



255 Fuller Road, Suite 274  
Albany, NY 12203

Voice: 518-437-8655  
Fax: 518-437-8659  
E-mail: bbailey@awstruewind.com

TO: Andy Raubvogel, SDKS  
FROM: Bruce Bailey  
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RE: Icing Analysis for UPC Sheffield Wind Energy Project

At the request of Shems Dunkiel Kassel & Saunders, on behalf of UPC Vermont Wind, AWS Truewind has prepared the following report regarding the proposed Sheffield Wind Farm. This report addresses the following topics:

- The expected incidence of icing at the proposed Sheffield wind energy project in northeastern Vermont.
- The estimated reduction in energy production due to icing effects on wind turbine operations.
- The probability of ice being thrown from operating wind turbines in terms of the risk to humans in proximity to the turbines when ice has accumulated on the turbine blades.

Icing of structures on elevated terrain in the northeastern United States is caused by two types of events: rime and freezing precipitation. Rime icing results from the direct exposure of objects to wind-driven cloud droplets when the air temperature is below freezing. Since the frequency of cloud is a function of elevation, higher terrain is more susceptible to rime icing during the cold season than lower terrain. Freezing precipitation is also known as freezing rain or drizzle, with the resulting ice coating on exposed surfaces sometimes called glaze. This phenomenon occurs when a warm (above freezing), precipitating air mass flows over a subfreezing air mass in contact with the ground. Thus areas of lower elevations are more susceptible to freezing precipitation.

For a given location on elevated terrain, the overall frequency of icing is not the sum of the individual frequencies of rime and freezing precipitation events. This is because both icing types sometimes occur at the same time. In other words, elevated terrain that is experiencing freezing precipitation (falling from a warm layer above) may also be immersed in a subfreezing cloud layer. For the purposes of this study, it is assumed that such concurrency occurs for half the freezing rain/drizzle events.

### Rime Icing

The expected frequency of rime icing at the Sheffield project site can be ascertained from an examination of regional low-level cloud observations. Two government-run weather stations—one located 30 miles to the southwest at Morrisville, VT (elevation 234 m) and the other 55 miles to the northeast in Sherbrooke, Quebec (elevation 305 m)—were selected to represent the cloud climatology for the project area. Both stations observe and record cloud coverage and

cloud base elevation every hour throughout the year. The Morrisville station was selected to represent the Sheffield project during southerly and easterly wind flow conditions, while the Sherbrooke station was selected for westerly and northerly wind flow conditions.

The elevation range of interest for cloud base is approximately 900 m (above sea level) and below. This elevation threshold was determined by identifying the base elevations of the proposed turbine locations (625-780 m) and adding 122 m of height to account for the total turbine structure height (78 m tower plus half the blade diameter of 87 m). In actuality, depending on a particular turbine's elevation, cloud base elevations within and below the range of 747-902 m corresponds to the elevations spanned by the turbine blades.

The cloud climatology analysis examined a seven-year period (1998-2004) and defined a low cloud event as one that consists of at least five-eighths cloud coverage (encompassing "broken" and "overcast" conditions) at a base height of either 900 m and below, or 700m and below. The two heights were selected to bracket the range of cloud base elevations most closely associated with the maximum and minimum wind turbine structure heights. These low cloud events were further grouped by air temperature: above freezing and below freezing. Air temperatures at cloud base height were estimated by applying a representative lapse rate (change in temperature with height) to the observed surface air temperatures at the two weather stations. To determine the lapse rate a third mountain weather station located at Mount Orford, Quebec, approximately 50 miles to the north, was utilized. This station is located at an elevation of 851 m and is representative of the Sheffield project. As this station does not record cloud data, it could not be used for this portion of the analysis. Temperature comparisons between Mount Orford and the two lower elevation cloud-observing stations suggest an average lapse rate of  $-1.5^{\circ}\text{C}$  per 1000 m rise in elevation. This rate is lower than the typical lapse rate above a sloped surface reported in the literature of  $-4.0^{\circ}\text{C}$  per 1000 m. This is likely due to the fact that the lapse rate was calculated using ground base temperature readings while the literature lapse rate utilizes free flying balloons. As a conservative measure, both lapse rates are used in this study.

