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A Framework for Characterizing the Risk of Ice Fall and Ice Throw from Small Wind Turbines

September 2022

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U.S. DEPARTMENT OF ENERGY

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Abstract

Small wind turbines rated up through 100 kW in size are typically deployed as distributed energy resources. Their proximity to populations, buildings, and other infrastructure can generate safety concerns regarding ice throw (ice detaching from operational turbines) and ice fall (ice detaching from a turbine during standstill or idling) even when the turbines are not installed in cold climates. This paper presents a data-driven approach to characterize and mitigate the potential risk from icing on small wind turbines. A step-by-step framework is created by identifying how likely it is that an icing event will occur each year through publicly available data, estimating the distances at which ice could throw or fall from the turbine through simple methods that rely on easily accessible data, defining a community's risk context, and establishing risk management practices. An example in Richland, WA illustrates how the ice throw and ice fall calculations can be applied. This framework is intended to be used by small wind turbine developers and installers as they address communities' safety concerns.

Acronyms and Abbreviations

IEA	International Energy Agency
WIceAtlas	Wind Power Icing Atlas

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1.0 Introduction

Small wind turbines rated up through 100 kW in size are typically deployed as distributed energy resources. As such, they are located close to the point at which their energy is consumed. Their proximity to populations, buildings, and other infrastructure can generate safety concerns regarding ice throw (ice detaching from operational turbines) and ice fall (ice detaching from a turbine during standstill or idling) even when they are not installed in cold climates. Using a data-driven approach to characterize and mitigate the potential risk from icing on small wind turbines can address communities' safety concerns.

Icing research has largely been limited to wind farms, large-scale wind turbines, and climates with high probabilities of icing (Bredesen et al. 2015; Biswas, Taylor, and Salmon 2012; Szász, Leroyer, and Revstedt 2019; Alsabagh et al. 2012) with a more limited number of studies considering small wind turbines (Drapalik, Zajicek, and Purker 2021). Many models for estimating ice throw and ice fall rely on statistical methods to map the probability of ice fragments reaching specific distances from the turbine (Rogers and Costello 2022; Lennie et al. 2018). These bodies of work have helped inform international best practices for wind farms in cold climates. These best practices include the use of site-specific wind data in at least 10-minute intervals in statistical models to measure the probability of ice fragments reaching those distances; modeling the trajectories of ice fragments with gravity and aerodynamic drag considering turbine parameters, operational mode, and site topography; and understanding long-term representation of icing conditions at the site (Krenn et al. 2018). While existing work offers methods and approaches for understanding the risks that can be useful for small wind installers and developers, further exploration is necessary to determine which methods are most suitable for small wind installers given their often-limited budgets and access to data, short timelines for development, and means for applying complex models or conducting icing campaigns. This is especially true when those installations are located outside of cold climates.

As such, this paper presents simple methods to calculate ice throw and ice fall and provides an approachable, cost-effective framework to understand the associated risks for developing small wind turbine projects. This framework is not intended to replace formal risk assessments such as the standard approach in DIN ISO 12100 (International Organization for Standardization 2010) or the guidelines in *International Recommendations for Ice Fall and Ice Throw Risk Assessments* (Krenn et al. 2018). The methods presented within this report are particularly useful for first order analyses when considering risk associated with icing on small wind turbines and deciding if a formal risk assessment is necessary.

To understand the risk that ice fall and throw from a small wind turbine might create for the surrounding community, the framework presented in this paper addresses the following questions:

- How likely is it that an icing event will occur each year?
- In the event that ice accumulates on turbine blades, at what distances could ice throw or fall occur?
- How is risk characterized, and what is the risk context? How does the risk generated by potential turbine icing compare to other risks that the community accepts?
- How can risk be managed? Is further assessment of icing required?

Key definitions required to answer these questions and the context for this paper are presented in Section 2, and data-driven approaches to answer each of these questions are presented in Sections 3 through 5. Section 6 presents conclusions.

2.0 Context and Definitions

To assess the potential risk of icing on small wind turbines, it is important to understand what risk is, as well as distinguish between types of icing phenomena.

2.1 Risk

Risk is most often defined:

Risk = Likelihood (probability of occurrence) x Consequence (impact of occurrence),

where the likelihood is the probability that an impact from an event occurs and the consequence is a representation of the impact that such an occurrence can have. This definition of risk allows decision makers to understand how risk can be minimized. For example, if the probability of occurrence is high but the impact of occurrence can be decreased, then the overall risk may become permissible. Risk is often compared to other known risks, so decision makers can determine if the level of risk is acceptable.

