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BROOKFIELD RENEWABLE ENERGY

ICE THROW RISK ASSESSMENT FOR DIXVILLE PEAK

MAY 29, 2015

GRANITE RELIABLE WIND FARM

NEW HAMPSHIRE

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DOCUMENT HISTORY

ISSUE	DATE
A	May 8, 2015
B	May 22, 2015
C	May 29, 2015

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INTRODUCTION

The purpose of this study is to provide Brookfield Renewable Power with an ice throw risk assessment from wind turbines within the Dixville Peak portion of the Granite Reliable Wind Farm in northern New Hampshire. Currently, a 396 m (1300 ft) safety buffer exists in which public access is discouraged due to the risk of impacts from ice fragments potentially being thrown from the wind turbines during the cold season. How this buffer size was originally determined is unknown to AWS Truepower, however it is not inconsistent with some general industry guidance that was available at the time the wind farm was permitted.

This assessment takes into account the available literature on ice throw mechanisms and trajectory determination as well the wind farm-specific turbine specifications and meteorology. The key result provided is an estimate of the maximum potential throwing distance of an ice fragment from a turbine on Dixville Peak.

FORMS OF WIND TURBINE ICING

There are three main types of icing observed at elevated terrain sites in the northeastern US: glaze, hard rime, and soft rime. The differences in icing types play a role in how ice accumulates on, and is shed by, wind turbines. Glaze is a relatively smooth, hard, and transparent form of ice and is the most dense (~900 kg/m^3). It is deposited either by a freezing rain or drizzle event, or by exposure to supercooled cloud (or fog), especially during windy conditions, when the air temperature is slightly below freezing (0° C). Rime ice occurs under similar in-cloud conditions but at lower air temperatures. While riming entraps more air than glaze ice and is thus opaque or white in appearance, the freezing rate of cloud droplets on surfaces determines whether the rime is of the hard or soft variety. A slower freezing rate produces hard rime (density of 600-900 kg/m^3) which still has strong adhesive properties, although not as strong as glaze. A faster freezing rate entraps more air to form soft rime, which is the most brittle and least dense form of icing (<600 kg/ m^3).

Rime ice tends to form on the upwind side of structures and on the leading edge of blades; ice feathers that grow into the wind are a common signature. Glaze is more evenly distributed and adapts to the shape of the object; icicles can form as well.

All three icing types occur at Dixville Peak, with rime icing being the most frequent due to the site's high elevation and exposure to low-level cloud. Average cloud base height (above sea level) for the region has been observed to be in the range of 760-915 m (2500-3000 ft) (Warren et al., 1986). Low-level cloudiness occurs most frequently from late fall to early spring across the mountains of New England. At Dixville Peak, the frequency of low-level cloud during the cold season is on the order of 15% (Bailey, 1990).

DESCRIPTION OF DIXVILLE PEAK TURBINES, WINDS AND ICING FREQUENCY

The Granite Reliable wind project is located in northern New Hampshire, roughly 18 km southeast of Colebrook, NH and 38 km north-northwest of Berlin, NH. The wind farm is located in a region of complex terrain and is comprised of a series of small ridgelines and isolated features covering a north-south distance of approximately 12 km. The project consists of 33 Vestas V90-3MW turbines with a rotor diameter of 90 m and a hub height of 80 m. The turbines have a rotational speed of 18.4 rpm at rated speed and a maximum blade tip speed on the order of 89.4 m/s (200 mph). The turbines are positioned in small clearings within a region of dense forest. Figure 1 presents the locations of the 7 turbines on Dixville Peak, which are the turbines of interest for this analysis. These turbines are at a mean base elevation of 986 m, about 80 m higher in elevation than the array-average.

