Understanding and acknowledging the ice throw hazard - consequences for regulatory frameworks, risk perception and risk communication

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Abstract. This study attempts to provide the necessary framework required to make sufficiently informed decisions regarding the safety implications of ice throw. The framework elaborates on how to cope with uncertainties, and how to describe results in a meaningful and useful manner to decision makers. Moreover, it points out the moral, judicial and economical obligations of wind turbine owners such that they are able to minimize risk of ice throws as much as possible. Building on the strength of knowledge as well as accounting for uncertainty are also essential in enabling clear communication with stakeholders on the most important/critical/vital issues. With increasing empirical evidence, one can assign a higher confidence level on the expert opinions on safety. Findings regarding key uncertainties of ice risk assessments are presented here to support the ongoing IEA Wind Task 19’s work on creating the international guidelines on ice risk assessment due in 2018 (Krenn et al. 2017)[1-6]. In addition the study also incorporates the findings of a Norwegian information project, which focuses on the ice throw hazard for the public (Bredesen, Flage, Butt, Winterwind 2018)[7-9]. This includes measures to reduce damage and hazard from wind turbines for the general public. Recent theory of risk assessment questions the use of risk criteria for achieving optimum risk reduction and favours the use of the ALARA (as low as reasonably achievable) principle. Given the several practical problems associated with the ALARA approach (e.g. judicial realization), a joint approach, which uses a minimum set of criteria as well as the obligation to meet ALARA is suggested (associated with acceptable cost). The actual decision about acceptance criteria or obligations is a societal one, thus suggestions can be made at best. Risk acceptance, risk perception and risk communication are inextricably linked and should thus never be considered separately. Risk communication can shape risk perception, which again is vital for defining risk acceptance. Moreover, risk communication should be seen as an opportunity to demonstrate trustworthiness and an open, responsible and caring attitude. It is important for the wind industry to avoid accidents: In Winterwind 2017 (Ronsten)[10], the importance for the wind power community to proactively take safety measures for passers-by and service personnel was emphasized: Establishing good practices and communication routines is key to avoid accidents. Visually attractive ways of presenting the risk of ice throw are recommended.
1. Introduction
All wind turbines operating in an icing climate introduce the hazard of ice throw or icefall on the nearest surrounding area although with highly varying frequency and probability. The associated risk can be mitigated, but choosing the best, sufficient or optimal methods requires a good understanding of this phenomenon, and other related risks relevant for a given planned or built wind farm. Knowing, among others the ice risk magnitude in time and location with sufficient accuracy and precision is essential in choosing the best and adequate risk reducing efforts prioritized by e.g. risk acceptance criteria, cost-benefit considerations and (available) resources. Building on the strength of knowledge and accounting for uncertainty is also essential to enable clear communication with stakeholders on the most important issues.

Achieving nearly zero damages and fatalities from ice throw (Vision Zero) means that there is a public requirement of warning systems for the risk of ice throw. It has been a challenge to get the warning to be respected; therefore it is important to achieve good communication. The risk of ice throw is highest during icing and melting conditions but can also persist into good weather conditions. Also, the meteorological conditions at ground level may be different than in the rotor plane of the turbine. The most important point is that the owners must understand the risk picture in their own wind farms in order to clearly and effectively communicate with third parties and stakeholders.

Apart from the moral obligation, there is a judicial and economical responsibility, since criminal and compensatory liability depends on the commitment to perform effective risk mitigation efforts. This is tied to a personal responsibility for third-persons to respect signs and warning systems, assuming they are reasonable, i.e. well designed and only actively warn when there is a danger. However, the danger can be avoided. Moreover, risk communication should be seen as an opportunity to demonstrate trustworthiness and an open, responsible and caring attitude.

Additionally, different approaches to safety assessments are necessary for different demands: For questions of siting and regulations, a metric for comparison of the risk of (sometimes entirely) different systems is necessary. In this case the use of LIRA (Localized Individual Risk per Annum) contours with the established 40 J impact energy limit for fatal ice fragments should be applied. When including safety systems such as deicing, the reliability and effectiveness of these systems needs to be considered as well. It is estimated that dangerous ice amounts occur when the ice load on a reference object located at hub height reach a threshold in the vicinity of 0.5 kg/m, that is the border between Ice Class Rime 1 (ICR1) and Rime 2 (ICR2) following the ISO:12494 standard on atmospheric icing of structures [11] (see Figure 1).

![Ice Class Rime 1 (ICR1) - 0 to 0.5 kg/m](image1)

![Ice Class Rime 2 (ICR2) - 0.5 to 0.9 kg/m](image2)

**Figure 1.** Pictures presented by Wadham-Gagnon, M., (Winterwind2013)[12]. Ice profile Classification Based on ISO 12494. Courtesy of TechnoCentre éolien (Wind Energy TechnoCentre).
When addressing the placement of warnings (e.g. signs) or barriers (e.g. closing roads) only the relevant turbine with its specific surroundings needs to be considered and the safety goal will be extended to avoiding serious harm to people. In this case either different parameters for the existing metric or other conservative rules (e.g. the Seifert distance rule of 1.5 *(hub height + rotor diameter)) may be used [13-14]. Additionally warnings and barriers must be placed in a way that following them does not overly inconvenience the affected.

While methods for estimating icing frequency and ice loads on wind turbines as well as ballistic models for prediction of ice throw or shed distances are fairly advanced, thorough risk assessment demands the inclusion of uncertainties. This is seriously hindered, since these models are intrinsically deterministic and thus not suitable to give uncertainties per se. However, the probabilistic nature of ice throw and icefall can be partly considered by accounting for turbulence in the employed trajectory models. Also, using experiments with dropped ice fragment replicas and comparison with monitoring data, these uncertainties can be estimated and thus boundaries set.

Although the knowledge/research about uncertainties in ice risk assessments is increasing, this is far from sufficient. Further studies on trajectories of thrown ice, the impact kinetic energies, and the amount and shape of ice thrown are therefore important for increasing the credibility of risk assessments. Finally, since it is impossible to avoid all accidents further planning for communication of this fact is necessary.

