IEA Wind TCP Task 19

INTERNATIONAL RECOMMENDATIONS

for Ice Fall and Ice Throw Risk Assessments

iea wind

IEA Wind TCP Task 19:

International Recommendations for Ice Fall and Ice Throw Risk Assessments

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Preface

The purpose of this report is to provide the best available recommendations for the assessment of ice fall and ice throw from wind turbines with the aim of reducing the uncertainties involved in such assessments. As the result of a two-year creation process, the recommendations presented here intend to give answers regarding the selection and definition of the essential methodology and input parameters for ice throw / ice fall risk assessments. In this respect, the authors are confident that the findings presented in this document will pave the way forward to more transparency and increase the quality of ice-risk assessments internationally.

In addition to the recommendations presented here, the national laws and standards regarding the assessment of ice throw / ice fall risks need to be taken into account. It remains a responsibility of the authors of a risk assessment to decide to what extent the recommendations provided in this document are used.

Andreas Krenn

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Executive Summary

The aim of these recommendations is to collect the current knowledge of ice fall and ice throw from wind turbines and best-practices from the industry in order to lay the foundation to a more uniform approach and methodologies in the creation of ice fall and ice throw risk assessments internationally. The document at hand therefore covers the main building blocks required to assess the risk of ice fragments to cause harm to persons under or near the wind turbine. This comprises suitable numerical procedures, observational data (in particular on the number and properties and of ice fragments), conceptual approaches for the definition of acceptable risk levels, and possible risk reduction measures.

In terms of applicable information and conclusions, the contents of these international recommendations includes the following points:

- The spatial distribution of ice fragments falling or being thrown from the turbine shall be computed from a statistical model.
- The model for calculating the trajectories of ice fragments shall include gravity and aerodynamic drag and consider turbine parameters, operational mode, and site topography.
- Site-specific wind data in at least 10 minutes intervals shall be used.
- The total amount of ice and the number of ice pieces shall be determined from either: scaling of site observations, ice load distribution formulae, or ice accretion simulations.
- The size and mass distributions of the ice pieces need to be considered.
- Long term representativeness of the icing conditions shall be ensured.
- Societal and individual risks shall be considered and taken into account for defining measures.
- The Exposure of persons and road traffic to ice fall shall be considered.
- The treatment of uncertainties shall be clearly discussed in the assessment.
- The selection and adoption of risk reduction measures shall be decided on a site-specific basis.

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1. Introduction

Ice fall and ice throw from wind turbines is an important consideration on numerous locations with icing conditions that offer great wind energy potential in demanding climates around the world. The installed cumulative wind capacity at locations with icing conditions across Europe, North America and Asia was approximately 90 GW at the end of 2015, with an expected growth rate of approximately 8 GW per year until 2020 (Lethomäki, 2016). Ice risk and energy losses due to icing are two aspects of one phenomenon. Whereas energy losses due to icing are mainly a challenge at locations with moderate to severe icing, the risk of ice fall or ice throw also needs to be assessed at locations with only a few icing events per year, especially if the wind turbine is installed at locations with a high probability of people being present.

Ice builds up on wind turbines during periods of meteorological icing (see Figure 3). When this ice de-adheres from the blade, most commonly when the temperature increases above the melting point of ice, or due to activation of a rotor blade heating system, ice fragments either are thrown (from a rotating blade during power production mode) or drop from the blade (at standstill or idling). In either case, those ice fragments can cause harm to persons present underneath or near the wind turbine.

The risk from falling ice fragments needs to be taken into consideration as early as the design phase of the wind farm project. In this context, authorities in an increasing number of countries are requesting detailed ice throw / ice fall risk assessments during approval procedure. In those assessments, the risk for persons caused by ice fragments detached from a wind turbine can be compared with risks from other technologies or commonly accepted risk levels. This way, the risk of being hit by an ice fragment can be brought to a more objective and site-specific level than with the utilisation of general safety distances via rules of thumb. [See pages 50-53 in Krenn et al. (2016).]

However, the discrepancy in requirements of public authorities as well as the different methodologies used by individual consultants have become more and more obvious over the past few years. The experts of IEA Wind Task 19 have identified a lack of standards and consensus regarding the elaboration of risk assessments as the main reason for the deviations. In this respect, an international working group with experts from six different countries has been formed as a subtask of IEA-Task 19 with the objective to summarize industry-best-practice into international recommendations for ice fall / ice throw risk assessments.

The working group has divided the analysis process of those assessments in three separate sub-processes[1]: (a.) the details of the mathematical model for the calculation of the spatial distribution of ice fragments landing below the wind turbine; (b.) the relevant (wind and icing) data basis as well as (c.) aspects of the actual risk assessment. In order to reach a mutual understanding on the individual topics, the working group has subsequently evaluated various approaches through a cross-comparison of results for predefined case scenarios and discussed the differences in workshops. These three main parts are completed with considerations regarding safety measures and estimations of uncertainty.

In this document, the terms ice fall and ice throw are distinguished in the following manner: Ice fall is defined as ice detaching from a turbine during standstill or idling. Ice throw is defined as ice detaching from operational turbines. The distinction and definition is made to incorporate regulatory obligations to shut down turbines if a relevant amount of ice is detected on the rotor blades, with shutdown including

[1] These sub-processes also form the three main sections of this document.

standstill and idling. While ice or snow falling from the nacelle in principle may also contribute to the overall ice fall risk, the recommendations at hand focus on risks due to atmospheric icing of the turbine blades.

These recommendations follow the terminology of the International Organization for Standardization (2016). This way, the most important aspects can be clearly identified and distinguished from other less crucial recommendations (see Table 1).

Term	Definition
shall	Verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	Verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required
may	Verbal form used to indicate a course of action permissible within the limits of the document
can	Verbal form used to indicate possibilities and capabilities within the limits of the document

Table 1: Definition of verbal forms (see International Organization for Standardization (2016))

2. Mathematical Model

This section presents the physics of the motion of an ice fragment and introduces the different inputs and parameters that are necessary to assess the ice strike risk resulting from an ice throw or fall. It is divided into four subsections covering the equations of motion and important input parameters characterising the ice fragments, their initial location and speed, and environmental factors.

2.1. Trajectory Model

To assess the risk of ice strike below or near a wind turbine, one has to study the trajectories taken by the ice fragments from the moment they detach from the blade until they hit the ground or any other surface of interest.

In order to calculate the motion of an ice piece, one shall use a trajectory model considering at least drag and gravity.

Morgan & Bossanyi (1996) first provided a system of differential equations to describe the trajectories followed by ice falling or thrown from wind turbines. Biswas, Taylor & Salmon (2011) later modified that model by including a vertical wind profile. This model is presented here as an example of a suitable mathematical model that includes the relevant physical effects for the motion of an ice piece, adapted to the wind turbines' geometry. Other mathematical models can also be suitable if they fulfil the requirements laid down in this section.