This risk formula can be used to directly quantify the potential risk generated by ice fall and throw by calculating the relative frequency of ice fragments landing in the vicinity of the wind turbine and the subsequent likelihood of being hit by one of those ice fragments (i.e., likelihood) and the mortality rate of being hit by one of those fragments (i.e., consequence). The results of such computation can be compared to known risk for individuals and society. However, these equations rely on statistical models that may be impractical for small wind installers to implement, particularly when the installations are outside of cold climates.

The framework for understanding risk within this report draws upon the principles embodied within the risk formula but instead examines the likelihood of icing conditions at a turbine location and the maximum potential distances that ice could fall or be thrown from the turbine based on simple methods; the probability of occurrence and impact of occurrence are not directly calculated. Calculating the likelihood of icing conditions at the turbine location and the maximum distances that ice could fall or be thrown allows installers to better understand what consequences (i.e., hazards) may need to be mitigated. These parameters can be determined through data sources that are often publicly available and easily accessible.

2.2 Icing

For ice throw or fall to occur, ice must first accumulate on the turbine. Ice buildup on wind turbine rotor blades is influenced by wind speeds, air temperature, cloud height, and liquid water content combinations (Seifert 2004). Rime and glaze icing as well as freezing rain, freezing drizzle, and wet snow can all generate ice buildup on turbine rotor blades (Lehtomaki et al. 2018). There is then the potential for that ice to fall or be thrown from the turbine. Ice throw is characterized by the projection of accumulated ice from rotating blades, while ice fall occurs when ice drops from a stationary turbine. Table 1 provides the definitions of the different icing terminology applicable to this report.

Table 1 Icing terminology adapted from Lehtomaki et al. 2018.

Term	Definition
Rotor Icing	Period of time during which ice is present at the rotor blades of a wind turbine
Meteorological Icing	Period of time during which meteorological conditions allow ice accretion (i.e., active ice formation)
Instrumental Icing	Period of time when ice is present on a structure
Rime Icing	Supercooled liquid water droplets from clouds or fog that are transported by the wind and freeze immediately when they hit a surface
Glaze Icing	Caused by freezing rain or freezing drizzle, and forms a smooth, transparent, and homogenous ice layer with a strong adhesion on the structure
Wet Snow	Partly melted snow crystals with high liquid water content that become sticky and are able to adhere to the surface of an object
Ice Fall	Ice detaching from a turbine during standstill or idling
Ice Throw	Ice detaching from wind turbines rotating at a nominal speed

3.0 Icing Events, Ice Throw, and Ice Fall

While the referenced risk formula defined in Section 2 requires that the probability of occurrence (i.e., the probability of ice fall or ice throw generating harm) be calculated through a statistical model, this framework starts with identifying the frequency of meteorological icing periods that take place over the course of a year instead. If the meteorological conditions rarely align for ice to build-up on the wind turbine, then there is minimal potential for ice accumulation and subsequently a smaller risk associated with ice throw or fall from the turbine.

3.1 Estimating the Likelihood of Icing

There are various ways to identify the likelihood of icing events at a given location. A general understanding of the region's climate is useful in gauging the frequency of icing. If the general climate in the region does not lend itself to meteorological icing, icing maps and publicly available data sources are suitable for estimating probability of icing. Referencing icing maps and weather data can help a developer understand if there is a severe icing threat in the area and serve as a first-order assessment to answer the question: how likely is it that an icing event will occur each year? If wind turbines are installed in cold climates where icing conditions occur for a large duration of the year, those sites require a more detailed understanding of the frequency and duration of icing events.

3.1.1 Icing Data and Classification

The International Energy Agency (IEA) Wind Task 19 – Wind Energy in Cold Climates (Lehtomaki et al. 2018) developed an icing class metric. The IEA ice classes range in scale from 1 to 5, with 1 being the lowest probability of icing and 5 being the highest, and provide a metric for probability of icing. Each class is defined by meteorological icing frequency, instrumental icing frequency, and the expected reduction to energy production, as shown in Table 2. While potential reduction in energy production from icing is of interest to many project developers, that issue is beyond the scope of this framework. Meteorological icing in Table 2 represents the percentage of time during a year that the meteorological conditions that create icing events occur, and instrumental icing indicates the percentage of time during a year that ice is present on instruments or structures at the site of interest, including wind turbines.

