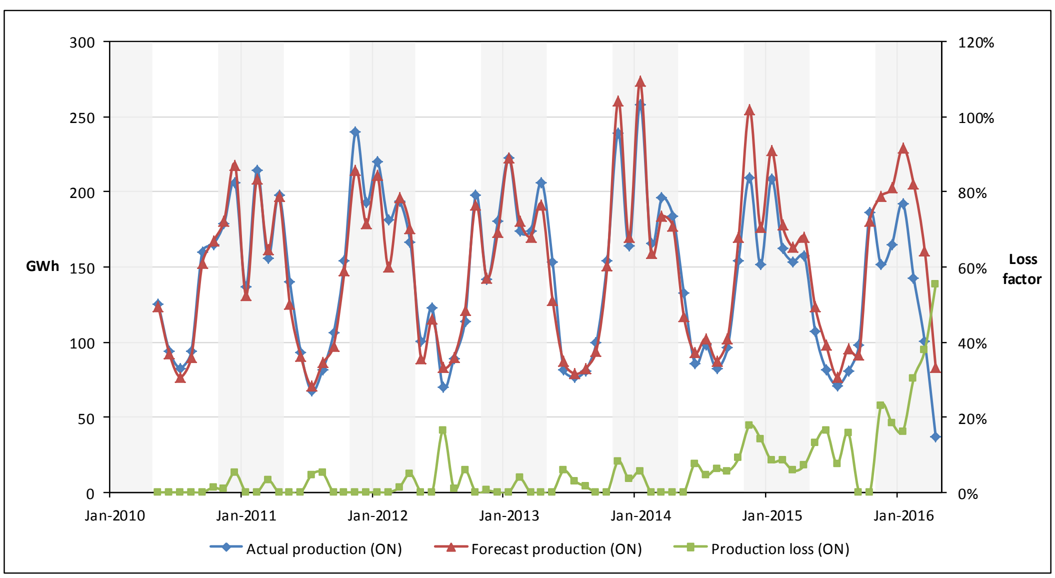

Figure 18. Monthly actual and forecast energy production in GWh (left axis) and production loss as percentage (right axis), aggregated for wind farms in Ontario.

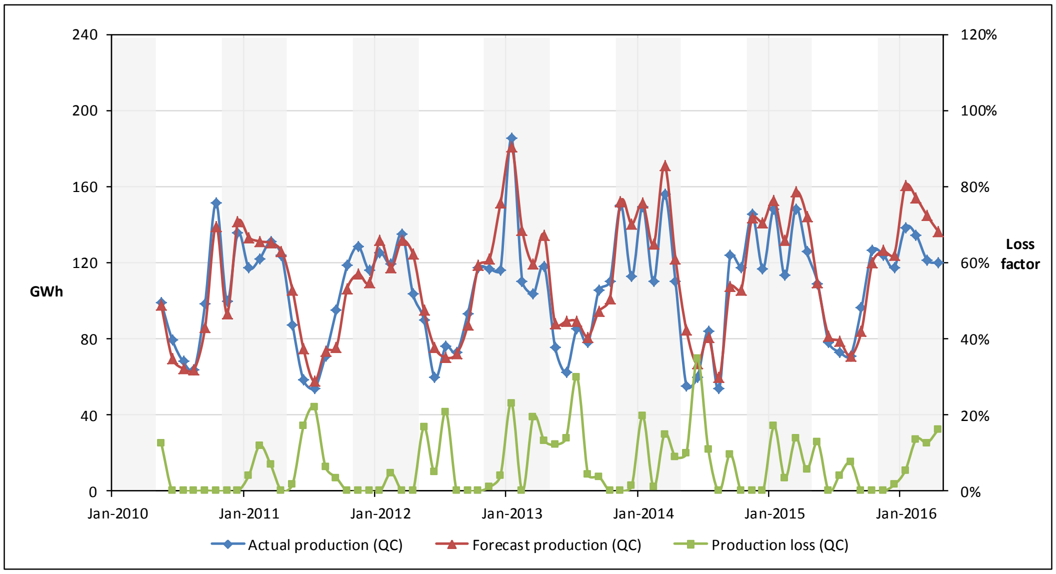

Figure 19. Monthly actual and forecast energy production in GWh (left axis) and production loss as percentage (right axis), aggregated for wind farms in Québec.