The model of Biswas, Taylor & Salmon (2011) is given in Equation 1 and Equation 2 below. It is based on a three-dimensional system of differential equations governing the trajectory of an ice fragment after release from a turbine blade. It assumes that the turbine is always facing into the wind (x-axis in the equations below).

If (x, y, z) represent the along-wind, lateral and vertical dimensions as illustrated in Figure 1, then the system of differential equations in Equation 1 can be used to describe the motion of an ice fragment over as time evolves.

$$m\frac{\partial^2 x}{\partial t^2} = -\frac{1}{2}\rho C_D A\left(\frac{\partial x}{\partial t} - V(z)\right)|U|$$

$$m\frac{\partial^2 y}{\partial t^2} = -\frac{1}{2}\rho C_D A\left(\frac{\partial y}{\partial t}\right)|U|$$

$$m\frac{\partial^2 z}{\partial t^2} = -mg - \frac{1}{2}\rho C_D A\left(\frac{\partial z}{\partial t}\right)|U|$$

Equation 1

In Equation 1, m is the mass of the ice fragment and A is its frontal area. $V(z)$ is the wind speed at height z. Gravity is given by g whilst ρ and C_D are the air density and drag coefficient, respectively. The total velocity, denoted $|U|$, in Equation 1, is calculated as

$$|U| = \sqrt{\left[\left(\frac{\partial x}{\partial t} - V(z)\right)^2 + \left(\frac{\partial y}{\partial t}\right)^2 + \left(\frac{\partial z}{\partial t}\right)^2\right]}$$

Equation 2

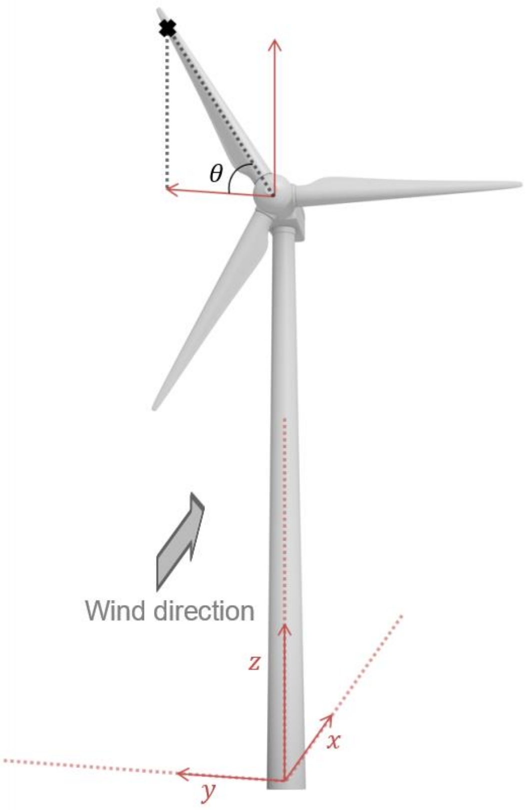

Figure 1: Illustration of the (x, y, z) reference coordinates

Note that these equations include aerodynamic drag while lift is not taken into account (i.e. a force perpendicular to the relative motion of the ice fragment through the air). Lift can, however, be included to the basic model given above. Good examples of more elaborate models can be found in Baker (2007) and Noda & Nagao (2010).

Depending on how the ice piece is being modelled, the drag can either be represented as a constant or be reassessed over the course of the trajectory form variable frontal areas and drag coefficients (Biswas, Taylor, & Salmon, 2011). This is further described in Section 2.2.

Solving these equations gives the position and speed of an ice fragment over time in three dimensions. The base of the turbine tower is the origin of the co-ordinate system and therefore solving for $z = 0$ (or for complex terrain, finding the point at which the ice hits the ground) gives the along-wind and lateral position as well as the impact velocity at the end of the flight of the ice fragment.

To assess the overall risk of ice strike or ice fall on a point or area of interest, is not enough to understand the trajectory of a given particular ice piece. The impact point depends on multiple parameters and each parameter can vary over a certain range. This includes variation of the initial position and velocity of the ice piece as well as the properties of the ice piece itself, which will be discussed in more details in sections 2.2 and 3.2.

To obtain the probability distribution for impact of ice pieces at the site, all these parameters need to be statistically combined. One shall therefore couple the trajectory model to a statistical model. This can be done using a deterministic model or a Monte Carlo simulation covering the different parameter ranges. For example, Figure 2 illustrates the trajectory of one ice fragment as part of an overall impact probability distribution.

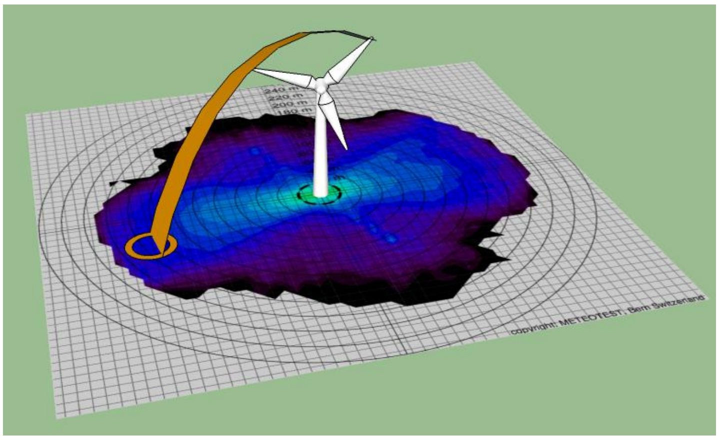

Figure 2: From one trajectory to a probability distribution (Source: courtesy of Meteotest)

2.2. Modelling the Ice Fragment

The equations of motion describe a single trajectory of one well defined ice fragment. The trajectory varies for different fragment dimensions and density. To achieve a reasonable result for ice throw risk assessments, the characterization of the variety of ice pieces is important. A single ice piece is defined by its mass (or density) and dimensions. Examination of the equation of motion (Equation 1) shows that the mass and dimensions of the ice fragment only enter in the form of the fraction of A/m ("form factor" A over m).

For ice throw and ice fall risk assessments, one shall use a representative description of the ice pieces for solving the equations of movement by adopting either one of the two approaches below.

- Use a fixed representative A/m distribution if known and a constant drag coefficient C_D.
- Use a mass distribution derived from size and density of a number of 'representative' fragments and a representative value of the drag coefficient C_D for the ice fragments.

If a mass distribution is used, the ice pieces can be approximated as a rectangular box with the side lengths a, b and c. It should be kept in mind that A is then not the same depending on the orientation of the ice piece and the direction of the relative motion through the air. In this case, rotation of the ice pieces shall also be considered.

For the observed ice piece distributions, see also Section 3.2.2.