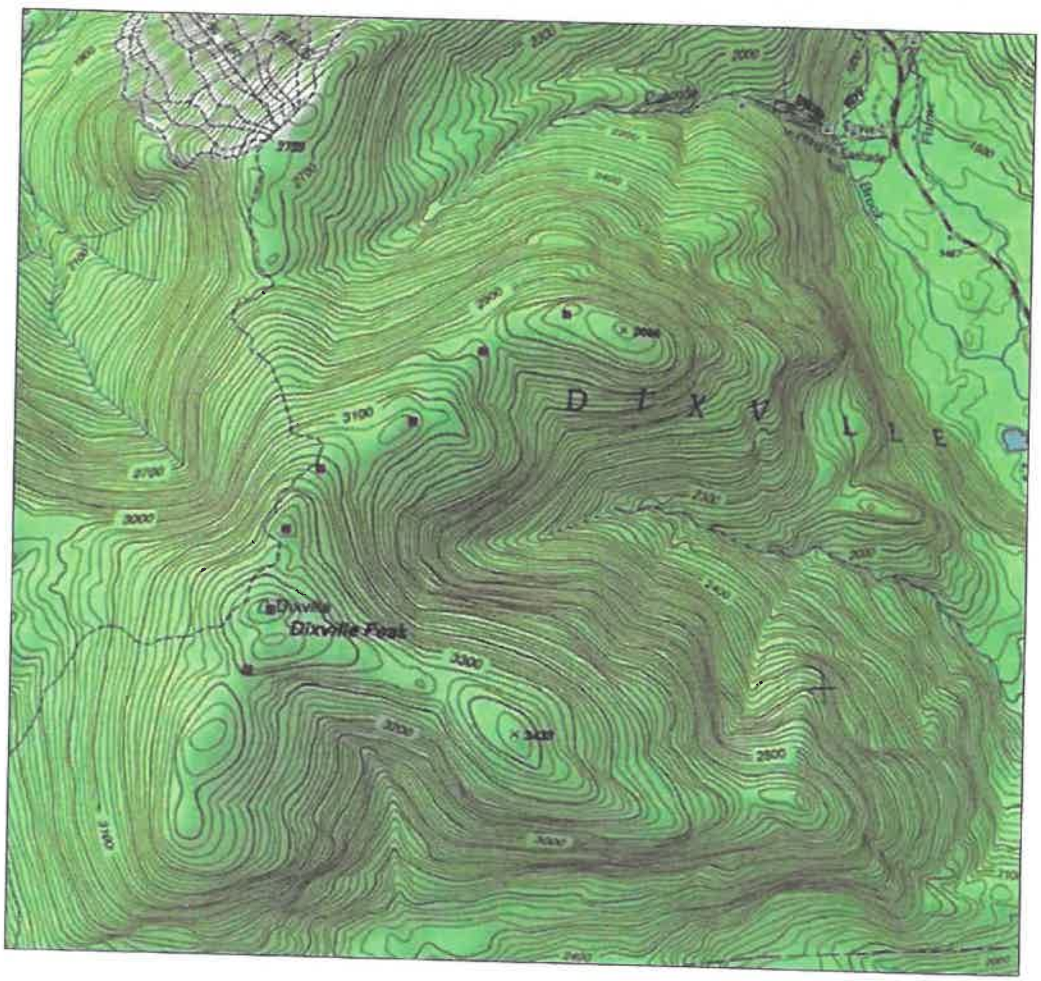

Figure 1. Granite Reliable Project – Dixville Peak Wind Turbines

The 80-m array-average wind speed of the 33 Granite Reliable wind turbines was estimated previously by AWS Truepower to be 8.71 m/s (19.5 mph). The predicted mean wind speed for the 7 Dixville Peak turbines is substantially higher, about 9.93 m/s (22.2 mph), since they are at a higher mean elevation. On a seasonal basis, the strongest winds are normally observed during the late fall to springs months. The mean wind speeds during the November to April timeframe average about 17% higher than the site's annual mean.

The annual wind frequency and energy by direction plot (wind rose) for Mast 0040, one of the previous on-site masts with more than two years of data, is presented below in Figure 2. Also plotted in this figure is the wind rose from the same mast for the icing season, defined as the months of November through April. The wind rose indicates a predominant west-northwest to northwest wind flow, which is dictated both by the site's high elevation and the directional orientation of the ridgeline that the project is built on. The annual and icing season wind roses are similar and indicate that approximately 70% of the energy available from the wind is observed in the west through northwest direction sectors.