In this paper we make use of the openly available data of collected ice pieces from the Swedish IceThrower project [15-18] in addition to similar databases from 4 wind farms in Austria. These data are described in Chapter 2 [19-22]. This chapter also contains the experimental setup of a conducted ice throw experiment along with a description of the risk assessment tool, IceRisk, developed by Kjeller Vindteknikk [23-25]. In Chapter 3, the results from the ice throw experiment are presented and discussed. This experiment and the gathered observational data is compared with results from IceRisk. The observations and model results for the basis of a new formulation for throw distances from an idling turbine with a dual detection system is presented in Section 3.3. A discussion on accuracy and uncertainty of modeled ice throw is given in Chapter 4. Finally a description of the national Norwegian guidelines regarding risk of ice throw, risk communication and the legal consequences in Chapters 5-8. The most relevant resources not specifically referenced in this document are listed in the bibliography [37-39] and [40-70]. Especially important are the documents Recommended Practices (2011, 2017 [13]) and Available Technologies (2016) by the expert group on wind energy in cold climates: International Energy Agency-Wind RD&D Task 19, https://www.ieawind.org/task_19.html.

### 2. Methodology

This chapter describes the data sources, experimental setup and models used.  

#### 2.1 IceThrower observations

The Swedish IceThrower project [15] produced the first open database of collected ice pieces from several wind farms [16], a detailed project report [18] with an updated recommendation on the set-back distance for Sweden as well as publicly available numerical software for calculating and presenting probability-distance functions for site- and turbine-specific risk assessments [16]. Results from the project has been presented by Lunden (2017)[17] and compared with the IceRisk model in Drapalik and Bredesen (2017)[22]. The project report (Göransson et al, 2017)[18] suggest H+D (hub height + rotor diameter) as a setback distance for Sweden. Figure 2 shows the statistics from 8 different ice throw cases from one of the turbines in the project.
2.2 Austrian field campaign for collecting ice debris

Legislation in Austria demands for turbines to be shut down when icing is detected, so only ice shed from still standing turbines can occur. In a monitoring campaign ice shed events have been observed and ice fragment positions and weights recorded [19]. Table 1 gives an overview of the conditions at the sites and the number of collected fragments. Detailed data of the monitoring program will be published as open online database on risk.boku.ac.at.

Table 1. Overview of monitored wind parks. Mean wind speed is the average wind during the recorded ice shed cases (double detection system of icing for stopping the turbine allowing idling).

| Wind park | # of collected recorded fragments | Mean wind speed (1 h) [m/s] | Hub height [m] | Rotor diameter [m] |
|-----------|----------------------------------|----------------------------|----------------|-------------------|
| WP 1      | 32                               | 12                         | 138            | 82                |
| WP 2      | 182                              | 6                          | 135            | 101               |
| WP 3      | 231                              | 6                          | 113            | 71                |
| WP 4      | 34                               | 4                          | 65             | 70                |

2.3 Experimental ice throw setup

In the course of the development of new methods for the assessment of small wind turbines (SWT) for urban use an experimental investigation of ice throw from SWTs was carried out [19,20]. In a short monitoring campaign several thrown ice pieces were collected and 3D scanned. These scans were used to produce realistic specimens via 3D printing. A throwing device was constructed with 1 m rotor radius and a maximum rotational speed of 200 rpm. The specimens were accelerated to the desired rotational speed and released at a defined rotor position. The throw trajectories were recorded with 3D imaging techniques.

2.4 IceRisk

In the IceRisk model, hourly time series of wind and icing conditions from a long-term meteorological simulation is used as input to the ballistic model described by Biswas [26]. This simplified ballistic model is considered valid for calculating the average (deterministic) trajectories associated with a given site-specific wind profile and the shape/form and density/weight specification of relatively compact ice pieces. That is, when the effects of the varying drag and lift, auto-rotation, and turbulence can be neglected for the considered ice pieces. For a site and turbine specific analysis where the purpose is to derive statistics on how the ice throw and ice fall hazard varies with distance and direction from the construction, this procedure is justified if the relevant statistics no longer are sensitive to the considered simplification; e.g. the sample size is sufficiently large and the associated parameters are adequately discretized.

For now-casting and fore-casting purposes considerations regarding the location-specific turbulence can be made to resample instantaneous wind measurements or hourly forecasted wind speeds on a short time horizon. By applying the IceRisk model and accounting for turbulence intensity a map giving risk zones and ice fall/throw probabilities can be created. Examples of this is shown in Figure 3 for the 209 m tall guyed telecom mast located at Tryvann in Oslo. For the forecasted wind conditions, a risk zone shown to the left are spanned by employing the 40 J distance function (Bredesen and Refsum, IWAIS2015)[23] for average hourly values as shown to the left in the Figure (verified as highly realistic impact locations by field studies at this site). Now, also the ISO-risk contours associated with a factor 10, and 100 lower risk than given at the edge of the indicated risk zone (left) can be presented. The strongest winds before resampling is 14.4 m/s at 209 m resulting in a maximum 40-J distance of 127 m. The strongest gusts after resampling are 19 m/s from the north.
showing the probability level for a possibly fatal strikes out to 220 m with the given assumptions. Similar methodologies could also indicate 3 consequence regions. e.g. of worst consequence/hazard, serious injury, and nuisance based on the considered energy threshold.

The example resampling technique that includes variation in the wind speed and wind direction within 10 minute intervals is: Hourly values of a 48 hour forecast are linearly interpolated to 10 minute values, then normal distributed for a width of 3 standard deviations for both the wind speed and direction. We have chosen a standard deviation value of 10 % on the wind speed (turbulence intensity TI = 0.1) and 20 degrees for the wind direction to illustrate the effect. Suitable values can be found by analyzing the wind measurements from the newly erect official 30 met mast at the location (Tryvann, Oslo) employing relations between maximum wind speeds and average wind speeds as described by Harstveit (1996)[27]. Also the height dependence on the variation of the turbulence should be considered.