The drag coefficient depends on the shape of the ice fragment and linearly enters the drag force. Typical values for an ice fragment range from $C_D = 1$ to $C_D = 1.2$ (Morgan & Bossanyi (1996); Seifert, Westerhellweg, & Kröning (2003)).

2.3. Wind Turbine Characteristics

While the previous section described the characterisation of the ice fragment itself, this section now aims at the influence of the turbine geometry and operational parameters on the initial condition of the ice fragment when it detaches from the blade and starts on its trajectory.

The geometry of the turbine, the position of the blade, and the position along the blade, from which the ice fragment detaches, give the initial position in space of the ice fragment. One shall therefore use the following four parameters to describe the (x, y, z) coordinates of the initial position of the fragment (see Figure 1).

- The hub height
- The rotor diameter
- The position of the blade (described by the angle θ as per Figure 1)
- The position on the blade from which the ice fragment is released

Additionally, some more turbine specific parameters like the tilt angle of the rotor, the rotor's offset from the tower centre, a more realistic blade shape than the idealized 'string geometry‘ model of the blade, and the pitch angle of the blade can help define the initial location with more accuracy. However, they have not been deemed part of the core assumptions defining the trajectory and are therefore not essentially required for ice throw and ice fall assessments.

The turbine specifications not only describe the initial position (x, y, z) of the ice fragment but also determine its initial speed (in the components u_x, u_y, and u_z). The operational status of the turbine implies a rotational speed of the rotor and therefore the speed of the ice fragment upon detaching from the blade. One shall therefore consider the operating mode (see Section 4) and the resulting rotational speed of the turbine at the time of throw.

If the turbine is operational, one shall consider the rotational speed of the rotor at the time of the throw in combination with the radial position of the fragment along the blade and the angle θ of the blade to calculate the initial speed in its three components. In cases where the turbine is idling, the rotational speed of the rotor shall also been taken into account.

When the turbine is fully operational, the rotational speed of the rotor will depend on the wind speed. The climatic parameters shall therefore be taken into account. This is further discussed in Sections 2.4 and 3.1.

For the radial position of the ice on the blade, one can either assume a probability distribution or use a heuristic model (see Section 3.2.1 for further details).

2.4. Environmental Characteristics

Wind speed and wind direction affect the position and the rotational speed of the turbine blades which define the initial position and the initial speed for the calculation of the trajectory. As the wind speed is changing with altitude due to terrain roughness, the wind speed variation with height above ground level – denoted as $V(z)$ in Equation 1 and 2 – shall be considered. This can be approximated by, e.g., a logarithmic or exponential vertical wind profile. Further details on wind data are given in Section 3.1.

Optionally, turbulence intensity and gust can be added in the model for additional variance of the wind data along the trajectory.

The air density ρ linearly enters the drag force and thus its impact on the drag is of the same magnitude as the drag coefficient. Air density is essentially altitude dependent and ranges from about 1.3 kg m^{-3} at sea level to about 1.0 kg m^{-3} at 800 hPa (~2000 m above sea level).

In case of complex terrain (e.g. wind turbine on a mountain ridge), the impact positions of the ice fragments will in general not be at $z = 0$ but at some other level according to the slopes of the surrounding area and one therefore shall account for the effect of terrain variation. It can be included directly in the model or corrections to the landing points of the trajectories can be added by a manual post-processing. In case of flat terrain, with only fractional changes in elevation, the topography can be neglected.

Summarizing the paragraphs above, the following environmental parameters shall be considered:

- Wind speed, wind direction, and vertical wind profile (see Section 3.1)
- Air density
- Topography in complex terrain

Optionally, the following may be considered:

- Gust
- Turbulence intensity

3. Data Set

3.1. Wind Data

The methods for determining the wind statistics used for ice throw and fall assessments shall in general follow international and regional standards and best practice. Additionally, the following points shall be taken into account:

- Wind statistics based on 10 minute (or less) averaging representative for periods when ice throw and ice fall may occur.
- Long term correction necessary if available data cannot be regarded as a long term dataset.
- Wind statistics representative for the turbine location considering horizontal and vertical extrapolation, with respect to risk assessment.

The bin width of any wind speed used in the above shall be 2 m/s or less and the wind direction sectors shall be 30° or less. Wind measurements with a higher temporal resolution than 10 minutes or alternatively, information about the standard deviation of wind speed, can be taken into account at sites with a significant impact of gusts on the trajectories of the ice pieces.

Seasonal variations in wind conditions can be more or less significant depending on local wind climate. The relevance of the adopted wind statistics for periods when ice throw and ice fall may occur, shall therefore be considered and motivated. As illustrated in Figure 3, rotor icing periods differ from meteorological or instrumental icing due to a delayed start of the actual rotor icing (incubation) and a delayed end of the rotor icing (persistence). These effects can be important to consider when deriving wind statistics relevant for periods when ice throw and fall may occur. Wind statistics based on e.g. only a few icing events shall be avoided since it can result in too narrow wind distributions not covering all plausible events.

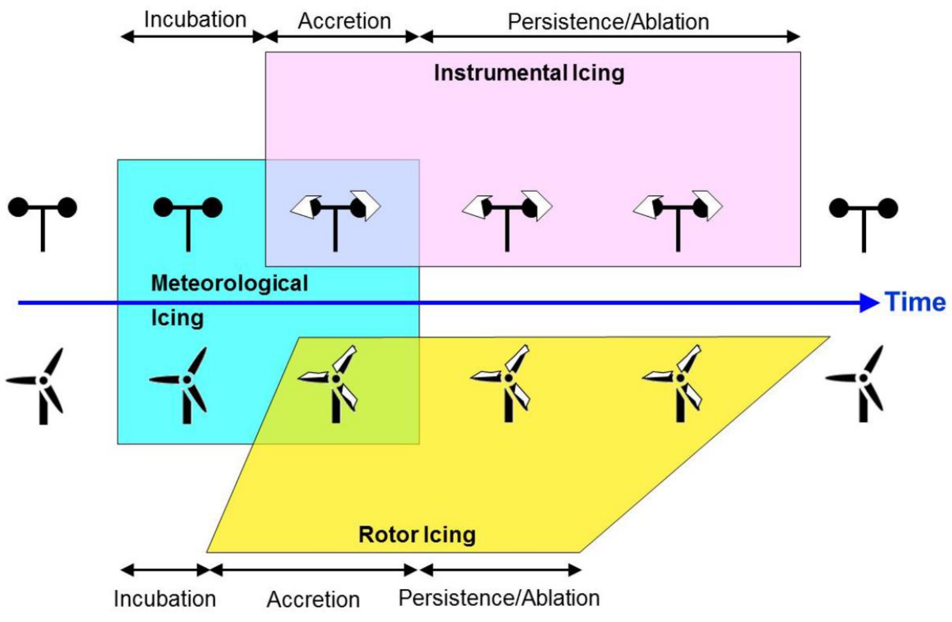

Figure 3 Definition of Meteorological Icing, Instrumental Icing, Rotor Icing, Incubation, Accretion, Persistence, and Ablation (IEA Wind, 2017)

The site wind parameters shall be either measured and extrapolated or calculated using appropriate methods (e.g. monitoring measurements made at the site, long-term records from local meteorological stations, simulation models or local codes and standards). Simulation models shall be calibrated against site representative data.