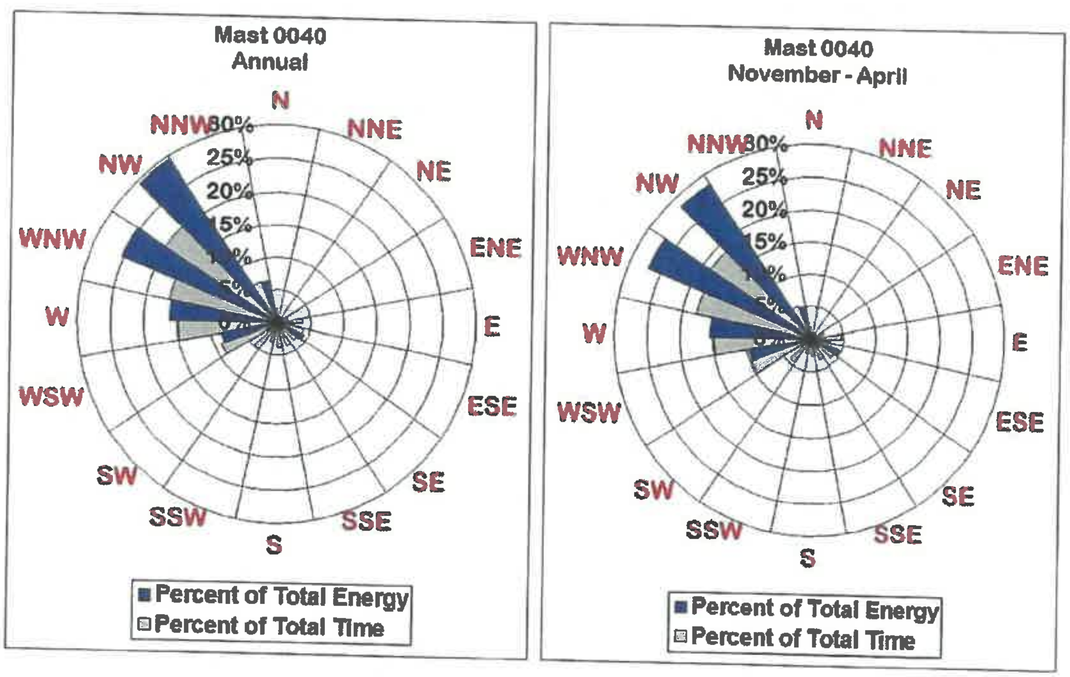

Figure 2. Granite Reliable Mast 0040 Annual and Icing Season Wind Roses

A wind speed frequency distribution, which provides the number of observations within 1 m/s (2.2 mph) wind speed bins, was created for the Dixville Peak turbines at hub height for the November to April period using 10-minute wind speed data from Mast 0040. The estimated distribution is presented in Figure 3. The results suggest that 80 m wind speeds in excess of 20 m/s (44.8 mph) can be expected to occur about 8% of the time near these turbines during the icing season. Wind speeds in excess of 25 m/s (56.0 mph; e.g. the turbine cut-out speed) are expected to occur just less than 2% of the time.

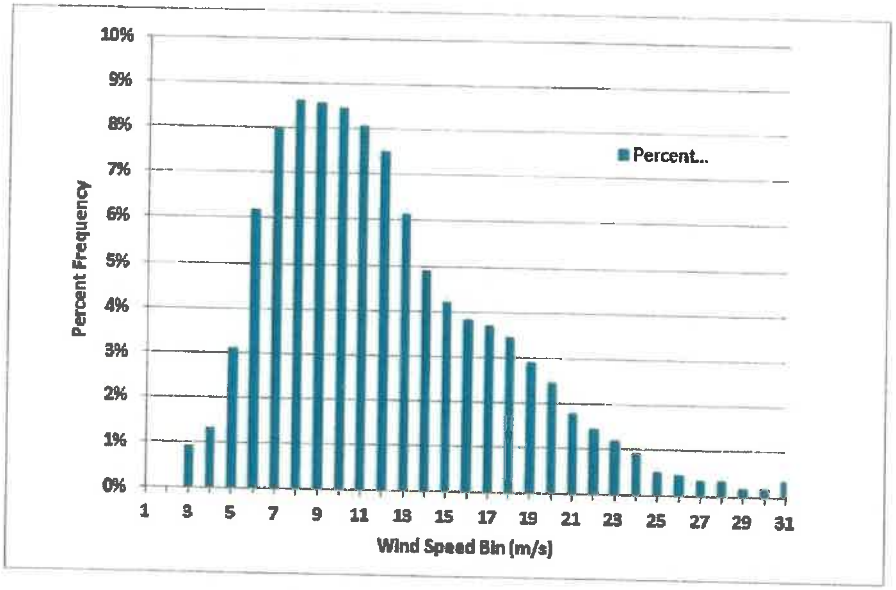

Figure 3. Dixville Peak Wind Turbines Estimated Wind Speed Frequency Distribution (November – April)