Figure 3. Left: Forecasted risk zone (ice fall) spanned by the impact locations from 48 hourly values of wind speed and direction using the 40 J distance function for ice debris released from a single point in top of the 209 m telecom mast. Right: Zoomed forecast of hazard zones with ISO-risk contours in multiples of factor 10. The probability map are calculated using the long-term size-distribution and resampled wind conditions, combined for all weighted release positions in the construction which consists of mast and 12 guys. Terrain effects have not been considered in the presented graphic. The indicated colored risk values are not scaled that is the absolute values are not representative to the risk at the given time, but the risk decay with distance is realistic.

Considering ice throw from the blade of wind turbines, results with the current setup are presented as the average of 4 separate calculations: 50 % by the wind statistics during melting conditions and 50 % by dangerous ice amount present on the blade (~instrumental icing). Each of these cases are then again subdivided by using an upper rpm-curve and lower reduced rpm-curve due to icing describing the velocity of the wind turbine blade as function of the wind speed. Figure 5 shows the average of these 4 scenarios for the considered V90 turbine in Sweden. In the IceRisk modeling, ice continues to accrete in repeated cycles during meteorological icing conditions. The maximum expected throwing distances of ice debris are associated with the form-factor (Cd A/M=0.008) solving the Biswas equations. Meteorological icing conditions are included as part of the period with ice present, but has
not been weighted further. This is a natural improvement in the modeling as repeated cycles of shedding only occur during meteorological icing conditions.

3. Results

3.1 Dissemination of IceThrower results using the IceRisk Model
In the IceThrower field study 75% of the ice was found within one rotor diameter distance from the turbine tower, and 1% beyond 1.5 rotor diameter distance. 40% of the ice debris weighed more than 1 kg and 3% weighed more than 2 kg. The observed peak probability of recorded non-crushed ice debris in the IceThrower database occurs from 0-35 m distance with a probability at 8x10^-5 ice strikes/ice event/square meter. The probability of ice debris impacting one square meter per event drops linearly with distance with 2 decades reduction over the next 100 m as shown in Figure 4.

![Figure 4](image1.png)

**Figure 4.** The probability of ice throw per m² and ice event based on all available data (532 pieces) from the field study. Courtesy of Bengt Göransson (Pöyry).

The results using the IceRisk method and the IceThrower software (Lunden, 2017) for the considered location in Sweden was compared in Drapalik and Bredesen (WWEC2017) showing very similar shapes on the expected radial probability distribution of ice throw. This discussion is a continuation of the study in Drapalik and Bredesen (2017, WWEC)[22]. The IceRisk simulation shown in Figure 5 is based on a long-term meteorological simulation [22, 23, 24]. Kjeller Vindteknikk recommends risk mitigation for ski-tracks and foot-paths especially within the distance associated with the millennium ice piece (with an impact kinetic energy level above 40 J), here calculated at 200 m.

An extrapolation factor based on measurements indicates that the associated LIRA (Localized Individual Risk) contours for power ten reductions of risk is at 250 and 300 m valid for turbines in comparable wind and icing climate (mid to north Sweden). Such a consideration is conservative as the risk decayed even faster with distance in the numerical simulations with rates of three decades reduction per 100 m.

By the use of the open Swedish IceThrower database on collected ice debris [16], a cross comparison is ongoing with meteorological modeled parameters as well as SCADA (Supervisory Control And Data Acquisition) data. This ongoing comparison is essential in increasing the precision of ice risk analysis in general, and to adjust the lower and upper uncertainty band as previously...
discussed in Drapalik and Bredesen (2017) [22]. Further results of this study will be presented in Bredesen (2017, Revision 1) [24] as a verification study of the IceRisk model.

In Figure 6 all collected ice pieces for events A-H from IceThrower are plotted by location (each location has been rotated to correct for the given wind direction for easy comparison). From the collected ice pieces in the IceThrower project we observe that the maximum across-wind distance component is 120 m, while 140 m is the maximum throwing distance. We observe that directional wind-shifts have most likely occurred for at least two episodes: grey (13.1 m/s) and red (5.4 m/s).

For the 8.4 m/s event (purple) two 2 kg pieces were thrown 130 m for angles around 20 degrees from the along wind direction. Ice pieces weighing 2 kg were expected for higher across-wind to along-wind distances only (see Figures in Drapalik and Bredesen, 2017)[22]. Further comparisons, refinement and/or choice in modeling are therefore required to enable correct modeling of angular distributions.

Regarding the uncertainty on the absolute value of risk/probability we can make the following simplified comparison: from the 8.4 m/s episode (event E, purple markers), we count for example 20 impacts in a 40 x 40 square meter area between 100 and 140 m for a 40 m wide area at angles below 45 degrees. This gives an average areal strike probability of 0.0125 strikes per square meter. For comparison the IceRisk simulation result (Figure 5) was 0.06 strikes/square meter per year at a distance of 120 m which includes crushed ice. A similar exercise can be performed for example for the 4.5 m/s episode (A: yellow markers). This simple comparison indicates that the IceRisk simulation gives realistic results without being overly conservative in terms of the absolute risk/probability level for the indicated area. However, the risk is lower for other directions relative to the turbine location resulting in the lower observed directional averaged probability density of non-crushed ice debris reported in Figure 4.

A preliminary comparison of the SCADA data in terms of power production indicates only minor penalties on the performance (short-term) for most of the ice collection episodes, that is the ice amounts associated with the collected ice debris did not stop the operation of the turbine. The turbine was in operation at all ice events except for 11 December 2013 when the turbine was manually paused (event G, blue, 11 m/s).