The following parameters shall be derived for the position of the wind turbine at hub height:

- Wind speed probability density function (e.g. Weibull) or time series
- Wind shear (representative for the entire height of the wind turbine)

3.2. Icing Data

The icing data used for ice throw and fall assessments depend on icing conditions at the site and the icing characteristics of the wind turbine. Both affect the two main parameters of the icing data relevant for ice throw and fall assessments, which are:

- Amount of ice
- Properties of ice pieces

The first two subsections introduce and describe the above mentioned icing parameters, followed by two subsections about how the site icing conditions and wind turbine icing characteristics can be considered when assessing suitable values and ranges with regard to icing parameters.

3.2.1. Amount of Ice

The amount of ice can be described in terms of e.g. number of ice pieces per year or accumulated ice mass per event together with the number of events per year and weight of each ice piece. The amount of ice constitutes one of the most significant uncertainties for an ice fall / ice throw assessment, and shall therefore be carefully considered and justified. Below are three examples of methodologies which may be used to determine the amount of ice:

- Scaling of site measurements of ice throw data
- Ice load distribution formula
- Ice accretion simulations

The methodologies are briefly described below. All methodologies based on models or simulations are highly dependent on their assumptions, and should be verified with experimental data, e.g. ice throw site measurements from field studies. Care should be taken with on-site ice throw measurements as not all ice pieces and events might have been considered and the year-to-year variability of icing is significant (Cattin, Koller, & Heikkilä, 2016).

Scaling of site measurements of ice throw data from a site study to the site of interest can be done by e.g.:

$$N_{\mathrm{site}} = sf_{\mathrm{ice}} \cdot sf_{\mathrm{rotor}} \cdot sf_{\mathrm{op}} \cdot N_{\mathrm{obs}}$$

Equation 3

Where N_{site} is the amount of ice at the site of interest derived by scaling the amount of ice from site measurements (N_{obs}) with scaling factors for site icing conditions, (sf_{ice}), rotor dimensions (sf_{rotor}), and operational mode (sf_{op}). The uncertainty of this method highly depends on the validity of each scaling factor.

The ice load distribution from IEC 61400 (IEC, 2018) can be used to estimate the amount of ice on the leading edge of a single blade. In this approach, the specific ice mass per length increases linearly from the root to the tip of the blade:

$$M(r) = 0.125\ \mathrm{kg/m^3} \cdot Ch_{85\%} \cdot r$$

Equation 4

Where $M(r)$ is the ice mass distribution (mass per unit length) on the leading edge, $Ch_{85\%}$ is the chord length at 85% of the rotor radius, and r is the radial position from rotor axis. Integrating the mass distribution over the entire blade length gives the total ice mass on the blade per event (one accretion/shed cycle). As this blade ice mass distribution is meant to be used for design load cases of the wind turbine, it should be scaled to the site by, e.g., measurements of ice throw data from site studies.

Ice accretion simulations, based on a representative blade cylinder model (i.e. International Organization for Standardization (2017)) or more advanced blade ice accretion modelling (e.g. Lamraoui, et al. (2014)), can be used to derive the amount of ice. The models rely on meteorological input, which can be obtained by, e.g., measurements or meso-scale numerical weather prediction models together with a suitable microphysics scheme. Both the ice accumulation model and modelling of the meteorological parameters rely on the correctness of their parameterization, simplifications and assumptions. Current research results show an uncertainty of several orders of magnitude in derived strike probabilities, when comparing ice accretion models with observations (Drapalik & Bredesen (2017), Bredesen, Drapalik, & Butt (2017)).

3.2.2. Properties of Ice Pieces

The properties of the ice pieces thrown or falling from the wind turbine relevant for modelling can be described by several combinations of their physical properties e.g.

1. Area and mass.
2. Three dimensions (length, width and thickness) and ice density of the ice piece.
3. Ratio of area and mass (A/m).

Several ice piece collection campaigns have been conducted in the past, measuring dimensions and weights of ice pieces thrown or fallen from wind turbines (e.g. Müller & Bourgeois (2017), Lundén (2017)). The results from different campaigns show differences in weight and area distributions, which may be a result of several factors, such as icing conditions, de-icing and control system set-up, turbine size etc. However, less variation between different data sets was observed for the ratio of area over mass (A/m). The A/m ratio is a key factor in ice throw trajectory simulations using e.g. the equations from Biwas, Taylor & Salmon (2011). A merge of five different campaigns containing in total approximately 1250 ice pieces with recordings of area and weight exemplifies the range of observed A/m from small to medium size wind turbines in Figure 4 below:

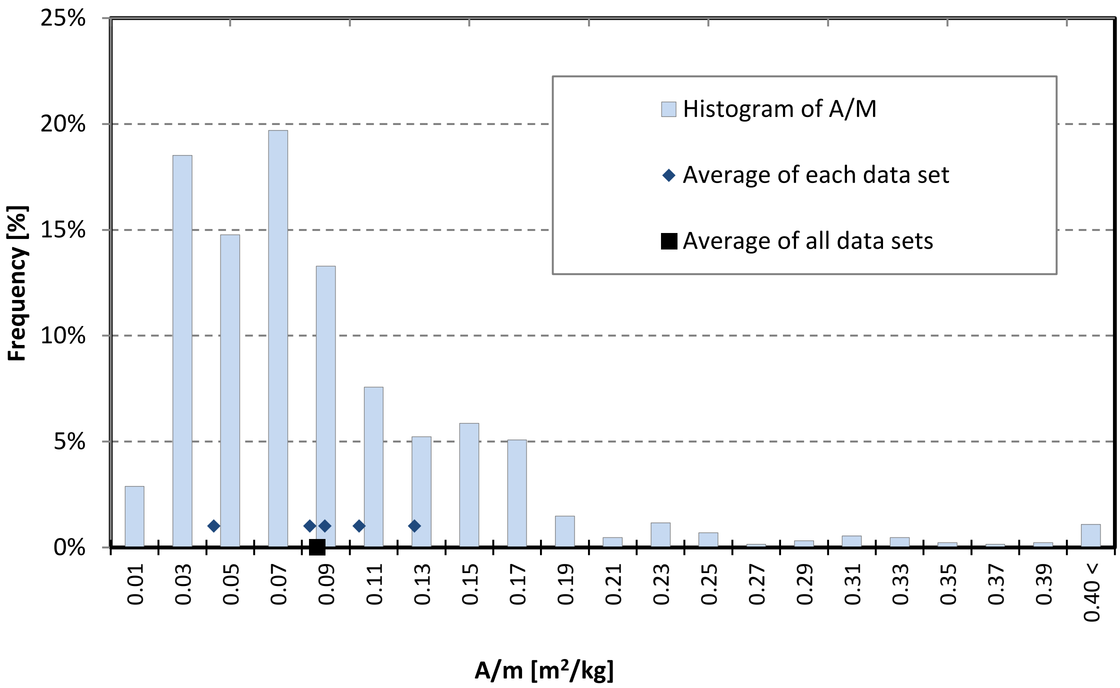

Figure 4: A/m histogram (columns) and average values for merged data set and individual data sets (cross).