Table 1 presents the results of the cloud frequency analysis for the project area. The data values indicate the monthly and annual percent frequencies when cloud base is observed to intersect the elevations of interest when cloud temperatures are below freezing. As expected, the highest frequencies of freezing cloud occur from December through March, with a significantly lower incidence during the shoulder months of October, November, and April. The frequency of subfreezing cloud at 900 m and below is approximately double that for 700 m and below: 2.7% vs 1.2%. In addition, higher frequencies of subfreezing clouds are found at both elevations for the steeper lapse rate. On an annual basis at the steeper lapse rate, subfreezing cloud can be expected 3.5% of the time (306 hrs) at 900 m compared to 1.7% (149 hrs) at 700 m.

These results compare favorably with a 1990 study that analyzed low-cloud frequencies as a function of elevation across the northeastern United States (reference: *B. Bailey, 1990: The Potential for Icing of Wind Turbines in the Northeastern U.S., Proceeding of Windpower Conference, Washington, DC, American Wind Energy Assoc.*). As presented in this study, the northern area of Vermont and New Hampshire, between the Green Mountains and White Mountains, cloud base frequencies in the 700-900 m elevation range occur approximately 5-9% of the time, across all air temperatures. Since regional data indicate that temperatures are below freezing approximately one-third of the time at this elevation, the frequencies of subfreezing cloud would be 1.7-3.0%, which is virtually the same as that determined from the two weather stations.

**Table 1. Frequency of subfreezing cloud within Sheffield project area at the 700 m and 900 m elevations for two lapse rates**

Month	% time with base of subfreezing cloud below 700 m elevation		% time with base of subfreezing cloud below 900 m elevation	
	-1.5°C/1000m lapse rate	-4.0°C/1000m lapse rate	-1.5°C/1000m lapse rate	-4.0°C/1000m lapse rate
1	4.1	4.5	8.2	9.3
2	2.2	2.5	6.2	7.2
3	2.8	3.3	5.5	7.1
4	0.8	1.2	1.9	3.1
5	<0.1	<0.1	<0.1	0.2
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	<0.1	0.2	<0.1	0.2
10	0.6	0.9	0.9	1.7
11	1.2	1.7	2.8	4.8
12	2.6	2.8	7.2	8.7
<b>Annual</b>	<b>1.2</b>	<b>1.7</b>	<b>2.7</b>	<b>3.5</b>

### Freezing Precipitation

The frequency of freezing rain or drizzle was also assessed utilizing the Morrisville and Sherbrooke weather stations. The incidence of these forms of freezing precipitation averaged 21 to 39 hours per year, depending on the station. Since this type of precipitation occurs more frequently in valleys where cold air is trapped while warmer, moist air blows into the region at higher elevations, these frequencies are likely to be greater than what is actually occurring at elevations higher than the reporting stations. Nonetheless, they reflect actual incidences observed within the immediate region. Therefore, a midpoint value of 30 hours per year (0.34% frequency) of freezing precipitation was assumed for the project site.

As discussed previously, the combined frequency of potential icing conditions—including subfreezing cloud and freezing rain/drizzle—is not likely to be additive because the presence of low-level cloud is normally indicative of a moist and often precipitating air mass. In other words, elevations of 700 to 900 m that are experiencing freezing rain/drizzle may be within subfreezing cloud at the same time. Therefore, for the purposes of this study, it is assumed that this is the case for half the freezing rain/drizzle events. Consequently, the annual frequency of potential icing from freezing cloud and/or precipitation is expected to be as high as 3.8% (336 hrs) at the 900 m elevation, and 2.0% (179 hrs) at 700 m. Thus, across both elevations an average icing condition of 3% is assumed.

### Implications for Energy Production Losses

The accumulation of ice on the blades of a wind turbine can reduce the turbine's power output. The power reduction results from the modification of the blade airfoil, making it less efficient

aerodynamically. As ice accumulates (typically on the blades' leading edge for rime events), power output gradually decreases to a point where the turbine will automatically shut down because its energy output does not agree with the expected output as determined by a heated anemometer (i.e., wind speed sensor) mounted atop the turbine's nacelle (or housing). This automatic shut down feature is one of several incorporated into a turbine's control software to prevent a turbine from running outside its operating design conditions.

The degree to which an icing event may impact energy production at the Sheffield project depends on:

- The amount of ice deposited on the turbine blades
- The characteristics of the deposited ice and its impact on airfoil aerodynamics
- How long the ice lasts after being deposited
- The wind speeds while ice is present on the blades.

There is insufficient site-specific information to quantify each of these factors and determine an exact energy loss value. However, a set of assumptions can be used to estimate the average impact of icing on energy production.