![Angular ice-throw distances from 8 agents rotated by binned wind direction](image)

**Figure 6.** 417 ice pieces from the IceThrower database for the considered V90 turbine with a tipheight of 140 m. The location of all ice pieces are rotated by the given wind direction for each given case. Events are listed A-H by colored markers for increasing wind velocities.
3.2 Results from the ice throw experiments
Comparing the first results from the experimental ice throw project with model calculations based on the Biswas equations [26] two main points need to be addressed: Firstly, the Biswas equations tend to overestimate the throw distance by 10-15% (see example in Figure 7). A closer investigation of the video data from the throws shows that after approximately half the traveling distance chaotic autorotation of the fragment starts. This could lead to additional drag resistance due to turbulent flow, which results in shorter distances.

Secondly, the distance traveled along the wind is largely underestimated by the simulation, as can be seen in Figure 8. While this distance is small compared to the total distance, it has a significant impact on a non-isotropic risk map. The results presented in Figure 6 indicate the same differences when compared to the model. This is discussed in more detail in Section 4.

3.3 Description of the Austrian ice shed samples and estimation of shed distances
For this Austrian field campaign the turbines were stopped (allowed to idle) during icing events. Figure 9 and 10 shows the distance distribution of collected fragments as well as the rotor radius and the expected maximum shed distance (d) from the Seifert formula (2003)[14]: $D_{max} = v \cdot (R + H)/15$, which is by far lower than the recommended 1.5 x total height by ISO12494 [11], which would correspond to the Seifert formula at 22.5 m/s. Here, v is the velocity at hub height (H) and R is the rotor radius. As expected, for low wind speeds and low hub height, most fragments drop within the rotor radius. In the case of the highest wind speed 55% of fragments were shed farther than the Seifert distance; the maximum distance found was 1.25 times the total height.

Figure 7. Comparison of calculated and experimentally found throw distance for 1 m radius, 200 rpm, 45° release angle and 4 m/s wind speed.

Figure 8. Comparison of calculated and experimentally found travel distance along wind for 1 m radius, 200 rpm, 45° vertical release angle along the positive x-direction and 4 m/s wind speed. The wind velocity is along the negative y-direction.

Figure 9. Shed distances for 4 m/s mean wind speed, 65 m hub height and 70 m rotor diameter.

Figure 10. Shed distances for 12 m/s mean wind speed, 138 m hub height and 82 m rotor diameter. Outliers are included in shown bins.
For the high wind speed case in Figure 10 the highest shed distance was 225 m for a 240 g piece of glace ice. The thickness of this piece varied roughly from 3 to 8 mm as can be seen in Figure 11. Further pieces were found at distances around 150 m. For ice shed we note that thin and less compact ice pieces drifting the furthest with the wind have a lower energy density than more compact object reaching the same distance by ice throw. Also the damage potential considering a random orientation is lower compared to the most unfavorable setup possible.

Figure 11. Ice piece with the highest recorded shed distance of 225 m from a turbine with 138 m hub height and 41 m rotor radius. The length of this piece was 38 cm, the width 16 cm and the thickness varies between 3 and 8 mm. It was pure glace ice with a weight of 240 g.

Size and geometry of the found ice pieces varied strongly and ranged from 20 cm to 3 m. Most fragments found had a length between 40 and 60 cm. Figure 12 shows a histogram of the found lengths with a fitted log-logistic function. For several of the observed events a positive correlation between length and width of the ice pieces was found as well as increasing fall distance with decreasing fragment size. This is expected as lighter and less compact fragments travel further. All of the largest ice pieces was found for distances shorter than H. A scatter showing the distance and size of the ice pieces is shown in Figure 13.

Figure 12. Histogram of the length of found ice pieces. A log-logistic function with $\mu = 4.04$ and $\sigma = 0.37$ is fitted to the distribution.

Figure 13.
Scatter plot of mass and distance of found ice fragments in WP 1. The shed distance decreases with increasing mass, but only for high distances.
When trying to generate an empiric formula for maximum shed distances, a simple assumption can be made: the mean drop distance needs to reduce to zero for zero wind speed as well as for zero drop height. Next, it is assumed that drop distance increases linearly with the two mentioned factors. Finally it can be reasoned, that the mean drop distance should depend on the hub height instead of the total height, since the rotor diameter should only affect the maximum distance but not the mean. Applying this to the data from the four recorded events the following expression for the mean drop distance can be found:

$$D_{mean} = \frac{v \cdot H}{11.9}$$  \hspace{1cm} (1)

To get the maximum distance, it is here assumed that the fall distances are normal distributed (this assumption is not necessarily true and can be improved on especially with emerging evidence regarding higher wind speed and longer observed drifting distances, e.g. including results from Drapalik and Bredesen (2017) [22]). The width of this distribution depends on wind speed and total height, resulting in the following formula for the relative width of the fall distance distribution:

$$w_{rel} = 0.57 - \frac{\sqrt{H + R}}{5.570}$$  \hspace{1cm} (2)

Defining the maximum shed distance with the 3 sigma limit (99.9% of fragments are found within this limit), the maximum distance becomes

$$D_{max} = D_{mean} \cdot (1 + 3 \cdot w_{rel})$$  \hspace{1cm} (3)

While this estimation is by far more complex than the Seifert formula, it is entirely based on monitored data and can still be easily calculated for a given turbine.

Since these equations are modeled on relatively few monitoring cases it is limited to the range of these samples. For practical use we recommend the use for up to 15 m/s wind speed, 150 m hub height and a rotor radius to hub height ratio smaller than 0.5. Low wind speeds and large rotor diameters may also be problematic, since the equations are based on the assumption of normal distributed distances. This is based on the assumption that the distance along the wind direction will be more important than the distribution across the wind direction resulting from the rotor radius and the yaw and roll angle.

Figure 14 shows distributions of the monitored data scaled linearly for wind speed and hub height, with the estimated mean distance and maximum distance from equations 1 and 3. The maximum and mean distance for two of the pieces are also shown in Figure 9,10.