The frequency of icing at the Granite Reliable site has been estimated using the on-site tall tower measurements, specifically by analyzing the readings and response of the wind vanes and anemometers. Wind vanes tend to be more sensitive to icing and often ice over more quickly than cup anemometers since their overall movement is inherently more limited when compared to a rotating anemometer. Icing on the anemometry can sometimes be harder to detect, for example when a small buildup of ice on the tower's anemometry causes a roughly uniform slowdown in the recorded wind speeds on all anemometers. For this study, the frequency of icing on Mast 0040 was determined using the wind vane data during the winters of 2007-2008 and 2008-2009. The average icing frequency on the mast during these two winter seasons was about 11.5%. This value is in good agreement with the results from an icing frequency map generated by AWS Truepower for the United States and southern Canada.

INDUSTRY METHODS FOR ESTIMATING POTENTIAL ICE THROW DISTANCES

The estimation of ice throw distances from structures such as wind turbines has been addressed by various studies using theoretical approaches which take into account such factors as ice characteristics, wind conditions, and structural dimensions. Figure 4 is an illustration of an ice fragment trajectory (from Biswas et al., 2011), which is a function of four primary factors: the properties (shape, mass, density) of the ice fragment itself, the turbine dimensions and rotational speed, the position of the blade and the location of the fragment on the blade when it detaches, and the wind speed. These factors combine to affect the total distance the ice fragment travels and where it ultimately lands. When an ice fragment detaches from a moving blade, it will initially have the same speed and direction of the blade; the speed is greatest at the blade tip and slowest near the root. The ice trajectory will be in-plane, or lateral, such that ice will be thrown upward if the blade is ascending, or downward if descending. The ambient wind will also play a factor by blowing the fragment downwind. The downwind distance will depend on the wind speed, the position and movement of the rotor at the time of release, and the mass and shape of the fragment. The shape and area of the fragment will also influence the drag forces, which will be larger for fragments having a large cross-sectional area such as a sheet of ice.

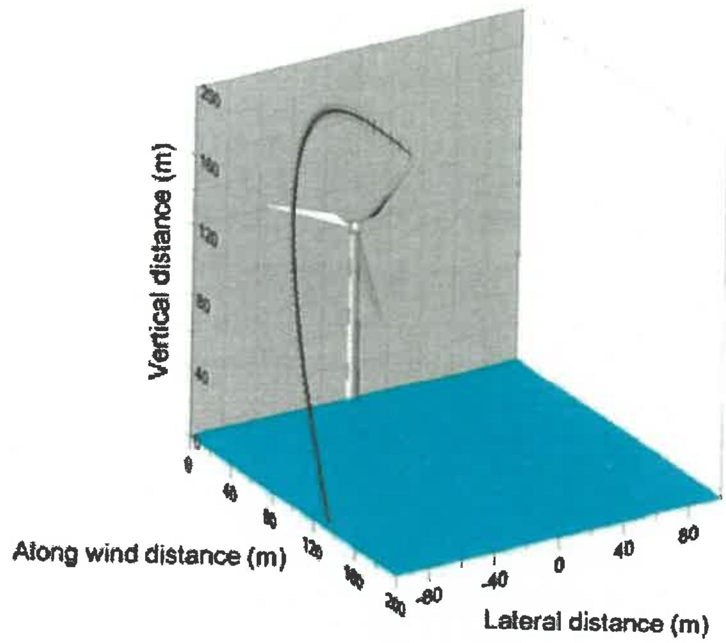

Figure 4. Illustration of an ice fragment trajectory (from Biswas et al., 2011)

For the simulated case shown in Figure 4, the ice fragment detaches from a blade tip at an angle of 45° (from horizontal) as it rotates upwards; the wind speed was 15 m/s (33.6 mph). The rotor diameter is 90 m, the hub height is 100 m, and the rotor's rotational speed is 14.5 rpm. Assuming a typical drag force, the fragment lands 127 m (417 ft) downwind and 100 m (328 ft) laterally, or 162 m (531 ft) from the base of the turbine (assuming flat ground). Figure 5 presents an array of potential trajectories from the blade tip (the most conservative scenario) using the same turbine assumptions. The plot assumes that the reader is looking upwind and the turbine is rotating counter-clockwise.