Table 2 IEA icing classes with respect to meteorological icing, instrumental icing, and reduced production.

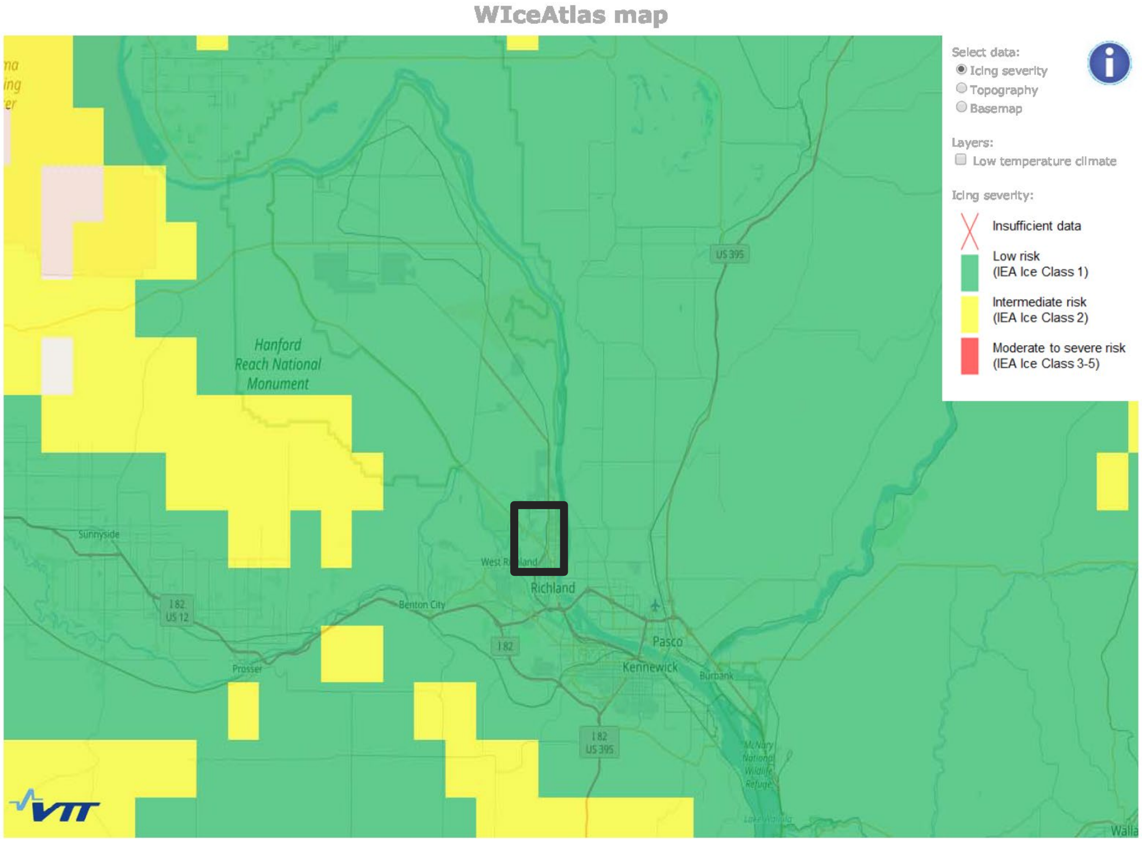
IEA Ice Class	Meteorological Icing	Instrumental Icing	Reduced Production
	% of year	% of year	% of annual production
5	>10	>20	>20
4	5–10	10–30	10–25
3	3–5	6–15	3–12
2	0.5–3	1–9	0.5–5
1	0–0.5	<1.5	0–0.5

Small wind installers can use publicly available icing maps to determine the likelihood of icing at small wind turbine locations. For example, VTT Technical Research Centre of Finland's Wind Power Icing Atlas (WIceAtlas) uses the IEA ice classes in its publicly available map (VTT Technical Research Centre of Finland). The public WIceAtlas map displays the likelihood of icing across the globe, based on cloud base height and temperature, and includes observations from 1979 to 2015 to develop long-term icing trends. These estimates are calculated at 150 meters above ground. Although this height is well above the height of small wind turbines, the estimates can be considered a conservative upper bound. Icing maps are also available for specific regions.[1]

Another way to approximate the likelihood of icing is to review the frequency of freezing rain in the area. Freezing rain data are collected by meteorological stations (Hanford Meteorological Station 2019a), such as those at airports. That frequency data can then be compared to the ranges in each of the ice classes to determine which class is applicable to the location of interest.