**Figure 14.** Comparison of shed distance distributions for the monitored wind parks. Distances have been modified with linear factors to reach the target wind speed and hub height. The dashed lines signify the calculated mean distance from equation 1 and the maximum distance from equation 3, assuming a 50 m rotor radius.
4. Discussion on uncertainties

For ice throw calculations, further comparisons, refinement and/or choice in modeling are recommended to enable better modeling of the angular distributions of ice throw. As a starting point it is recommended to include the effect of turbulence, the rotor tilt angle and to adjust the average drag coefficient from 1.0 towards 1.2 in the model. For non-compact debris shapes, the modeled ice shed drift distances are underestimated with the current assumptions as demonstrated in Figure 8 and 10.

No risk assessment should be based solely on the collection of uncrushed ice pieces found without considering the total amount of ice being released from the construction during an icing event. The amount of crushed ice debris in terms of number of throws can sometimes be visible in the form of craters on the ground if a snow cover exist. It is important to acknowledge that larger ice pieces are more likely to crush on impact which can cause a systematic bias in ice risk assessments. The IceRisk results presented in Figure 5 avoids this specific uncertainty by modeling the ice accretions directly on a representative model of the wind turbine's blades.

Ice risk assessments are especially sensitive on the operational mode of a turbine. During icing conditions, some turbines shut down early either intentionally, due to the control system or performance degradation. Other turbines, on the other hand, can operate with ice on the blade permitting repeated cycles of re-accretions and shedding for even a single icing episode. Following the initial risk comparison made by Drapalik and Bredeesen (2017), a cross-comparison of the considered turbine's SCADA data, long-term simulations of meteorological parameters, and cataloged ice debris data collected from 8 separate icing episodes is ongoing. Furthermore, the timing of field observations to modeled and observed icing events are inspected as well as the performance degradation of the turbine during icing periods. This comparison is essential in increasing the precision of ice risk analysis in general, and to adjust the lower and upper uncertainty band as previously discussed in Drapalik and Bredeesen (2017).

Most of the ice pieces collected in the IceThrower database come from work by Dala Vind in one of their wind farms consisting of V90 turbines. When their wind farm was built in 2008, a safety distance of 160 m was made in agreement between operators, responsible stakeholders of a surrounding ski track, and the wind farm service technicians. Here, 160 m is also the minimum distance between the ski track and one of the turbines in the wind farm. The ski track grooming crew performed ice collection in Dala Vind's wind farm on behalf of the IceThrower project. The wind farm is located in forested terrain, and the search has been thorough in the surroundings independent on search direction, distance and vegetation. For this location it is not easier to perform the search at 120-140 distance compared to e.g. distances of 140-170m. For the 8.4 m/s episode, it was coincidence that most of the ice debris landed in the one-sector with more open terrain. As a consequence of the field study an updated recommendation of a safety distance of H+D (=185 m) is given the Swedish Report. Also worth noticing is that ice debris has not been observed on the mentioned ski-track by the grooming crew. H+D for this wind farm is 90+95 = 185 m. The furthest observed ice piece thrown from this wind farm was within the tip height of the construction (140 m). Based on the preliminary comparison performed here it is reasonable to assume that the IceRisk results with the current model setup (excluding [23]) are conservative by a factor of 5 accounting for the number of ice pieces being thrown. As a result of this consideration the millennium ice piece distance (IceRisk) presented in figure 5 is no longer at 200 m but expected within the 175 m distance for the considered location.

4.1. Discussion of risk decay with distance

In Figure 4 one can note that for distances beyond 40 m there is approximately a decadal reduction in probability for every 50 m in the range 40-140 m where ice pieces were found. If an assumption of 50 m decadal decay risk outside 40 m is made we can present the fraction of thrown pieces that are expected outside given distance circles. This is useful since large distances are not represented in typical field studies due to natural limitations in the large search areas and the lower probabilities. With the employed function 1 out of 1900 ice pieces will be expected outside the H+D distance, that is less than 0.1 % of the ice pieces. In addition 1 out of 100 000 ice pieces are expected outside the
Seifert distance of 1.5*(H+D). For a distance of 350 m from the turbine 1 out of 4 million ice pieces are then expected (see figure 15). Since there are no field studies that have found ice pieces at these distances and the probability of a field study finding ice at these distances is so low, a top down evaluation for Sweden was made. Assuming average installed capacity during the years 2012-2016 of 5228MW, all turbines were of the V90-2MW type studied, and all turbines are exposed to light icing thereby casting 200 dangerous ice pieces per year. This means total thrown dangerous ice pieces in Sweden during these five years exceeds 2.6 million, 1400 should have been cast further than H+D (185 m), and 26 000 beyond the tip height (140m). Because of their rarity, ice pieces found at long distances are expected to be points of discussion among neighbors, wind farm operators, service personnel, and media even when found outside of planned field studies. The number of reported ice pieces found beyond tip height in the media and among operators seems to be too low to support an extrapolation of the decadal decay beyond the range where ice pieces were recorded in the Icethrower study, and even more so if it is considered the total number of turbines in Europe which are exposed to icing conditions. Independent of the ice thrower study the author knows about only one far throw or fall (third hand anecdotal evidence); that is of one fist size ice piece (glaze) that has been observed at a distance of 300 m +/- 50 m by a service technician for a site in south-eastern Europe with a different wind and icing climate than in Sweden.

To built on the empirical evidence we note that Enercon for 3 years has collected 25 000 ice pieces from 4 E82 turbines with different operating modes in one of their wind farms (as presented by Héctor Rodríguez et al., 2017) [3]. The maximum observed distance is there 170 m, which is adjusted to 203 m accounting for uncertainty. Presented ice throw and ice fall maps (simulations) show direction dependence with higher probability along the dominant wind directions.

Figure 15. Fraction [%] (y-axis) of ice pieces thrown outside given distances (x-axis). The extrapolation function is based on the observed risk decay and presented on a linear scale (left) and logarithmic scale (right). Outside 200 m, the expected risk decay is even steeper with distance for this location (not shown).