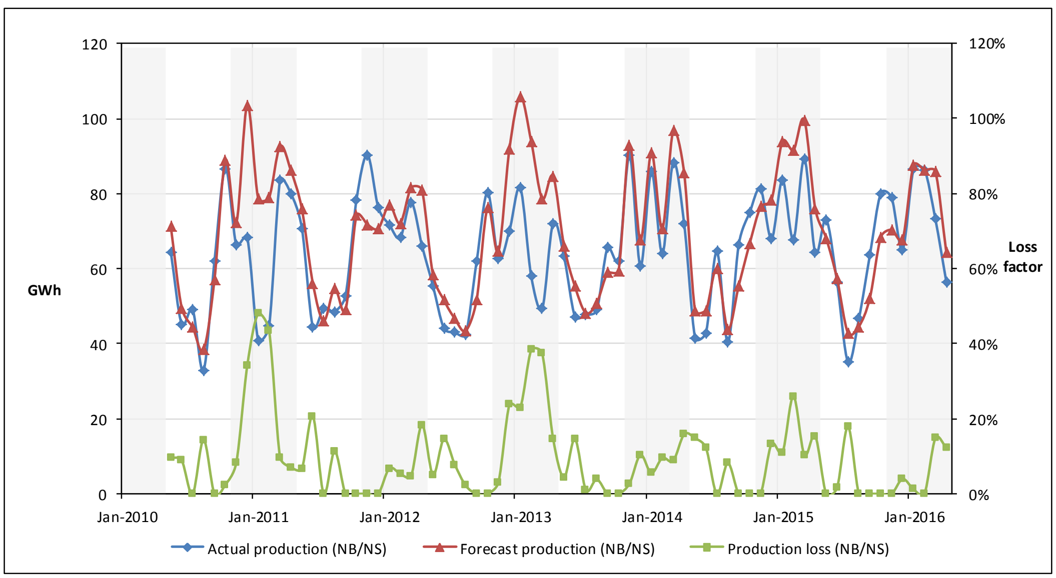

Figure 20. Monthly actual and forecast energy production in GWh (left axis) and production loss as percentage (right axis), aggregated for wind farms in New Brunswick and Nova Scotia.

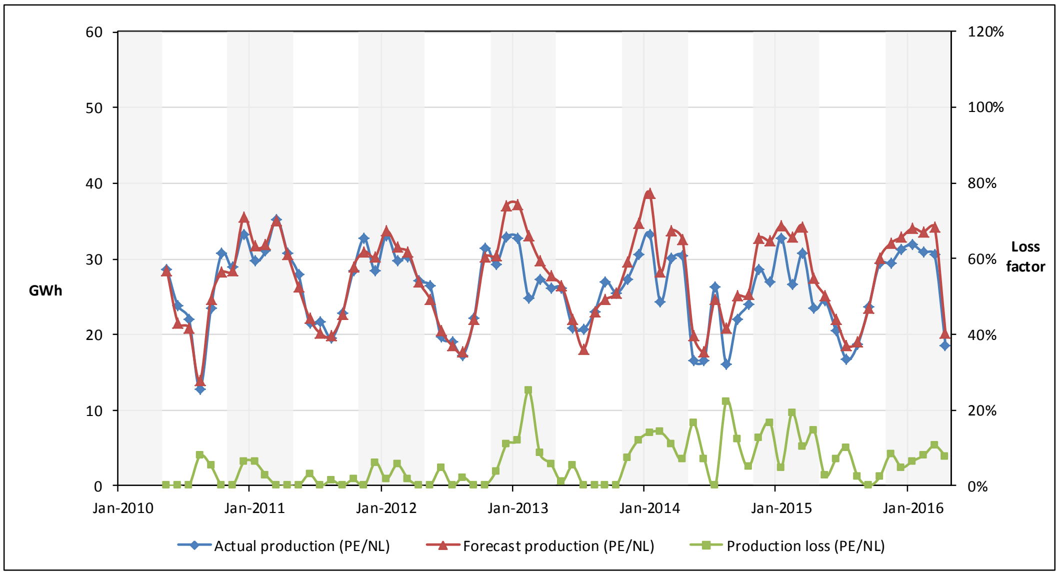

Figure 21. Monthly actual and forecast energy production in GWh (left axis) and production loss as percentage (right axis), aggregated for wind farms in Prince Edward Island and Newfoundland.