First, the average 3% annual icing exposure should be qualified since icing is concentrated during the cold portion of the year, which is also windier than the warm portion. Based on an analysis of monthly wind speed data, approximately 62% of the annual wind power is produced during the six-month cold season (November to April). This means that icing has a disproportionately higher influence on energy production from wind turbines than might be assumed from the fact that the icing season spans approximately 50% of the year. Consequently, the maximum potential of icing impact on power production increases from 3% to approximately 3.7% (i.e.,  $(62\% \div 50\%) \times 3\%$ , or a 24% increase). Of this frequency, what is the actual impact on power production, since a wind turbine can still operate during icing conditions?

#### Duration of Rime Icing Events

In the previous cloud frequency analysis for the two weather stations, the average duration of a subfreezing cloud event was determined to be short-lived at both elevations: between 2.5 and 2.7 hours. Nearly half the events (49%) lasted only one hour, 80% of events were 3 hours or less in duration, and 95% of events were seven hours or less in duration; the longest event lasted 26 hours. These statistics indicate that most rime icing events are of very short duration and consequently deposit very little ice. It logically follows that very light icing would not significantly reduce wind power output because the airfoils are not significantly compromised.

#### Impacts of Icing Events on Power Production

In order to estimate the overall impact of icing on power production based on these findings, we conservatively assumed four categories of icing conditions, each accounting for a quarter of all icing events. Each category assumes the following reductions in power output: 0%, 25%, 50%, 100%. In other words, for a quarter of icing events, power output remains at full output, while for each of the other quarters, power output is 75%, 50%, and 0% of full. For all icing events, this translates into an effective net power reduction of 56% (i.e., the average of the four power output levels). The conservatism applied here is intended to reflect not only the influences on power production while the ice is being deposited, but also the influences of the ice remaining on the blades for variable but undefined periods after the ice deposition period.

When applied to the 3.7% relative icing exposure on wind power, the effective net power reduction of 56% results in an estimated annual energy loss due to icing for the wind plant of

2.1%.

### Implications for Ice Shedding

The principal mechanisms of ice removal from wind turbines following an icing event include melting, shedding, and sublimation. The removal mechanism for any given icing event will vary with weather conditions (temperature, wind speed, solar radiation, humidity) and with the operational status of the turbines. Industry experience indicates that for the large majority of icing events, ice removal will result from melting and gravitational shedding due to partial melting, whereby the ice falls off the tower and blades directly to the ground below. Only in rare cases is there the potential for accumulated ice to be thrown a significant distance from a turbine by a rotating blade. This is because a) icing deposits will rarely be heavy enough to be thrown; b) significant icing will cause the blades to be inefficient airfoils, reducing their ability to operate, and may cause the wind turbine to automatically shutdown on a control alarm; and c) ice deposited in thin sheets (as on broad blade surfaces) are usually brittle, easily shattered, and have poor trajectory properties.

The risk of an ice throw is therefore a function of multiple variables:

- The probability of ice build-up on the blades
- The probability of ice fragments being detached from a blade
- The wind and weather conditions existing at the time
- The operational status and logic of the turbine (a function of turbine control strategies & alarms, wind speed, and grid availability).

Should there be an ice throw, the risk of a person being hit and injured by an ice fragment thrown from an operating wind turbine also depends on:

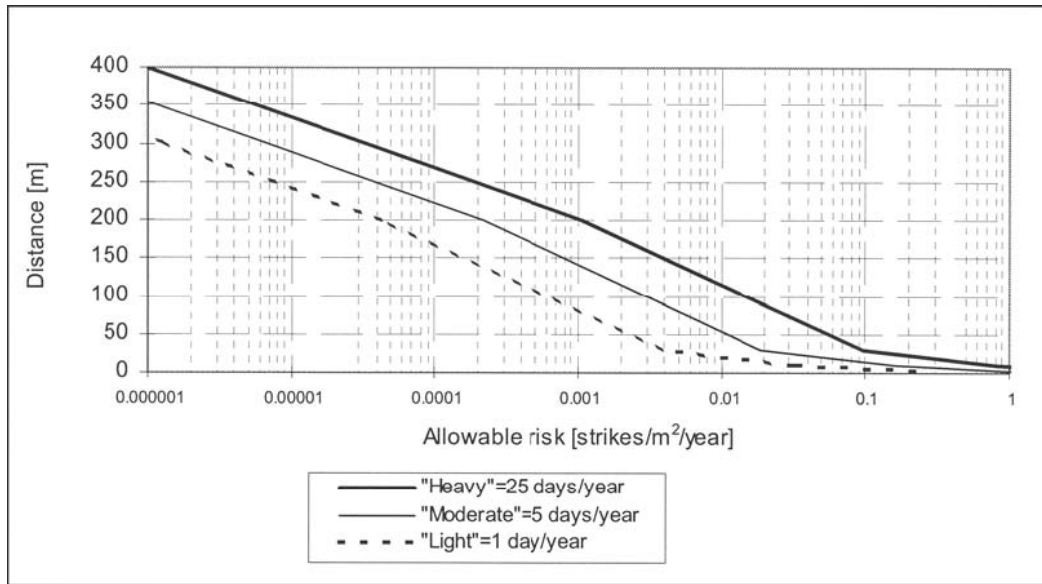
- The point where the detached ice fragment lands (function of wind speed & direction, rotor speed, radial position on blade, blade azimuth, etc.)
- The mass, shape, and speed of the fragment
- The structural integrity of the fragment (i.e., may it break up in flight?)
- The probability of a person being in time at the exact point of landfall.

The topic of ice shedding and throws from wind turbines, and human strike probabilities, has been addressed in a comprehensive study by the consulting firm Garrad Hassan in conjunction with the Finnish Meteorological Institute and Deutches Windenergie-Institut as part of a research project on the application of wind energy in cold climates (WECO) (Reference: *C. Morgan, E. Bossanyi, and H. Seifert, 1998: Assessment of Safety Risks Arising From Wind Turbine Icing. Proceedings of BOREAS IV Conference, Hetta, Finland*). The study confirms the points made above regarding principal ice shedding mechanisms and ice throw risk factors. The study relied on numerous field observations which indicated that most ice shedding consists of ice fragments being dropped off, rather than thrown from, the rotor. The study also conducted an assessment of potential ice throw distances during exceptional events and the probabilities of a person being struck by an ice fragment under specific operational conditions. A chart summarizing the results of this study is shown below. Based on our weather analysis, the “Moderate” event most closely approximates the conditions expected at the Sheffield location.

For a moderate icing location, the maximum achievable distance (i.e., worst case scenario) for ice to be thrown was conservatively considered to be approximately 350 m (1150 ft). If a person is always present within proximity of the turbine during icing conditions, and no control method is incorporated into a wind turbine’s control logic to prevent an ice throw, the risk of that person

being struck by an ice fragment is estimated to be greater than one in 1 million. This risk is less than the risk of a person being struck by lightning (approximately 1 in 750,000; reference: *H. Blatt, Our Geologic Environment, Prentice Hall, 1997, p. 35*). The existing forest cover would significantly reduce this risk further since ice fragments would likely hit trees.

Probability of an ice fragment strike as a function of distance from a turbine operating without any icing control function, under three ice formation scenarios (from Morgan et al., 1998)



Numerous control technologies exist to further reduce the potential risk of ice throw events. These include: (1) Heated wind speed sensors and improved control strategies so that the turbines are unlikely to operate during significant icing events; (2) Ice detection sensors can also be used as a redundant measure to control turbine operations when icing is accumulating on objects or exceeds a given thickness. When such technologies and practices are observed, the probability of ice fragments falling a significant distance from a turbine becomes, for practical purposes, insignificant.

However, ice shedding can pose a risk to people located directly below and adjacent (i.e., within 50 m) to the wind turbines and their blades when they are iced. Maintenance personnel should be instructed on safety procedures when such conditions occur.

### Summary

This report has identified the expected types and frequencies of turbine icing at the proposed Sheffield wind energy project. Rime will likely be the predominant form of ice at this site given the elevated locations. Based on regional observations, weather conditions contributing to icing are expected to occur between 2.0% and 3.8% of the time within the project, depending on elevation. Overall, the average expected frequency of icing on turbines is 3%, resulting in an annual energy loss from icing of 2.1%. The regional weather observations also indicate that the large majority of icing events will be short-lived and light in magnitude. As observed at other wind projects located in cold climates, ice is usually removed through shedding mechanisms whereby fragments fall to the ground in close proximity to the turbine. The potential for ice being thrown significant distances from a modern turbine is extremely low and is mitigated relative to earlier generation turbine technologies by advanced control algorithms and the use of heated and other specialty sensors.