4.2. Sensitivity study of ice piece size and wind speed distribution using the IceThrower model

The numerical software for the IceThrower project has been prepared by Jenny Lunden (Pöyry) available to the public valid for calculating omni-directional strike probabilities given the wind conditions, turbine characteristics and size distribution of expected ice debris.

Pöyry’s sensitivity study (Figure 16 and 17) showed that at distances up to 140 m (tipheight) the results were similar when 1) changing the average mass in the size distribution from 0.5 kg to 3 kg, and 2) for the combination of increasing the wind speed average from 7.6 m/s to 9.6 m/s and the mean mass of fragments from 0.5kg to 2 kg (for 100 000 modeled throws). It shows also that the probability of ice pieces at distances further than tip height is highly dependent on the mass of the ice pieces assumed near the blade tip where the highest velocities are found. Figure 16 shows a 1 decade
difference in probability at H+D (185m) and the difference increases to a two decade difference in probability at 225m. Observations indicate that the largest ice pieces are found near the middle of the blade where the ice forms on a larger leading edge radius and there is less flexing of the blade and lower aerodynamic forces acting to break loose the ice (Homola, p. 6) [71]. Ice accretes fastest near the tip, but is broken off with limited thickness (observations seem to show about 6-7cm) when the forces acting on the ice exceed the ice strength. This effect, which limits the maximum size of ice accretions near the blade tip, could explain the relative lack of reports of ice pieces at distances beyond 140 m. This illustrates the sensitivity in the modeling of ice throw for wind farms. It will be important also to communicate such uncertainties in an ice risk assessment.

Figure 16. Probability, ice strikes/ice event/m2, for four random mass distributions with mean values of 0, 5, 10, 20 and 3.0 kg. The random wind distribution has a mean wind speed of 7.6 m/s. The turbine rotor radius = 45 m and hub height = 95 m. Courtesy of Bengt Göransson (Pöyry).

Figure 17. Probability, ice strikes/ice event/m2, for distribution with mean wind speed at hub height of 7.6 m/s (blue) and 9.6 m/s (red) and for three distributions of mass (average of 0.5, 1.0 and 2.0 kg). The turbine used has a rotor radius = of 45 m and 95 m hub height = 95 m. Courtesy of Bengt Göransson (Pöyry).

5. Risk and Risk communication
The classical definition of risk – risk = probability x consequences – is effectively tied to three assumptions.

First, the consequences in questions must acceptable regardless of the probability. In other words: some consequences are in any case unacceptable and must not occur.

Second, probabilities and consequences are quantifiable and the knowledge about them is sufficient. Quantification of consequences is sometimes difficult due to practical or ethical reasons, but needs to be made in a way that allows comparison with acceptance criteria. Quantification also demands for a test of the strength of knowledge, i.e. a thorough description of the necessary assumptions, simplifications and uncertainties. Methods of quantification that do not produce quantified uncertainty ranges for the used values are especially problematic in this context.

Third: The knowledge about possible events is sufficient. This can never be formally shown, but it is advisable to put reasonable effort in identifying events, increasingly so for complex systems e.g. chemical plants.

In communicating risks, these three assumptions should be explicitly addressed and the state of the assessment concerning them made clear.
5.1 Risk acceptance criteria

Risk acceptance criteria are always a result of an explicit (approval of a proposed regulation) or implicit (acceptance of established practices) societal decision. Many existing criteria or principles are based on the comparison of a new risk with existing, similar risks. This is not applicable for the risk of ice throw, since no comparable situations exist. Thus one possibility is the application of the MEM (minimum endogenous mortality) principle, which demands that a single technical system does not increase the endogenous mortality by more than 5%. The endogenous mortality is usually chosen with $2 \times 10^{-4}$ (mortality of a 15 year-old) [33], leading to a maximum risk of $10^{-5}$ deaths per year.

While this fixed value is convenient for practical use, it has several drawbacks. First, the choice of 5% is arbitrary and cannot be well communicated. Second, fixed values give no incentive for improvement of safety measures once this value has been reached. Especially the second argument makes the ALARA (as low as reasonably achievable) principle a considerably more attractive choice. The ALARA principle uses two limit values: the upper value defines an intolerable risk and demands like MEM that a risk is reduced until it falls below this value. The second limit value defines an negligible risk, which does not need to be reduced. The region between these values defines tolerable risks which need to be reduced a far as possible, i.e. until the costs are too high or until they become negligible. This definition incorporates a legal in addition to the moral obligation to reach the highest possible safety standards. While this concept principally supports far reaching and cost effective risk reduction, it is prone to misuse due to its rather open definition. The boundary condition of “reasonably achievable” is mainly dependent on the point of view of the user, leading to different understanding e.g. of operators and public. This approach should be openly communicated and the criteria for the choice of certain measurements made clear. The MEM principle is further described in the German study by Hahm and Stoffels (2016) [34].

5.2 Risk perception and communication

Risk acceptance, risk perception and risk communication are inextricably linked and should thus never be considered separately. Risk communication can shape risk perception, which again is vital for defining risk acceptance.

Risk communication is classically seen in a one-way direction – experts inform the concerned public of the risks and correct behavior, often after the completion of the associated project. This may result in additional opposition and little understanding. Additionally the risks of complex technologies are often difficult to explain lacking the relevant technological knowledge.

Thus, an early involvement of the public in project realization and application of safety measures is highly advisable.

6. The wind energy community's preferred policies regarding ice risk assessments

As there is a lack of understanding of the ice throw phenomenon among authorities, this has led to the fact that there is no coherence in the applied ice throw mitigation policies in various countries and regions, which can cause safety- and financial hazards for wind farms in icing climates (Nøel de Wild, 2017)[35]: “Together with six researchers on ice throw from wind turbines, mitigation policy scenarios have been suggested in two forms:

- **Method A**, politically induced general regulations, like curtailment, obligated blade heating or safety zones around turbines.
- **Method B**, site specific mitigation methods based on guidelines for risk assessment.