3.1.2 Example

To understand how to use the WIceAtlas map within the risk framework, consider the region shown in Figure 1. Figure 1 shows the WIceAtlas map in the area surrounding Richland, WA, USA. While some of the area falls into IEA Ice Class 2, the specific area of interest (indicated by the black box) falls in IEA Ice Class 1, the lowest icing probability class, indicating that meteorological icing could occur for 0.5% of the year, instrumental icing could occur for less than 1.5% of the year, and icing could create a gross annual production decrease of up to 0.5%.


Select data:
● Icing severity
○ Topography
○ Basemap

Layers:
☐ Low temperature climate

Figure 1 WIceAtlas icing map in the area surrounding Richland, WA, USA. The area of interest is marked by the black box.

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[1] For a list of regional icing maps, readers are directed to Table 3 in Lehtomaki et al. 2018.

In addition to the WIceAtlas map, there is also a local meteorological station in the area that has collected data on freezing rain in the area since 1946. Again, note that local airports and certain federal agencies, such as the National Oceanic and Atmospheric Administration in the United States or the European Organisation for the Exploitation of Meteorological Satellites in Europe, may also have weather data resources.

The long-term data from the meteorological station indicates an average of six days a year when freezing rain occurs near the site of interest (Hanford Meteorological Station 2019a). It is important to acknowledge that this data set of freezing rain only indicates the presence of freezing rain on a given day, not the duration of the freezing rain each day. For example, the freezing rain could have lasted for only an hour on a given day, or it could have lasted for the entirety of the day. Thus, the actual persistence of ice during these events is unknown but a conservative estimate can be calculated at 1.64% of the year (i.e., 6 out of 365 days), which would fall into IEA Class 2. The data show there are few times each year where icing buildup on a turbine in the area could occur. Although this slightly deviates from the bounds for Ice Class 1 identified for the location in the WIceAtlas Map, it does help confirm that the overall likelihood of the types of icing that generate concern for wind turbines is relatively low in the area. As such, a small wind turbine installed at the location is still unlikely to experience ice throw or fall.

3.2 Simple Methods to Calculate Ice Fall and Throw

The next step in the framework is to estimate potential distances at which ice can fall or be thrown from the turbine. In other words, in the event that ice accumulates on turbine blades, at what distances could ice throw or fall occur? Simplified calculations that estimate the maximum distance that ice can fall or throw from the turbine can inform small wind turbine developers on possible setbacks to mitigate potential hazards or serve as a reference when establishing other safety protocols for the area surrounding the turbine.

Generally, distances further away from the turbine are less likely to have ice throw or fall reach them, whereas distances closer to the turbine have a higher probability of experiencing ice throw or ice fall. Therefore, to understand the risk associated with ice throw or fall, the maximum distance parameter for each can be estimated. These maximum distances should not be taken as direct recommendations for setback requirements but should instead be holistically considered in the development of risk mitigation options.

3.2.1 Calculating Ice Throw

The potential maximum distance that ice can be thrown by a turbine is estimated by

$$dt = 1.5 \times (D + H), \qquad \text{Eq.1}$$

where *dt* is maximum throwing distance (in meters [m]), *D* is the rotor diameter of the turbine (m), and *H* is the hub height of the turbine (m) (CanREA 2020; Tammelin et al. 2000). This formula was developed through a combination of models and observed distances for ice throw to determine a safe distance from the turbine when ice has the potential to be shed from the machine.

Empirical data indicates that ice throw has only been found at 68% of this maximum distance (Bredesen, Drapalik, and Butt 2017). Therefore, the presented formula is thought to be an overestimate, and multiplying the result from the formula (Eq. 1) by 68% provides a more realistic distance for maximum ice throw. This estimate was largely informed by a large-scale wind turbine, but there is no indication that the distances would be different for smaller turbines. Rather than multiplying the maximum distance for ice throw equation (Eq. 1) by 68%, some agencies have begun to rely on a distance of *H* + *D* when designing their safety measures given the overestimation generated by the original equation (Goransson et al. 2017).

3.2.2 Example

Continuing with the example for the location in Figure 1, the maximum ice throw in Richland, WA,USA can be estimated for different turbines. Three different turbine models are assessed: the Bergey Excel 10, the Eocycle EOX S-16, and the NPS 100-24. Hub heights are assumed to be 43 m for the Bergey Excel 10 and the Eocycle EOX S-16, as this was the most frequently reported small wind turbine hub height in the *2017 Distributed Wind Market Report* and could be a feasible height for either of the evaluated turbines (Orrell et al. 2018). The hub height for the NPS 100-24 is assumed to be 37 m per the turbine manufacturer's specifications. Table 3 shows each turbine's rotor diameter and the calculated maximum ice throw (Eq. 1).