Figure 6 shows the general pattern of ground strike locations for ice fragments ejected from the blade tip at different rotational blade locations. The pattern approximates an oval, with all ice spreading laterally downwind of the turbine. The width of the oval depends on the hub height wind speed, with stronger speeds transporting fragments further downwind. The ice striking the ground closest to the turbine occurs when the blade is near the bottom of its rotation. The farthest flights of ice occur when the blade is rotating upward within 30-45° of horizontal; these fragments land downwind and off to the side of the turbine but not directly downwind.

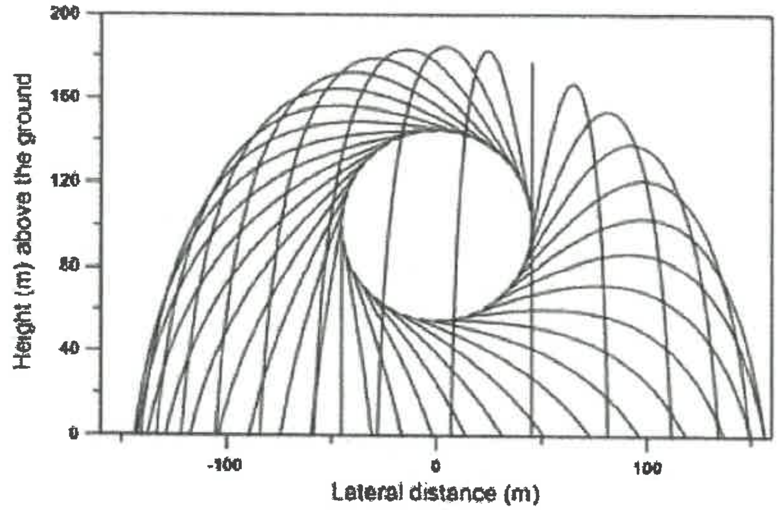

Figure 5. Simulated trajectories of ice fragments launched at various angles (from Biswas et al., 2011).

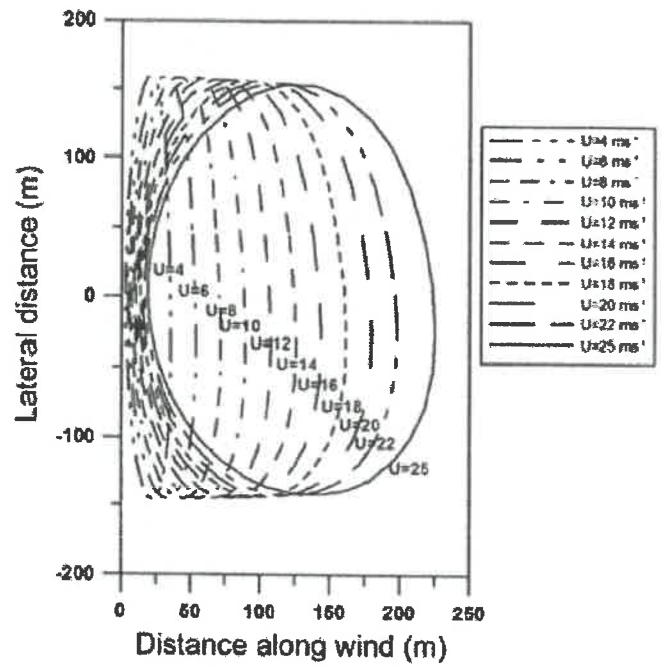

Figure 6. Simulated impact locations for ice fragments released from the blade tip at different blade positions, for different hub height wind speeds (from Biswas et al., 2011).