This histogram illustrates how the ice piece properties can look like when considering all fragments above 50 g released from all positions on the blade. Note that its shape and mean value can vary from site to site and that another distribution may be considered to be more accurate for a given site or turbine configuration. The ice pieces' frontal area A used in the histogram is assumed to be a rectangle based on the two largest dimensions of the observed ice pieces. This is an overestimation compared to the actual projected area of the ice piece. Depending on the defined reference area and the corresponding drag coefficient used in the trajectory model, it may be necessary to adjust the distribution. Müller & Bourgeois (2017) show an example of A/m histogram from ice piece collection campaigns based on the mean area of each ice piece ($A = [a \cdot b + b \cdot c + a \cdot c]/2$, where a, b and c are the three spatial dimensions of the ice piece).

Figure 4 also depicts the average A/m value for the merged set (black diamond) as well as for the individual data sets (blue diamonds). The spread of the individual data sets is partly due to the statistical basis since the number of pieces from each individual data set range from 54 to 580, but also due to variations in icing conditions, and wind turbine set-up. Each ice piece from all the collection campaigns is equally weighted in the merged histogram.

3.2.3. Site Icing Conditions

The method for determining the icing conditions at the site shall in general follow international and regional recommendations and best practice (e.g. IEA Wind (2017), DNV-GL (2017)). Additionally, the following points shall be taken into account:

- Method(s) clearly defined and motivated
- Icing conditions representative for the long term

Methods for determining the site icing conditions include, but are not limited to: instrumental icing determined from wind measurements, icing maps, SCADA data analysis, and ice detectors (see Bredesen et al. (2017)). Using two methods to verify and justify the conditions should be considered to reduce uncertainty. The site icing conditions mainly influence the amount of ice accreted according to current state of knowledge. The conditions can be applied to the site-specific assessment by, e.g., scaling data from ice throw measurements, counting the number of icing events or direct simulations of accreted ice.

Long term representativeness of the icing conditions shall be ensured by using long term data or correcting short term data with long term meteorological conditions. Simple and approximate corrections can be done by, e.g., comparing number of frost and ice days between short and long term period.

3.2.4. Wind Turbine Icing Characteristics

The wind turbine characteristics which shall be considered in terms of influence on icing data are at least:

- Rotor dimensions
- Operational mode

The rotor dimensions mainly influence the amount of ice according to current state of knowledge. Influence on the weights and dimensions of the ice pieces could also be possible. The literature suggests different equations to calculate the amount of ice accumulated on a blade (see Section 3.2.1), which can be used for scaling site measurements from one turbine rotor size to another (i.e. sf_{rotor} in Equation 3). These equations are simplifications of the complex nature of ice accumulation. Furthermore, the lack of experimental data when it comes to the differences between rotor dimensions implies a high uncertainty and necessity to use a conservative approach.

The operational mode of the turbine may influence both the amount of ice accreted and the ratio between thrown and fallen ice pieces according to current state of knowledge. Due to the many systems and solutions available on the market (see Krenn et al. (2016)), each wind turbine with specified settings and system capabilities should be examined to determine its consequences with regard to ice throw and fall. The operational mode is herein defined by the following sub-systems:

- Ice detection system
- Ice protection system (e.g. anti- or de-icing system)
- Control system

For the ice detection system, considerations can be made to what extent the system accurately detects rotor icing, consequences of delay and accuracy of detection method etc. Several technical solutions for ice protection systems are available on the market, and the capabilities and reliability therefore differ. The control system defines whether the wind turbine stops rotating, idles or continues to operate when the ice detection system detects ice, as well as at which preconditions the turbine re-starts if it was stopped. The control system can also trigger a potential ice protection system, such as a blade heating system which can be active during operation, idling or at standstill. The operational mode and its consequences with regard to ice throw and fall shall be described and motivated. In case the consequences of an operational mode are unknown, conservative assumptions shall be made and justified.

Manual ice throw and fall measurements carried out on several ENERCON E-82 turbines in an IEA icing class 4 site for 3 years have shown an average yearly number of ice pieces of the magnitude shown in Table 2. The number of pieces for icing class 4 was extrapolated to the other classes by considering meteorological icing. Manual ice throw and fall measurements of the same turbine type in IEA icing class 3 site have confirmed the magnitude shown in Table 2.

IEA Icing Class	Meteorological icing (% of year)	Instrumental icing (% of year)	Production loss (% of year)	Yearly number of ice pieces per wind turbine (ice pieces/year)
5	> 10	> 20	> 20	> 8000
4	5 – 10	10 – 30	10 – 25	4000
3	3 – 5	6 – 15	3 – 12	2000
2	0.5 – 3	1 – 9	0.5 – 5	1000
1	0 – 0.5	0 – 1.5	0 – 0.5	200

Table 2: IEA icing class including yearly number of ice pieces per wind turbine, based on manual site measurements of ENERCON E-82 turbines with and without de-icing system and in different operational modes.

The values are corrected for missed events, uncertainties in collection efficiency etc. Several different de-icing and control system settings were investigated, and a variation in number of pieces of ±50% was observed. This ±50% range could be exceeded for other turbine types and operating modes than the ones investigated. The table includes ice pieces weighing 50 g or more. A weight threshold of 100 g would result in approximately 25 % less ice pieces. These values are affected by uncertainties but can serve as an indicative range.

4. Risk Assessment

Risk assessments use tools 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. The iterative process of a risk assessment following the DIN ISO 12100 and of gaining risk understanding in the knowledge domain and in the physical domain is shown in Figure 5. The key question is whether the risk is as low as reasonably achievable. A risk analyst therefore needs the competence and experience to be able to identify relevant risks and to give concrete advice on the most beneficial risk reducing measures on a case by case basis. In any risk assessment, it is important to be aware of 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.