Overall, the potential maximum range for ice throw from the evaluated turbines is between 75 and 92 m when the original maximum distance formula is used, with the NPS-100 at the upper end of that range. The rotor diameter of the NPS-100 is much larger than that of the Bergey Excel 10 and the Eocycle EOX S-16, increasing the potential ice throw distances. Table 3 also shows the empirical maximum ice throw (maximum ice throw multiplied by 68%), the maximum ice throw normalized by tip height,[1] and the empirical maximum ice throw normalized by tip height.

Table 3 Ice throw potential for three turbines in Richland, WA, US.

	Bergey 10	**Eocycle EOX S-16**	**NPS-100**
Hub Height (m)	43	42	37
Rotor Diameter (m)	7.0	15.8	24.4
Tip Height (m)[2]	46.5	49.9	49.2
Maximum Ice Throw (m)	75.0	86.7	92.1
Empirical Maximum Ice Throw (m)	51.0	59.0	62.6
Maximum Ice Throw Normalized by Tip Height	1.6	1.7	1.9
Empirical Maximum Ice Throw Normalized by Tip Height	1.1	1.2	1.3

3.2.3 Calculating Ice Fall

In addition to ice throw, ice can also fall from turbine blades. The turbine's height, the rotor diameter, and the wind speed inform the maximum distance that ice can fall from the turbine. The maximum distance is estimated by

$$df = v \ (D/2 + H)/15, \qquad \text{Eq. 2}$$

where *df* is the maximum falling distance, *v* is wind speed at hub height (m/s), *D* is the rotor diameter (m), *H* is the hub height (m), and 15 is based upon empirical measurements (Tammelin et al. 2000; CanREA 2020). This formula is conservative, and the probability of ice fall outside this distance from the turbine is unlikely (CanREA 2020).

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[1] Many setback requirements are defined relative to a turbine's tip height (U.S. Department of Energy Wind Energy Technologies Office 2007). Each distance is divided by the turbine's tip height to normalize the value.

[2] Tip height = hub height plus rotor radius.

3.2.4 Example

The ice fall calculation requires a wind speed at hub height, so calculations can consider a range of wind speeds. For example, both the mean wind speed and the maximum wind speed can be evaluated to give a sense of maximum distances for ice fall under different conditions at the turbine site. The maximum wind speed may be reserved for when a conservative, worst case scenario estimate is needed. The average wind speed at 40 meters in Richland is 3.81 m/s (Hanford Meteorological Station 2019b). The highest likely wind speed is approximately 16.5 m/s, with a frequency of 0.1% of the year (Hanford Meteorological Station 2019b).

Table 4 shows the ice fall distance (Eq. 2) at mean wind speed, ice fall distance at maximum wind speed, and ice fall at maximum wind speed normalized by tip height. Note that even at the highest wind speeds at this location, the ice fall distances are less than the ice throw distances, and the ice fall distances at the mean wind speed are far less than the ice throw distances shown in Table 3.

Table 4 Ice fall potential for three turbines in Richland, WA, US.

	Bergey 10	**Eocycle EOX S-16**	**NPS-100**
Hub Height (m)	43	42	37
Rotor Diameter (m)	7.0	15.8	24.4
Tip Height (m)	46.5	49.9	49.2
Ice Fall Distance at Mean Wind Speed (m)	11.8	12.7	12.5
Ice Fall Distance at Maximum Wind Speed (m)	51.1	54.9	54.1
Ice Fall at Maximum Wind Speed Normalized by Tip Height	1.1	1.1	1.1

4.0 Potential Consequences and Risk Characterization

Once the likelihood of icing events is characterized and the maximum distances for potential ice throw and fall are estimated, the associated risk to the surrounding community within those distances can be considered. These consequences include potential injury, damage to buildings or equipment, or even death generated by ice striking people or infrastructure. If there is significant foot traffic or sensitive infrastructure well-within the maximum distances for ice throw or fall, they need to be documented and considered when determining best approaches for managing and mitigating risk. Considering these hazards help characterize the risk and understand the risk context in which the turbine exists. These are largely influenced by the community in which the turbine is located. Through such consideration, other risks the community accepts in the area can be compared to that of ice throw and ice fall from the small wind turbine.