There are a limited number of published field studies of ice throws from wind turbines. In a 2003 study, a survey (Seifert et al., 2003) of European wind farm operators found that ice fragments are rarely thrown beyond 125 m (410 ft; see Figure 7); the majority of turbines at that time had rotor diameters of 40 m or less. Data available from a Tacke TW600 wind turbine near Kincardine, Ontario, Canada for six winter seasons noted icing on 13 occasions, with ice fragments observed up to 100 m (328 ft) from the tower (Leblanc, 2007). In a 2-year field study of a 600 kW Enercon E-40 wind turbine in the Swiss Alps, Cattlin et al. (2007) observed a maximum ice throw distance of 92 m (302 ft). For this body of cases, thrown fragments weighed 0.1 to 1.1 kg (0.2 to 2.2 lb), with some observations noting a tendency for the ice to shatter in flight. Guidance from research in northern Europe recommends that signs be located at least 150 m (336 ft) from a turbine in all directions (T. Laakso et al., 2010).

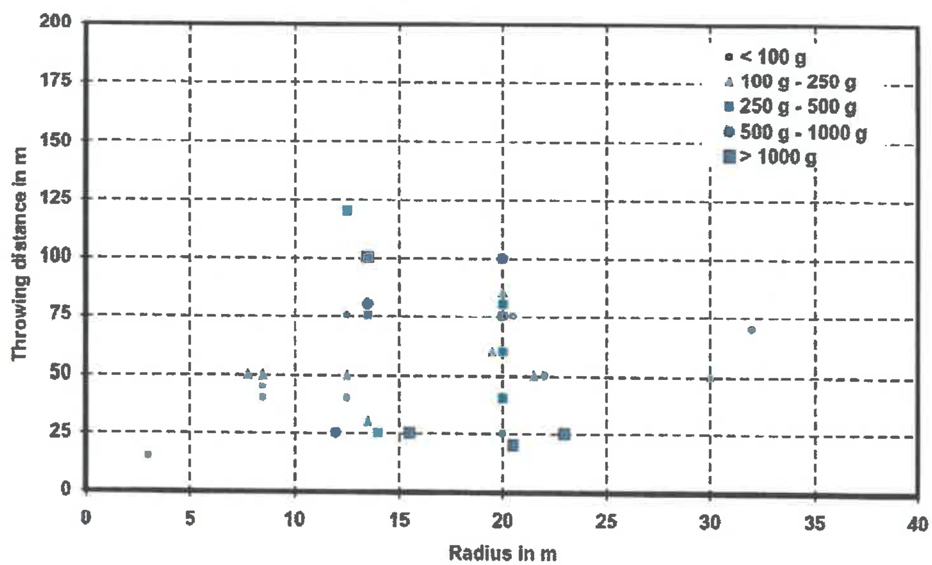

Figure 7. Observed ice fragments from the Wind Energy Production in Cold Climate database. (from Seifert et al., 2003)

In an assessment of ice throw risk potential in Ontario Province, Leblanc (2007) calculated the distance-dependent probability per square meter of ground that a single ice fragment strike would occur for an 80 m hub-height turbine and 80 m rotor diameter. The analysis employed a Monte Carlo simulation of 100,000 ice fragments shed from the blades of a turbine. A critical distance of 220 m (722 ft) from a turbine was determined, beyond which the probability of an impact from thrown ice diminishes rapidly. The assumed mean wind speed was 8.0 m/s (17.9 mph). Using the technique developed by Biswas et al. (2011), Taylor et al. (2012) calculated ice throw distances for a range of turbine models and hub heights assuming a 10 m/s (22.4 mph) mean wind speed for a potential project in Ontario, Canada. The determined maximum throw distances were between 175 m (574 ft) and 195 m (640 ft). Other results from this study show a probability of an ice strike per square meter of ground to be less than one in tenthousand at 100 m (328 ft) from a turbine, with 3.1% of all fragments landing beyond 100 m, and 0.02% beyond 200 m (656 ft). These results compare well with those from Biswas et al. (2011) where the sensitivity of ice shed distances for varying model parameters, including wind speed and blade tip speed, was examined. They indicate that the maximum distance a 1 kg ice fragment could travel is 200 m (656 ft; Jowitt, 2013).