8. Appendix C

8.1 Wind energy installed capacity

Table 5 shows cumulative wind energy installed capacity by province, for each year during the period 2010–2015.

Table 5. Wind energy installed capacity, by province and by year [13]

Province	Installed capacity (MW)					
	2010	**2011**	**2012**	**2013**	**2014**	**2015**
BC	104	248	390	489	489	489
AB	806	894	1,120	1,120	1,472	1,501
SK	171	198	198	198	198	221
MB	104	242	258	258	258	258
ON	1,497	2,019	2,103	2,540	3,539	4,411
QC	690	950	1,381	2,431	2,865	3,262
NB	249	294	294	294	294	294
NS	276	320	358	370	395	566
PE	164	164	164	174	204	204
NL	55	55	55	55	55	55
Total	4,116	5,383	6,320	7,929	9,768	11,261

8.2 Provincial grid emission factors

Provincial grid emission factors used in the assessment were taken from the 2016 National Inventory Report [14], which contains preliminary data for 2014, the latest year available. These values are presented in Table 6. Provincial emission factors change from year to year depending on the electricity supply mix and the estimate of GHG emissions associated with winter losses will be affected accordingly. While the grid emission factor declined for most provinces over the 2010-2014 period, some provinces (MB, PE, NL) experienced an increase. Ontario experienced the sharpest drop of any province, a 68% reduction in generation intensity between 2010 and 2014, largely due to its retirement of coal-fired power plants during this time. The decline may continue as data for 2015 and 2016 becomes available.

Table 6. Provincial electricity emission factors, 2014 preliminary data [14]

Province	Generation intensity ($g\ CO_2$ eq / kWh)
BC	14.7
AB	790
SK	780
MB	3.4
ON	41
QC	2.1
NB	300
NS	700
PE	8
NL	30

8.3 Wind energy purchase rates

Wind energy purchase rates used in this assessment are presented in Table 7. In some provinces, PPA rates are publicly available, while in others, the rates are privately negotiated and not disclosed. The nominal, high and low rates used in this assessment were determined as follows:

- For provinces in which the PPA rate was known for all operating wind farms in the province, the nominal rate was taken as the weighted average of the PPA rates according to installed capacity at a particular rate.
- For provinces in which the PPA rate was known for only some wind farms, a weighted average of the known rates was used to determine the nominal rate, and the high and low rates were estimated as +/- 30% of the nominal rate, respectively. In some cases, aggregated data on average rates paid to multiple independent power producers that included various generation sources was available. This information was used in the absence of wind specific data to establish a nominal rate.
- For provinces where no information on PPA rates was available, the nominal rate was set as the average of the nominal rates of all provinces, and the high and low rates were estimated as +/- 30% of the nominal rate, respectively.
- In Alberta, which has a deregulated electricity market and variable pool price, the nominal rate was taken as the average pool price from 2010-2015, and the high and low rates taken as the highest and lowest of the annual average rates from that period.
- For provinces with escalating rates, the nominal value was taken as the average rate between 2010 and 2016, and the high and low values as the highest and lowest rates during that period.
- No adjustments were made for inflation.

Table 7. Wind energy purchase rates

	Purchase rate ($/kWh)		
Province	**Nominal**	**High**	**Low**
BC	0.0902	0.1196	0.0710
AB	0.0591	0.0802	0.0333
SK	0.0838	0.1061	0.0600
MB	0.0879	0.1143	0.0615
ON	0.1226	0.1377	0.0859
QC	0.0797	0.0870	0.0650
NB	0.0879	0.1143	0.0615
NS	0.1021	0.1310	0.0910
PE	0.0780	0.1014	0.0546
NL	0.0879	0.1143	0.0615

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