Advances in wind power forecasting and power loss mitigation for cold climate operation

R J Kilpatrick\(^1\,^4\), S Hildebrandt\(^2\), N Swytink-Binnema\(^3\) and M Clément\(^3\)

\(^1\) CanmetENERGY-Ottawa, Natural Resources Canada, 1 Haanel Drive, Ottawa ON K1A1M1, Canada
\(^2\) Faculty of Mechanical and Manufacturing Engineering, University of Calgary, Calgary AB Canada
\(^3\) Nergica, 70 rue Bolduc, Gaspé, QC G4X 1G2, Canada
\(^4\) Author to whom correspondence should be addressed

Corresponding author’s e-mail: ryan.kilpatrick@canada.ca

Abstract. Key challenges related to operating wind farms in cold climates include lost power production due to ice accumulation on wind turbine blades, increased vibrations, and site safety due to the risk of ice throw. This paper presents the results of recent efforts to estimate the overall impact of cold climate impacts on wind energy in Canada, and describes the latest progress in developing an icing forecast model based on meteorological forecasts generated from the Environment and Climate Change Canada GEM-LAM mesoscale model. Two recent studies – an energy production analysis of 89 Canadian wind farms, and an operator survey of 43 wind farms – showed similar results in terms of estimated annual energy production losses due to cold climate, indicating that a good understanding of the magnitude of cold climate impacts on Canadian wind farms has been achieved. Improved forecasting offers the possibility to better manage icing events and other cold climate issues, reducing lost energy and improving overall system efficiency. The GPEO model being developed by Nergica aims to provide accurate forecasts of ice accumulation and energy loss from meteorological input data and is intended to be used by wind farms and utilities in an operational setting.

1. Introduction

Wind energy’s contributions as a reliable source of clean energy continue to grow, both in North America and globally. In Canada, wind energy has increased by 20% annually from 2008 to 2018 in terms of installed capacity and has become one of the lowest cost sources of new generating capacity in the country [1]. There are however multiple challenges associated with the operation of wind turbines in countries with cold climates such as Canada. Ice that accumulates on the wind turbine rotor, either from freezing precipitation (glaze) or by supercooled water droplets formed in clouds (rime) changes the shape and surface roughness of the airfoil profiles, affecting the aerodynamic efficiency of the turbine and reducing power production [2, 3, 4]. Production is further impacted if site safety is affected by the risk of ice throw or if turbine shutdowns are triggered. Ice accumulation can also increase vibrations and fatigue of wind turbine components [5, 6, 7]. Nearly all wind turbines operating in Canada and in many northern U.S. states have the potential to experience icing events, although the typical
production losses suffered by a wind farm from icing and other cold climate related challenges varies significantly by region.

Research on improving scientific understanding of meteorological icing, and mitigating the effects of cold climate on wind farm power production has been ongoing for several decades. The International Energy Agency (IEA) Wind Programme initiated Task 19, Wind Energy in Cold Climates, in 2001, and since then a number of expert group studies and best practices reports have been issued under this task [8]. The second edition of the Available Technologies report [9] includes detailed descriptions of various meteorological and accretion models for icing, and discusses the use of icing forecasts as part of an operations and maintenance strategy. Significant efforts have also been undertaken by the Nordic countries of Denmark, Finland, Iceland, Norway and Sweden to develop improved icing forecasting models as part of the IceWind initiative [10] and other collaborations.

Despite significant progress, gaps remain in translating advances in atmospheric science into products that can be readily applied by utilities, system operators and the wind energy industry. Natural Resources Canada (NRCan) has been active in the field of cold climate research for the better part of a decade in support of such efforts. While initial research focused on understanding the extent and severity of cold climate impacts on Canadian wind farms, more recently, attention has been directed toward developing reliable methods of forecasting ice accumulation and associated power loss on wind turbines based on meteorological conditions. In 2016, NRCan initiated a multi-year collaborative research program on advanced wind power forecasting with the University of New Brunswick (UNB), Environment and Climate Change Canada (ECCC) and Nergica, a renewable energy research organization located in Gaspé, Quebec. Major elements of the program include short-term wind power forecasting, ramp forecasting and icing forecasting, with the common goal being to adapt Canadian meteorological forecasts to provide improved value for wind energy applications. Overall, the goal of this work is to provide additional situational awareness to utilities with regards to short term and day ahead wind power forecasts.