Method A is a clearly non-preferred scenario, however there is a fear of it becoming reality. Mandatory curtailment and safety zones could have a large negative impact on feasibility and development of wind power projects, whereas mandatory blade heating could give a false feeling of safety. Method B is therefore preferred. Having strict guidelines on how to perform risk assessment, will lead to site-appropriate mitigation solutions that are both safer, more understandable by the environment and less harmful to the feasibility of wind power development.”
7. National Norwegian guidelines regarding the risk of ice throw for the public (2018)

The Norwegian guidelines [9] gives advice on the possible consequences of ice throw from wind turbines for the public (third persons). The guideline is the result of an internal project at the Norwegian Water Resource and Energy Directorate (NVE), with external contributions from Roger Flage at IRIS (International Research Institute of Stavanger), and Rolv E. Bredesen from Kjeller Vindteknikk.

The background for R&D project is that all wind farms in Norway to various degrees are exposed to icing conditions enabling the hazard ice throw and ice fall from the blades of wind turbines onto the surrounding areas. The resulting risk of injury is a topic for interested stakeholders and proper communication of this risk is a challenge, which may result in that the risk of being hit by ice debris originating from wind turbines sometimes are exaggerated. Therefore NVE has actuated the current Research and Development project regarding ice throw and ice fall which focuses on how the risk should be managed and communicated based on currently available documentation, best practices and research.

The goal of the project is to prepare easily understood and relevant advise for wind farm concessionaires (owners/operators) and to the general public:

1) How to communicate the risk of injury and damage to the general public caused by ice throw and ice fall.

2) Relevant measures handling the risk of injury and damage.

3) Clarify the criminal and compensatory liability for incidents involving injury.

The Norwegian Guideline is meant as a supplement to the IEA Wind Task 19's internationally harmonized guidelines regarding ice throw risk assessments. However, the health and safety issue related to wind farm working personnel is not considered in this project.

There is a requirement from NVE to evaluate the extent of icing and to assess the risk of ice throw/ice fall when applying for a wind farm license in Norway. An evaluation shall be sent to NVE before operating the wind-power stations.

A recommended list of the most important items in such an evaluation are presented together with short guidance on how to perform said work, including how to describe the related uncertainties and strength of knowledge regarding key assumptions in a risk assessment.
7.1 Risk assessment

Risk assessments are tools used to understand the risk related to an activity or a system in order to properly mitigate or accept the associated risks in a risk management process. One requirement regarding the quality of work and competence of risk analysts are on whether they are able to identify relevant risks and give concrete advice on the most beneficial risk reducing measures on a case by case basis. In any risk assessment it is important to appropriately assess and describe the strength-of-knowledge (e.g. the analyst’s confidence in the presented results and/or underlying assumptions, models used, etc.) and the uncertainties involved (e.g. related to black swans (surprises) and completeness (aspects of the risk not described by risk indices/metrics)). Historically, risk acceptance criteria require a high accuracy of the risk assessment to be used as a sharp limit for when and where risk mitigation is required to consider the risk acceptable. The Norwegian National guidelines (2018) on how to perform ice throw and ice fall risk assessments acknowledges this precision issue, and accordingly question the procedure of using quantified risk estimates comparing calculated risk metric values against absolute risk acceptance criteria.

Figure 18. Risk assessment as a tool to gain risk understanding, which is necessary to manage and keep the risk under control. The risk management process in the knowledge and physical domain enables sufficient understanding and confident decision-making. Source: DNV-GL (2016)[36] Enabling confidence: Addressing uncertainty in risk assessments. Courtesy of Frank Børre Pedersen (DNV-GL).
In its simplest form the required warning system (Norway and Sweden) for the ice throw hazard for the public is suitable located signs. This may be enough for remote areas that rarely are visited during the 'often' bad weather associated with icing conditions. It is therefore important for the risk assessment analyst to identify to whom, when (including how often) and where there is a risk of ice throw and ice fall to incorporate the best and adequate measures. Also if effective risk mitigation options are inexpensive to implement (cost-efficient) they should be implemented according to the ALARA/ALARP principle (As low as reasonably achievable/practicable associated with acceptable cost). The publicly available background knowledge regarding ice throw and ice fall is at the moment not necessarily strong but rapidly increasing. Key assumptions typically made in ice risk assessments are currently being scrutinized, thus improving the strength of knowledge underlying such assessments. The background knowledge related to ice throw and ice fall among experts is far from poor, and there is consensus among experts on where the large uncertainties lie.

The iterative process of gaining risk understanding in the knowledge domain and in the physical domain is shown in Figure 18. The key question is on whether the risk is as low as reasonably achievable.

### 7.2 Suitable risk mitigating measures

In addition to the detailed planning of the actual wind farms, designed signs and warning routines, possible sound and light signals, direct warning systems (e.g. sms/app), and detection systems it is recommended to establish public knowledge about the risk and to consider physical safeguards and/or curtailment options (e.g. to stop the turbine during periods of particularly high risk).

#### 7.2.1. Establish knowledge about the risk

In order for the public to avoid injuries and damages due to the hazard ice throw and ice fall it is important that the threat is sufficiently understood leading to respect for the implemented signs and warning systems/routines. Signs and warning routines/systems should be supplemented with continuous and effective information transfer that helps the users of the area to understand the specific danger. This can be communicated through newspaper articles in local media, brochures / information in pocket format that can be distributed, QR codes on signs and more comprehensive information boards at the main entrance of the wind power plant. The information given should be repeated systematically prior to each winter season and reach different target groups. In some areas, it may be useful to provide information in several languages.

It is important that information about the risk is communicated in such a way that the receiver understands the message and becomes motivated to adapt his/her behavior. This requires a good dialogue and trust between the concessionaire and the users of the area. In areas of high usage, the concessionaire should facilitate involvement of users in assessing which measures are appropriate for managing the risk, so that stakeholder needs can be maintained through the actions that will be implemented.

It is an advantage that the information about the risk is correct and effective to ensure that the risk of damage from ice throw and icefall is not exaggerated or causes fear as this may cause the public to limit their stay in the area more than necessary for damage avoidance.