Although this is not a one-to-one comparison, nearby trees and buildings, although stationary, generate risk from ice fall during icing events as well. What level of tolerance does the community have for those structures? How does this compare to the potential risk generated from icing on the small wind turbine? Beyond risk generated from icing on any given structure, many daily risks, such as driving, are tolerated. Thus, part of understanding risk should include a comparison to risk generated by existing infrastructure. Such a comparison helps contextualize the risk, setting reasonable expectations with respect to development, and paving the way for a practical approach to siting the turbine and establishing mitigation approaches. Engaging the community, exchanging knowledge, and understanding concerns are key to achieving this in practice.

5.0 Managing and Mitigating Risk

Because it is not possible to control meteorological conditions that could lead to ice throw and ice fall, most risk mitigation is about reducing the probability of a negative consequence. As such, risk can be managed by the local community by reducing the probability of a negative consequence occurring.

One way to do this is by siting turbines away from infrastructure or people at distances deemed safe. Forecasting and monitoring weather to predict when there is an elevated level of risk is also a mitigation option. If forecasted meteorological conditions are likely to create the potential for icing, the turbine could be temporarily shut down to mitigate the risk associated with ice throw and fall. The risk is higher for the surrounding area during that period of time compared to time periods when conditions do not allow for icing. That is to say, risk is not constant over time.

Many other options are available to help mitigate risks as well. These include ice monitoring and warning systems, sign and light warning systems, text message warnings, perimeter fencing around the site's critical area, and websites detailing safety information (Swart, Kristiansen, and Bredesen 2019). If the probability of icing, the potential consequences, or the combined risk is deemed too high, further assessment through a more formal icing assessment and risk analysis may be necessary.

Overall, risk is commonly deemed acceptable when there is an inverse relationship between potential levels of damage and the likelihood of occurrence. For example, a turbine installed in an area with a high likelihood of icing events (i.e., IEA Ice Class 5) may only create a low risk from ice throw or fall if there is no infrastructure or human activity within the maximum throw distances. A similar relationship exists between high levels of damage and low likelihoods of occurrence. This relationship is critical for small wind turbines installed in distributed applications given that they are often sited near populations and infrastructure. If there are very few times during a year when icing occurs, but infrastructure is within maximum distances for ice throw or fall, the overall risk to the community may remain minimal with sufficient mitigation. The likelihood of icing occurrence, the expected level of damage that could occur from ice striking, or both together could still exceed a community or developer's risk threshold, but established mitigation practices can help manage that risk.

6.0 Conclusion

A data-driven framework to characterize potential risk from ice throw or fall from a small wind turbine allows decision makers to determine appropriate mitigation techniques and siting practices. This framework walks a decision maker through a series of questions:

1. **How likely is it that an icing event will occur each year?** To answer this question, reference icing maps, such as VTT's WIceAtlas, and other meteorological data available for the area. If the data indicate there is little chance of icing at your location, the overall risk that ice throw and ice fall will create a hazardous environment is likely minimal with mitigation practices put into place. During active icing, that level of risk is elevated, but when icing conditions are not present, the risk is non-existent.
2. **In the event that ice accumulates on turbine blades, at what distances could ice throw or fall occur?** Performing simple calculations to estimate the maximum ice throw and ice fall provides the context to determine the risk to surrounding populations and infrastructure.
3. **How is risk characterized, and what is the risk context? How does the risk generated by potential turbine icing compare to other risks that the community accepts?** If a turbine is located in an area with a higher chance of icing and is close to infrastructure or populations, the decision maker must consider the community's risk tolerance through community engagement processes and ensure safety measures are put in. Some situations may not require any adjustment to the proposed installation given the inverse relationship between probability of occurrence and potential consequences. Regardless, safety should always be prioritized and if the wind turbine installation crosses a risk threshold, additional mitigation plans should be adopted.
4. **How can risk be managed? Is further assessment of icing required?** Most efforts to manage and mitigate risks caused by icing involve reducing the probability of a negative consequence generated from ice throw or ice fall by siting turbines away from infrastructure or people at distances deemed safe. Forecasting and monitoring weather to predict when there is an elevated level of risk are recommended when possible. Additional options to manage risk include ice monitoring and warning systems, sign and light warning systems, text message warnings, perimeter fencing around the site's critical rea, and websites detailing safety information. When the probability of icing events is high, consider further assessment of the icing conditions and a formal risk analysis.

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