The goals of this paper are two-fold: to review the work accomplished to date to establish the scope and quantify the impact of cold climate operation on Canadian wind farms; and to present a summary of progress on development of an operational icing forecast based on the ECCC numerical weather prediction (NWP) model for use by wind farm operators and utilities.

2. Quantification of the impact of cold climate operation

Two recent studies are summarized in this section. The first is a data-driven study of losses due to cold climate using power production data from 89 wind farms across the country. The second is a survey-based study of cold climate challenges for wind power projects across Canada, which draws on the experience of operators at 43 wind farms. The results of the two studies, together covering commercial wind farms in all ten provinces, are described and compared to further inform the impact of cold climate on wind energy in Canada.

2.1. Estimation of national cold climate losses

An assessment of 89 wind farms across Canada over the time period 2009-2016 was conducted by NRCan to examine the effect of cold climate on Canadian wind farm performance by estimating losses due to cold climate in the form of energy losses, financial losses and avoidable greenhouse gas (GHG) emissions. The intention of this assessment was to gain a better appreciation of the national and regional magnitude of cold climate-induced losses at Canadian wind farms, so that research and development efforts can be strategically directed towards mitigating these losses and improving cold climate performance where feasible. This study of 89 wind farms follows a previous study of 23 wind farms in Canada [11] and employs similar methodology.

The study was conducted using monthly wind farm production data obtained through the Wind Power Production Incentive (WPPI) and EcoEnergy for Renewable Power (EcoERP) federal incentive programs launched in 2002 and 2007 respectively. Under these programs, participating wind farms
submitted production data on a monthly basis for the first ten years of its operation. To estimate cold climate losses, actual wind farm electricity generation was compared to the expected generation based on turbine power curves and local wind resource data, on a monthly basis from January 1st, 2009 to December 31st, 2016, for each wind farm in the study group. The monthly losses from the winter periods were compared to those from the summer periods, with the summer periods assumed to have zero cold climate losses. Summer and winter periods were defined for this study as May 1st to October 31st and November 1st to April 30th respectively. The net difference in losses between the winter and summer periods was taken to represent the combined losses incurred from blade icing, cold temperature shutdown, limited access and any other winter impacts which together comprised the cold climate energy losses. Sufficiently detailed data on wind power curtailment at Canadian wind farms was not available at the time of this study and therefore losses attributable to curtailment could not be separated from other losses in the analysis. Losses from the study group were extrapolated to the national level in proportion to overall provincial wind energy generation. Production data was not available for every wind farm in every year of the study, since new wind farms entered the incentive programs and others exited after ten years. Representation in the study group ranged from a minimum of 34 wind farms and 1580 MW of installed capacity in 2009, to a maximum of 80 wind farms and 4260 MW of installed capacity in 2013. As a fraction of national installed capacity, the study group installed capacity reached a peak of 60% in 2012.

For months where actual production was available, monthly losses were calculated for each wind farm by subtracting the actual wind farm production from the expected energy generation for the wind farm based on local wind conditions and wind turbine specifications. Since on-site wind data was not available for this analysis, wind data from the closest Environment Canada weather station with sufficient data quality during the time period of interest was used as a substitute. In order to account for the distance between the weather station and the wind farm, the linear regression Measure-Correlate-Predict (MCP) technique [12] was applied. For each wind farm and for each year, cold climate losses were estimated as the difference between winter and summer losses in GWh. Figure 1 shows resulting estimated cold climate losses aggregated by year and by province, normalized by annual generation in the specific province and year.