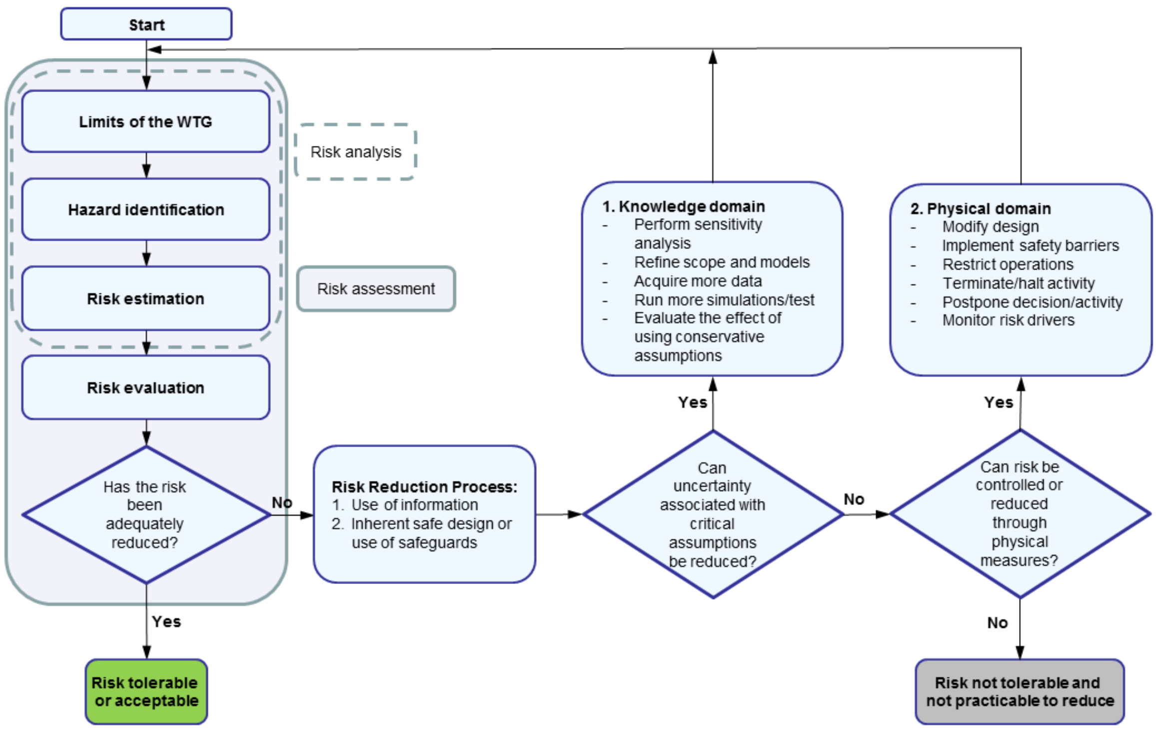

Figure 5 Risk assessment following DIN ISO 12100 as a tool to gain risk understanding, which is necessary to manage and keep the risk under control. The risk management process in the knowledge and physical domain enables sufficient understanding and confident decision-making (Source: courtesy of TÜV NORD)

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[2].

[2] Note that the Norwegian National guidelines (Directorate Norwegian Water Res.&Energy, 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.

For using the correct terminology in risk assessments and for a better understanding of this section, the most relevant terminology is summarised in the appendix of this document (see Section 7.1).

4.1. Methods of Risk Analysis

4.1.1. Introduction

Risk analyses are appropriate tools for establishing quality- or quantity-based descriptions of existing uncertainty and for calculating the effect of various decision-making options. To do this, risk analyses employ the common 'formula'

Risk = Likelihood (probability of occurrence) · Consequence (impact of occurrence).

Under this formula, a higher likelihood of occurrence is usually deemed acceptable where the level of damage is lower. At higher levels of damage, the frequency of occurrence must be reduced in order to reach an acceptable risk level. High levels of damage coupled with high frequency of occurrence are unacceptable. It is easy to understand that a 'grey area' or borderline exists between acceptable and unacceptable risk, in which improvements may be possible or useful.

Risk analyses are used to provide an initial statement about absolute risk. To prepare for taking risk-based decisions, this risk value must be classified and assessed by comparing it with the defined accepted risks. This obviously complex task is fraught with uncertainties (see Section 0), given that the borderline between acceptable and unacceptable risk is not clearly defined.

Example for the definition of an acceptable risk:

Setting a vehicle in motion presents a (permissible) hazard. Compliance with speed limits is based on the fundamental assumption that the frequency of incidents and impact of their consequences are then generally acceptable.

In general, two criteria can be considered:

1. If the level of damage exceeds a certain limit, measures must always be taken. An incident of this kind always falls into the 'unacceptable' chapter of the diagram, irrespective of the likelihood of its occurrence.
2. The same applies to incidents that occur excessively frequently. Here too, a limit applies from which – irrespective of the level of damage – the unacceptable range begins, since even on purely operational grounds the level of risk is deemed too high.

4.1.2. Likelihood of Occurrence

To determine the likelihood of occurrence, an ice fall analysis of the relative frequency of ice fragments in the vicinity of the wind turbines shall be performed for the planned sites of the turbines (see Sections 3 and 4). For further treatment, the results shall be normalized to a realistic number of ice fragments per year as shown exemplarily in Table 1 of Section 4.

Once this preparatory work is done, the likelihood of occurrence of being hit by an ice fragment can be calculated. Under consideration that each hit leads to a fatality, this value can be set equally to the localized individual risk (LIRA). If this value is lower than the risk acceptance criteria from Table 6 the analysis is done regarding the individual risk (the societal risk have to be evaluated nonetheless), otherwise the consequence and the exposure shall be considered to calculate the individual risk per annum (IRPA). (Compare Bredesen, Flage, & Butt (2018) and Bredesen & Refsum (2015).)

Note that these suggested acceptance criteria based on LIRA shall motivate further risk mitigating efforts. It is also suggested to present the risk in probability maps using iso-risk curves as described in the IEA recommended practices *Wind Energy Projects In Cold Climate* (IEA Wind, 2011):

"A risk analysis of ice throw can be presented as iso-IR (individual risk) lines. IR is defined as the risk per m^2 *and year to be hit by an object of significant size. The IR should be calculated for the winter season only."*