A simplified empirical equation was introduced by Seifert et al. (2003) to estimate the maximum throwing distance of ice from a rotating wind turbine on flat terrain:

$$d = (D + H) * 1.5$$

where d = maximum throwing distance in meters; D = rotor diameter (m); and H = turbine hub height (m). When compared to observations and simulations of maximum ice throw, this equation provides a reasonable if not conservative prediction. For the simulations presented in Figures 1 through 3, the equation predicts a maximum ice throw distance of 285 m (935 ft), which is somewhat higher than the longest distance (~260 m, or 853 ft) calculated for a wind speed of 25 m/s (56.0 mph). For the 2003 Seifert survey, the equation determines the maximum distance to be 150 m (336 ft; assuming a 60 m hub height and 40 m rotor diameter), which compares to the 125 m (410 ft) observed value. In the field study in the Swiss Alps by Cattlin et al. (2007), the observed maximum ice throw distance of 92 m (302 ft) compared to a predicted maximum of 135 m (443 ft) using the equation. This equation has also constituted guidance used by GE Energy, the certifying agencies Germanischer Lloyd (GL) and Deutsches Windenergie-Institut (DEWI) (Wahl and Giguere, 2006), Lloyd's Register Consulting (Bredesen et al., 2014), and the Massachusetts Department of Environmental Protection (2012).

PROBABILITIES OF LAND STRIKES FROM THROWN ICE

The concept of expressing ice fragment strike probabilities within a square meter area of ground as a function of distance from a turbine in one year was introduced in 1997 (Tammelin et al., 1997) as part of a European Union research program. The program was named Wind Energy Production in Cold Climate (WECO). The ice throw assessment guidelines produced by this program were based on a combination of numerical modeling and observations. The numerical modeling involved Monte Carlo simulations of numerous ice build-up and shedding scenarios.

An application of this approach is shown in Figure 8. An analysis was performed by GL Garrad Hassan in 2010 for a Vestas V112 turbine (hub height 84 m, 112 m rotor diameter) on a ridgeline in Vermont. The analysis assumed a frequency of 25 days of icing per year. Two sets of analysis were conducted for fragments weighing either 0.5 kg or 1.0 kg: one for ice falls when the blades are stationary, and the other for thrown ice when the blades are rotating. For thrown ice, it was estimated that 90% of events would occur within 160 m (525 ft) of the turbine. At this distance the probability of a ground strike from a thrown ice fragment is once every 100 years. At 260 m (853 ft) the probability is once every 1000 years, and at 290 m (951 ft) the probability is approximately once every 10,000 years. This last distance is equivalent to the maximum ice throw distance using the equation above.

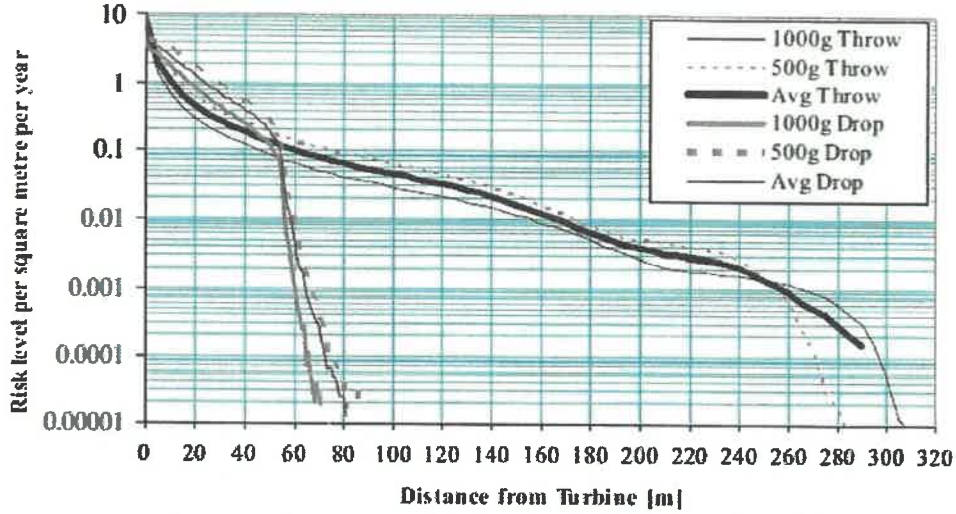

Figure 8. Ice Fragment Strikes Estimated Per Unit Area Per Year (from Boucetta and Heraud, 2010)