While considerable variability was present from year to year, several trends are evident. The highest losses were observed in Quebec and New Brunswick where, as a fraction of annual generation, average cold climate losses over the study period were 6.7% and 10.0% respectively. Losses in the other Atlantic provinces were low to moderate. Losses in the Western provinces of British Columbia, Alberta and Saskatchewan were virtually negligible, while losses in Manitoba and Ontario were higher, typically in the range of 1-3%. The significant increase in losses observed in Ontario in 2015 and 2016 is suspected to be the result of increased curtailment following the introduction of dispatching of wind turbines by the Independent Electricity System Operator (IESO) in 2013, although this has not been rigorously tested. The average cold climate energy loss across all study years and provinces was 4.2%.
Figure 1. Normalized cold climate losses by province and by year.

Estimated financial losses due to cold climate impacts at the national level are shown in figure 2. On a normalized basis, New Brunswick showed the highest financial loss, at CAD $10,830 per GWh of electricity generation. On an absolute basis, however, Quebec showed the highest loss at CAD $51.9 million per year. The total national financial loss due to cold climate based on 2016 levels of energy generation was estimated to be CAD $107 million per year.

Figure 2. Left axis: Normalized financial losses due to cold climate, by province, averaged over 2009-2016. Right axis: Estimate of absolute financial losses due to cold climate using 2016 values of energy generation. Error bars account for the range of published Power Purchase Agreement (PPA) rates.
2.2. Survey of cold climate operations

While academic research on cold climate challenges for wind turbines is relatively widespread, the actual experience of industry players is less well documented. To overcome this knowledge gap, a survey-based study was recently conducted by the University of Calgary to directly engage with experienced wind farm operators. The Cold Climate Challenges for Wind Power Projects in Canada Survey [13] provided useful insights on cold climate challenges for project developers and operators, including regional differences in wind turbine icing, site safety accessibility impacts, and observed cold climate induced losses at commercial wind project sites.

The survey was distributed in the spring of 2017, with responses collected until December of that year. Overall, 43 wind power projects from across Canada participated in the survey, representing 13 unique operating companies and 3,540 MW of installed capacity, roughly 30% of Canada’s total wind power capacity at the end of 2017. Responses were only collected from wind farms with at least two years of operating data. The average rated capacity of participating projects was 82 MW, with a range from 4 MW to 350 MW. The average number of wind turbines at each project was 45, with individual projects ranging from 2 to 175 turbines. Survey responses were generalized into seven regions – Alberta, British Columbia, North Ontario, South Ontario, South Quebec, the Gaspé Peninsula, and the Maritimes, as indicated in figure 3(a).

The survey addressed a variety of aspects of cold climate operations, including general challenges, annual energy production (AEP) losses, turbine shutdown events, winter site accessibility, occurrence and severity of icing events, and ice detection and prevention approaches. Significant findings are briefly described here. Asked to identify significant challenges or risks faced by their project sites due to cold climate from a list of options compiled from literature [2], operators listed the following, with the percentage of operators listing the challenge in brackets: reduced power production (95%), ice throw risk (86%), turbine shutdowns (60%), increased vibrations (33%) and component damage (7%).

Average AEP losses due to cold climate compiled from survey respondents are shown in figure 3(b), aggregated by region. The number of survey responses gathered from each region is indicated below the region labels. Apart from the North Ontario region, where only one response was obtained, AEP losses were generally in line with the results of the wind energy production analysis described in Section 2.1. Losses in Alberta and British Columbia were low in both cases. The average loss in Quebec from the production analysis was 6.7%, slightly lower than the survey results obtained for the two Quebec regions (8.5% and 7.8%), while the average loss from the production analysis for the four Atlantic provinces taken together was 4.2%, slightly below the value of 5.8% for the Maritimes obtained from the survey. Survey results showed low AEP losses for South Ontario, reinforcing the possibility of curtailment being a potential driver of winter losses in the production analysis.

Figure 3. (a) Survey responses by region, (b) Average AEP losses due to cold climate by region compiled from survey responses.