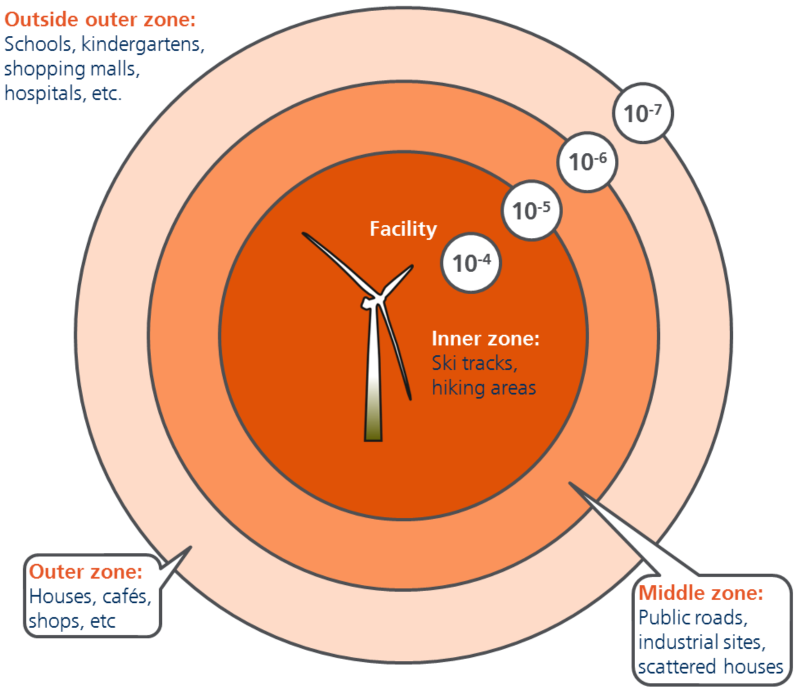

Figure 6: Suggested safety zones around installation that may cause risk of ice throw or ice fall. The numbers indicate the iso-risk contours for localized individual risk (LIRA), the probability that an average unprotected person, permanently present at a specified location, is killed during one year due to ice fall or throw from the facility.[3] *(Source: courtesy of Lloyds Register / Kjeller Vindteknikk)*

4.1.3. Consequence

Dependent on the given scenarios, different approaches for setting the consequences and the exposure (see next section) are possible, e.g.

1. Individual persons moving on roads / paths
2. Vehicles moving on roads
3. Persons inside areas
4. Vehicles inside areas

[3] Note that the 10^{-4} LIRA risk contour corresponds to a time exposure for one person 0.2 percent of the time with an IRPA level of $2x10^{-7}$ or the societal risk associated with, e.g., 500 people present 0.2 percent of the time.

The difference between 1 and 2 and between 3 and 4 is that persons in vehicles are sheltered and a fatality as a direct consequence of the hit is unlikely. Nonetheless, an indirect hit on a vehicle could have fatal consequences due to speed of the vehicle, oncoming traffic or other obstacles and has to be taken into account. Between [1, 2] and [3, 4] the difference is in the calculation method for the exposure.

Probit function

To determine the consequences more realistically, the probit function method described in Royal Library (1989) can be used to assess the mortality rate of unprotected persons (likelihood of fatality from projectile impact to the head). The probit function is expressed as

$$Pr = -15.56 + 5.3 \cdot \ln S$$

where

$$S = \frac{1}{2} m \cdot u^2$$

Equation 5

and thus depends on the kinetic energy of the projectile (in units of [kg m^2 s^{-2}]). This function is used to determine the likelihood of fatality when an individual experiences impact at velocity v to the head by a projectile with mass m. The function is valid for masses from 0.1 to 4.5 kg. Mortality as a function of the probit function is shown in the following Table 3 (see also Royal Library (1989)).

%	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.90	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33

%	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

Table 3 Correlation between likelihood of fatality and probit function value.

Values of the probit function beyond the range shown in Table 3 are either negligible (lower or negative values) or lead to a definitive fatality if they are bigger.

4.1.4. Exposure

When considering individual risk, a realistic assumption about the exposure for a hypothetical person can be e.g. a commuter traveling forth and back on a road once per day. For the evaluation of the exposure for the societal risk, the following points shall be considered:

- Exact knowledge about the number of by-passers or presence during a day (recommended).
- If the knowledge is not available, the number has to be estimated conservatively.
- In special cases, site visits can lead to a more reliable estimation.
- Exposure time shall cover activities during conditions when ice fall and ice throw may occur.

Pedestrians

As for the leisure use on footpaths usually no exact numbers are available, a categorization of these paths can be undertaken as exemplarily shown in Table 4[4].

Category	Definition
Regularly used route	Given the state of development, accessibility and proximity to settlements, the route must be assumed to be used regularly, i.e. practically daily, by walkers or joggers. For this classification it is sufficient if a single jogger or walker regularly uses the route.
Frequently used route	Not all the above characteristics apply to this route; for example, greater distance from settlements and poor access lead to the assumption that this route is not used daily, but still frequently used by walkers or joggers.
Occasionally used route	This category includes routes that are clearly identifiable as such but not clearly identifiable as main routes, and with a state of development and accessibility that indicate occasional use.
Rarely used route	This category includes routes that are identifiable as such and feature condition and accessibility indicating rare use.
Route usually unused	Routes that are clearly identifiable as access tracks for forestry or agricultural use or that are a long distance from the nearest residential settlement are generally regarded as usually unused. Exposure is determined in terms of the chance presence of a single person in the vicinity.

Table 4 Categories of routes in the analysis (example)

[4] Numbers allocated to this type of table should have a logarithmic scale, e.g. an exposure during icing conditions ranging from 10 times per year for the highest category down to 0.1 times per year for the lowest category.

Vehicles

For superior roads like highways and federal roads, numbers of a national traffic census should be available and shall be used. For smaller roads, often a local traffic census has been made, so these numbers shall be inquired from the local authorities. If no numbers are available, an estimation of the traffic density can be done[5].

Relevant impact area

To determine the likelihood of impact the following assumptions for the relevant impact areas should be taken.

Impact area Vehicles
Relevant impact area: 2 m² (the windscreen is taken as the relevant point).

Pedestrians and bikers
Relevant impact area: 0.04 m² (head impact is taken as relevant) up to 0.1 m² (torso impact is additionally taken into account).

4.2. Risk Acceptance Criteria

Following the usual definition of risk as combination of the likelihood of an event and its consequences, the task of risk analyses is to determine systematically the sources of risk and the associated parameters probability and consequence (International Organization for Standardization, 2009). Risk evaluation is then the process of comparing the risk against given risk criteria to determine the significance of risk (International Organization for Standardization, 2009). Risk assessment as the overall process of risk analysis and risk evaluation can then be used to demonstrate that specific protection goals for occupational health and safety or for the safety of the public are achieved. This demonstration requires a definition of what risk is acceptable or not.

4.2.1. Generic Approaches for Defining Risk Acceptance Criteria

The MEM – Principle

The MEM (*minimum endogenous mortality*) principle requires that a new technological system must not cause significant increase in the individual risk compared to the minimum endogenous mortality rate. Endogenous mortality means death due to internal causes such as injuries connected with birth or degenerative diseases. The lowest endogenous mortality rate in Western countries is given for children between 5 and 15 years of age, known as 'minimum endogenous mortality' and designated Rm, is expressed as

[5] There are big regional differences. For example, in Germany on highways the range is from 10,000 to 150,000 cars per day, municipal roads start from 100 cars per day or less, state roads and federal roads are between these numbers.

$$Rm = 2 \cdot 10^{-4} \quad [\text{fatalities}/(\text{person} \cdot \text{year})]$$

Equation 6

According to the EN 50126 (CENELEC, 2017), a significant increase is 5 % of MEM, which translates into the following limits:

- *R1* ≤ 10^{-5} fatalities per person and year
- *R2* ≤ 10^{-4} serious injuries per person and year
- *R3* ≤ 10^{-3} minor injuries per person and year

These limits can be taken as absolute upper limits. Risks that exceed them are absolutely unacceptable for individuals[6].