#### 7.2.2. Physical safeguards and shutdown of turbines

In order to facilitate safe traffic and stay in the area, suitable measures can in some cases be different physical safeguards. If there are ski slopes, snowmobile routes and hiking trails, etc. in areas where ice throw and icefall may occur, these should be relocated and marked. It may also be appropriate with temporary cordons to prevent traffic during periods of particularly high risk of ice throw and ice fall. Other examples of security measures may be to reinforce the roof on the buildings located in exposed areas and roof over parking spaces, etc. to prevent damage to equipment and materials.

It may also be advisable to stop the turbines during periods of particularly high risk of damage from ice throw and icefall.
8. Legal consequences

Ice throw from wind turbines can potentially invoke serious legal consequences for wind farm owners in case the ice throw result in any serious damages. In Norway NVE can carry out supervision in both the construction and operational phases to ensure that the risk of damage by ice throws is handled in accordance with the current terms and conditions. In case of any discrepancy, NVE may react with different means, such as orders for rectification or termination of the license.

Terms and conditions for measures to deal with the risk of damage by ice throw are intended to prevent serious accidents. These accidents may occur even if the owners follow the regulations imposed by NVE. In such a scenario the affected party can claim compensation for any damages caused. The licensee of the wind farm can be held responsible even if all public-law requirements are satisfied. Owners and employees of the licensee may also be liable to criminal proceedings even if they act in accordance with public-law requirements set by the NVE. The police authorities investigate and prosecute criminal offenses.

8.1. Liability

The licensee may be held liable for damage caused by ice throw and icefall in accordance with the general principles of compensation. The affected party may claim compensation from whosoever he/she believes is responsible including board members, general managers and shareholders. In case the parties cannot arrive at a consensus, the case may be brought to the courts for the final decision.

There are three conditions that must be met in order for a liability to arise. These are discussed briefly below.

8.1.1. Basis for liability

To be held financially responsible for injuries the wind farm owners must have acted negligently. Both active actions and omissions may be classified as negligent and can therefore invoke the right for compensation.

In case law, the following factors are used to assess whether a party has acted negligently:

- The risk of injury is taken into account. The greater the risk is, the greater the requirement for attention. For example, if a wind farm is located in an area that is used extensively for outdoor activities, or if there is short distance to densely populated areas, more stringent requirements will be imposed on the attention than for wind farms in areas with limited human activity.

- What choice of actions the licensee had is also a critical factor. Emphasis is placed on whether the licensee could have avoided the damage by engaging in preemptive actions.

- Whether the licensee had complied with public-law rules is also a part of the assessment. However, the licensee may be held liable despite fulfilling all public-law requirements.

In addition to the basis of liability mentioned above, the owner of a wind power plant may be held liable without regard to negligence. According to Norwegian case law, there are three basic conditions that must be fulfilled in order to be liable without regard to negligence: 1) There must be an extraordinary risk that significantly exceeds the daily life risks; 2) The risk of injury is typical for the current business. 3) The risk of injury must be persistent. For example, it has been established in Norwegian case law that the owners of apartment buildings are liable, without regard to negligence for damage caused by the collapse of parts of the building.\(^1\)

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\(^1\) Rt. 1939 p. 766 (Gesimsdommen). Look also at Rt. 1972 p. 965 (Mønepannedomen)
8.1.2. Financial loss
The condition of financial loss will in most cases be fulfilled by damages to health and property.

8.1.3. Causation
There must be causation between the damage and the injurious act for the incident to trigger liability. In some cases, there may be multiple causes and more than one responsible for damage. An example might be where a tour operator facilitates traffic close to the wind farm without notifying the wind farm owners and as such increasing the risk of potential harm.

8.2. Criminal liability
According to section 10-5 of the Energy Act, violations of the Energy Act are punishable. It is the police, which investigates and prosecutes criminal offenses. The NVE may report an accident to the police. The police pursues violations of the provisions of the Criminal Code. Punishable circumstances can provide grounds for criminal proceedings against the enterprise, chairman, board members, operating company and employees / managers in the operating company. Supreme Court decision in Rt. 2013 p. 312 (Takrasdommen) is an example of criminal prosecution against both enterprises and individuals based on the Criminal Code after an ice cube of about 10 kilo fell down from the roof of an apartment building and hit a person. The Penal Code § 280 has a limit of imprisonment for up to 3 years for the person who "negligently causes significant harm to another's body or health." Penalty for causing death is up to 6 years.²

8.2.1. Corporate penalties
Penalties may be imposed on the enterprise in the form of a fine even if no one in the enterprise has been at fault. Penalties against the enterprise may be substituted for, or in addition to, penalties by individuals in the enterprise. In the example mentioned above about ice cube, the company was sentenced to a fine of NOK 2 million in the district court. This was adjusted to NOK 1.5 million in the Court of Appeal and in the Supreme Court the company was dismissed under dissent. In a case from 2009, both the company owning the apartment building and of the shareholder of the company were convicted of negligent killing after parts of a building fell down and caused death of a person passing by.³

8.2.2. Directors' liabilities
Board members of the company that own the wind farm may be liable to criminal proceedings for negligent harm.⁴ It is the board's duties under the “aksjeselskaploven” (The Company law), which is the basis for the assessment. The board must ensure proper organization of the company and guidelines for the work.⁵

8.2.3. Operations manager
In cases where the cause of damage is due to negligent omissions or actions by the operating company or employees of the operating company, it may become criminally liable. In evaluating whether there is a deviation from responsible conduct that imposes criminal liability, the courts assess whether public law requirements are complied and whether the acts are in accordance with industry practice.⁶

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² Ref. strl. § 281.
³ Look at LB-2009-55987.
⁴ Ref. straffeloven § 280.
⁵ Ref. aksjeloven §§ 6-12 and 6-13. Look also at Rt. 2013 p. 312 premiss 27 flg.
⁶ Example: Rt. 2013 s. 312.
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