Survey participants were also asked to indicate the method or methods of ice detection used, and the type of ice mitigation equipment installed at their wind farm, with results presented in table 1 and table
2 respectively. With regards to ice detection methods, the survey results indicate that market penetration for more sophisticated ice detection systems such as cameras and dedicated sensors is low, indicating a potential opportunity for technology developers if equipment costs are low enough to produce a reasonable return on investment. The majority of respondents did not employ any ice mitigation technologies. This held true even in regions that experienced significant icing-related power production losses. This presents a possible opportunity for improvement if advances in manufacturer and retrofit technology can yield lower system costs.

Table 1. Percentage of participating wind farms using a particular ice detection method

| Method                                      | Prevalence |
|---------------------------------------------|------------|
| Actual power vs. estimated power            | 83.7%      |
| Vibration analysis                          | 32.6%      |
| Heated vs. non-heated anemometers           | 20.9%      |
| Visual/sound inspection                     | 9.3%       |
| Cameras                                     | 2.3%       |
| Manufacturer supplied sensors               | 2.3%       |
| None                                        | 7.0%       |

Table 2. Percentage of participating wind farms using a particular ice mitigation technology

| Method                                      | Prevalence |
|---------------------------------------------|------------|
| No anti- or de-icing technology used        | 58%        |
| Hot air circulation in blades               | 26%        |
| Passive anti-icing coatings                 | 16%        |
| Pitching blades to sun                      | 2.3%       |

3. Progress on development of an operational ice forecasting model

Icing impacts both wind farm operations, as well as potentially power system operations in balancing areas that have a coincident high penetration wind in a territory that experiences icing events, such as Quebec. Thus, a reliable model for forecasting wind turbine ice accumulation and resulting power loss has multiple benefits. From the wind farm operator perspective, it enables more informed decisions on operational strategies to mitigate losses and optimize maintenance schedules, while from a system operations point of view, it can provide more accurate estimates of generator availability and production, ensuring most efficient use of electricity system resources. As the penetration of wind increases in regions prone to icing, the need for reliable ice forecasts is expected to increase.

Modeling ice thickness on rotating blades is a complex endeavour, given the number of parameters involved and the non-linear rates of ice accumulation and shedding. Significant efforts by researchers in Nordic countries have yielded several models for prediction of ice accretion and ablation on wind turbines as well as icing induced production losses [10, 14]. The present work involves development of an icing forecasting model using inputs from the ECCC meteorological forecasts that would be suitable for use in a Canadian context. Here, significant progress has been made to develop a transfer function to produce energy loss forecasts from observation data. Originally developed by Nergica under the name GLJM [15] with funding support from Natural Resources Canada, this model is now referred to as
GPEO, for “Modèle de Givre et de Pertes Énergétiques Opérationnelles” (Icing and Production Loss Model). Inputs to the GPEO model are obtained through specialized ECCC operational forecasts, and model outputs include ice accretion rates, total ice accumulation, and ice-related energy losses.

A schematic overview of the GPEO model is shown in figure 4. The latest iteration of the model GPEO comprises three ice accretion models (for freezing rain, in-cloud icing, and wet snow icing) based on models by Jones [16] and Makkonen [17], an ablation model that includes both melting and shedding of ice, and an ice-related energy loss model, which uses a transfer function to correlate ice accumulation on the cylinder with energy production loss on a wind turbine.

GPEO relies on input meteorological variables obtained from the Global Environmental Multiscale Limited-Area Model (GEM-LAM), a mesoscale model operated by ECCC with a horizontal spatial resolution of 2.5 km. The operational forecasts used by GPEO run four times per day, covering a period of 48 hours ahead. The first 24 hours of forecasts are at 30-minute intervals, while the last 24 hours are at 1-hour intervals.

Observation data used to develop and validate the GPEO model was obtained from Nergica’s experimental wind farm and test site located near Rivière-au-Renard, Quebec. The facility features two 2.05 MW Senvion MM92 CCV wind turbines equipped with standard weather sensors as well as specialized ice detection cameras, and two 126 m meteorological masts equipped with more than 30 meteorological sensors at fifteen different heights. Data from both turbine and met mast sensors have been used to validate the GPEO model.