When the equation is used for the Dixville Peak turbines, the maximum ice throw distance is calculated to be 255 m, or 836 ft. This value is consistent with the trajectory analysis approach developed by Biswas et al. (2011) and is significantly less than the 396 m (1300 ft) setback currently observed by the project. Note that this distance assumes flat terrain; where the terrain slopes downward away from the turbines, as is the case for Dixville Peak, the actual distance when following the contour of the ground will be somewhat longer (up to 5% longer for the steepest slopes). If a simple 2-dimensional setback radius is overlaid onto a topographic map, it will automatically encompass the areas where the actual ground distance is longer (relative to flat ground). Given that wind directions at Dixville Peak blow out of the northwest and west the large majority of the time, the area most vulnerable to ice throws is to the southeast and east of the line of turbines.

It is important to recognize that the maximize ice throw calculations are based largely on modeling approaches that have not been rigorously validated by field data. Wind farms are generally unmanned, and surveys of ice throws are not routine practice. Although the field observations that do exist agree with current prediction techniques, the observational database remains relatively small and limited to between one and six winter seasons at any one site. Hence, a case can be made to apply a safety margin to prediction results until substantially more field observations are accumulated.

On the other hand, it is equally important to note that the ice throw analyses are by nature conservative and assume worst case conditions. For example, the maximum ice throw calculations apply to the densest form of ice detaching from the blade tip, which is the fastest part of the blade. Most of the blade ice, however, will form on the inboard portions of the blade. Further, ice accretion on blades degrades airfoil performance, so the turbine rotor is unlikely to reach its design rotational speed when heavy icing is occurring. Lastly, icing often causes rotor imbalances and vibration sensor alarms that will automatically stop turbine operation. Without the centrifugal force imparted by blade rotation, ice shedding will impact the ground only in close proximity to the turbine base.

As for probabilities of ground strikes by thrown ice as a function of distance from a turbine, the analysis by Boucetta and Heraud for the Green Mountains (Figure 8) project is expected to be fairly representative of Dixville Peak. The turbines on Dixville Peak have a somewhat lower hub height and slower tip speed, but the wind speeds are stronger. The estimated frequency of icing events is comparable. Therefore, at a distance of 255 m (836 ft) from a turbine, the probability of an ice ground strike (under worst case scenarios) is on the order of 1 in 1000 years. There is unlikely to be a significant cumulative effect of ice strike probability at a particular location exposed to multiple turbines. This is because of the existing turbine spacing of approximately 230-390 m (755-1280 ft).

SUMMARY AND CONCLUSIONS

At Brookfield's request, AWS Truepower conducted an assessment of the potential ice throw distance from seven wind turbines within the Dixville Peak portion of the Granite Reliable Wind Farm in New Hampshire. Based on local observations, icing conditions are estimated to occur approximately 11% of the time during the cold season. While a range of icing types are expected, the predominant forms are expected to be hard and soft rime, which have a lower density than glaze ice. Due to the frequency of low-level cloud, the primary icing process is the deposition of supercooled cloud droplets on turbine blades. The assessment reviewed industry literature from Europe and North America regarding icing and shedding mechanisms for wind turbines, observations of ice throw distances, and techniques to calculate ice throw distances under different assumptions and weather scenarios.

The maximum ice throw distance for wind turbines on Dixville Peak is conservatively predicted to be 255 m (836 ft) when expressed horizontally from the base of the turbines. This value assumes worst case conditions during which a dense ice fragment (e.g. glaze) is shed from the fastest moving portion of the blade at the optimum point of its rotation during very windy conditions to achieve the longest trajectory. This trajectory would result in a ground impact downwind and lateral to the plane of the turbine rotor. The probability of an ice impact within a square meter area of ground at this maximum ice throw distance is estimated to be on the order of once every 1000 years.

Under normal operating conditions, it is expected that the large majority of ice falls and throws from the turbines will occur within 100 m of the tower base. Given the site's prevailing winds from the west and northwest, the areas most vulnerable to ice impacts will be to the east and southeast of the turbines. However, because winds at the site occasionally blow from other directions, the possibility exists for ice impacts to occur in most directions surrounding the turbines.

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