![Figure 4. Schematic description of GPEO](image)

Figure 5 shows the performance of GPEO in modelling ice accumulation over the period of January to May 2018 in comparison to other ice detection methods, which included a Goodrich meteorological ice detector measuring ice thickness between heating cycles, nacelle-mounted ice monitoring cameras, double anemometry (heated and unheated) and a Combitech instrumental ice detector measuring accumulated ice mass. Compared to the Goodrich detector (top graph), GPEO successfully identified most meteorological icing periods, with some exceptions in early March. GPEO appeared to be less accurate at modelling instrumental icing periods (bottom graph), with several events being too short or too long, and several others missed, pointing to a need for an improved ice ablation model. The fact that each of the sensors measures different parameters related to icing, producing different icing detection signals, and are positioned in different locations (e.g. met mast vs. wind turbine) underscores the
difficulty in establishing a single reference signal for icing against which to compare the performance of the GPEO model. The accuracy of the GPEO icing forecast is also highly dependent on the accuracy of the ECCC input forecasts. Several icing events that were not well captured by GPEO could be attributed to an absence of icing conditions (e.g. precipitation or clouds) in the meteorological forecasts.

Figure 5. Meteorological and instrumental ice signals obtained from Nergica’s experimental wind farm and test site, Jan-May 2018.

A time series comparison of energy losses from GPEO and form observations, from January to May 2018 is shown in figure 6(a). The comparison shows that GPEO tends to exaggerate icing losses in both the positive and negative directions, showing over-prediction of icing losses over several weeks in December and January, and under-prediction throughout March. Estimation of icing losses is complicated by the Senvion MM92 turbine’s built-in Ice Operation Mode (IOM), which acts to automatically change turbine behavior through either blade pitching, power output reduction or full stoppage depending on the severity of the icing conditions detected.

Figure 6(b) provides a closer examination of an icing event taking place over a three day period in January 2018. The first part of the event is captured by GPEO with reasonable accuracy, whereas losses predicted by GPEO in the second half of the event were not observed in reality, indicating a mismatch between instrumental and rotor icing. These types of results suggest that further development of the transfer function is required, particularly with regards to ice ablation on the rotor, and the specific characteristics of the turbine controller should be taken into account. While the initiation of icing events is typically well captured by GPEO, improvements to the ice shedding model are required to better account for the different environmental conditions between a stationary cylinder and a rotating blade. Other planned near-term activities include the calculation of probabilities and uncertainties of icing and energy loss events, and the use of machine learning between ice accumulation and power loss.
Figure 6. Time series comparison of icing induced energy loss from turbine measurements and from GPEO model: (a) Four month period from January to May 2018, (b) Three day period from January 13-15, 2018.

4. Discussion and conclusions

Recent studies conducted to better understand the scale and magnitude of cold climate impacts and challenges at Canadian wind farms have demonstrated that icing and cold climate represent lost opportunities if such events negatively impact wind farm operations. These losses can take the form of lost revenue for wind farm owners, and lost energy that is potentially replaced by carbon-emitting sources of generation such as natural gas. In discussions with utilities and system operators, uncertainty surrounding the implications of an icing event imply that they must hold additional reserves in their system to account for unexpected loss of production from wind farms that experience such an event. As the penetration of wind and other renewables increases, the negative implications of an unexpected loss of power due to an icing event may approach “contingency” conditions; absent a tool to forecast such events, system operators may hold additional reserves unnecessarily, or curtail wind farms in advance of a potential icing event.

In the near term, Nergica is planning to further develop the transfer functions between icing accumulation and energy loss, and conduct additional on-site validation of the model results with wind
farm operational and observation data. The main goal of the research program is to provide operational icing forecasts to Canadian utilities, representing a supplementary tool to assist in the operation of a power system with increasing amounts of variable renewable generation. In order to accomplish this, NRCan hopes to further support the validation and testing of the model within actual utility settings.

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