The ALARP Principle

For practical implementation in the risk assessment, the UK Health and Safety Executive suggested to distinguish three areas or regions of risks: “Broadly accepted”, “tolerable” and “unaccepted” or “intolerable” risk (Figure 7).

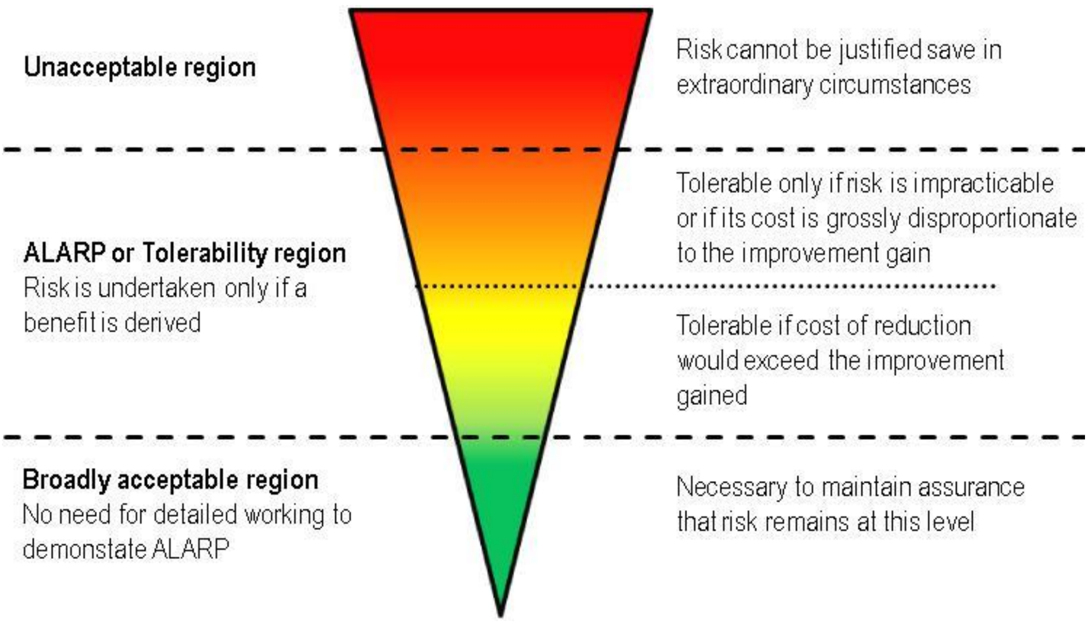

Figure 7: ALARP principle (HSE, Health and safety Executive)

Here, the general definitions as proposed in Kalberlah, Bloser, & Wachholz (2005) are adopted:

“The ‘acceptance threshold’ defines the transition to a low risk for harmful health effects. Exceeding this acceptance threshold but falling below the danger threshold indicates entry into the region of concern.”

[6] The acceptance limit for persons exposed to risk during their work should be multiplied with an additional factor when people have an advantage (e.g. financial) while taking the risk.

The region of concern is identical with the tolerability region of the UK Health and Safety Executive in Figure 7.

"The 'tolerance threshold' defines the transition to an unacceptable risk for harmful health effects. Exceeding the tolerance threshold indicates entry into the danger region" (Kalberlah, Bloser, & Wachholz, 2005).

Risk for the general population (leisure activities)

	Cause / Activity	Risk of fatalities per person
traffic	Railway	$4.4 \dots 15 \cdot 10^{-6}$/ a
traffic	car drivers	$2.0 \dots 2.2 \cdot 10^{-4}$/ a[7]
traffic	Aircraft (passengers)	$0.67 \dots 1.2 \cdot 10^{-4}$/ a
Leisure activities	Mountain climbing	$1.0 \dots 2.7 \cdot 10^{-3}$/ a
Leisure activities	Parachuting (USA)	$2.0 \cdot 10^{-3}$/ a
Leisure activities	Holiday (UK 1990)	$1.0 \cdot 10^{-4}$/ a
Everyday life	Fire in buildings	$8.0 \cdot 10^{-6}$/ a
Everyday life	Household activities	$1.0 \cdot 10^{-4}$/ a
Everyday life	Lightning (UK, USA)	$1.0 \dots 5.0 \cdot 10^{-7}$/ a

Table 5 Examples for individual risks of the general population (Proske, 2004)

Risk acceptance criteria to be applied shall be oriented towards relevant statistics representing local conditions or towards the values from Table 5 if there are no other meaningful statistics.[8]

As an example, for the determination of the acceptance criteria for superior roads in Germany the ease and safety of traffic has to be secured. Therefore, the fatal accidents ("death") and the accidents involving seriously injured persons from national traffic census should be used to define the actual risk on e.g. highways. The actual risk must not rise significantly, this results in the upper limit for the collective risk on superior roads. Similar to the basic idea of the MEM principle, a lower limit should also be defined (e.g. 5% or one magnitude below the risk to be compared with). Within the ALARP-range risk, reducing measures should be considered.

[7] $2.0 \cdot 10^{-5}$/ a is the current best performance index (achieved for Norway 2017).

[8] For specific aspects (e.g. roads) risk can have the unit [fatalities per km and year].

4.2.2. Individual and Societal Risk

With regard to tolerable risk, one shall, in addition to individual risks, also consider societal risks, due to the fact that accidents (e.g. on a highly frequented highway) can affect many persons.

Societal risk is here understood as the total risk for the sum of persons that could be affected in the considered scenario (sometimes evaluated by Potential Loss of Life - PLL). In contrast to the individual risk, the societal risk involves the total number of all possible victims. In this view, an event with many fatalities is stronger weighted than an event with fewer fatalities. To quantify the collective risk, the so-called F-N curves became largely accepted. They are based on the equation $F(N) = C/N^{\alpha}$. Here, $F(N)$ represents the corresponding frequency with a number of N or more fatalities. C is a constant factor defining the overall position of the F-N curve for $N = 1$ and corresponds to the individual risk. The so-called risk aversion factor α allows to represent the fact that an event with many victims is less accepted or tolerated the more fatalities could occur (Proske, 2004). Figure 8 shows two representative examples of F-N-curves from the UK and the Netherlands. The transition area (or ALARP region, see Figure 7) between acceptable and tolerable risk covers two orders of magnitude.

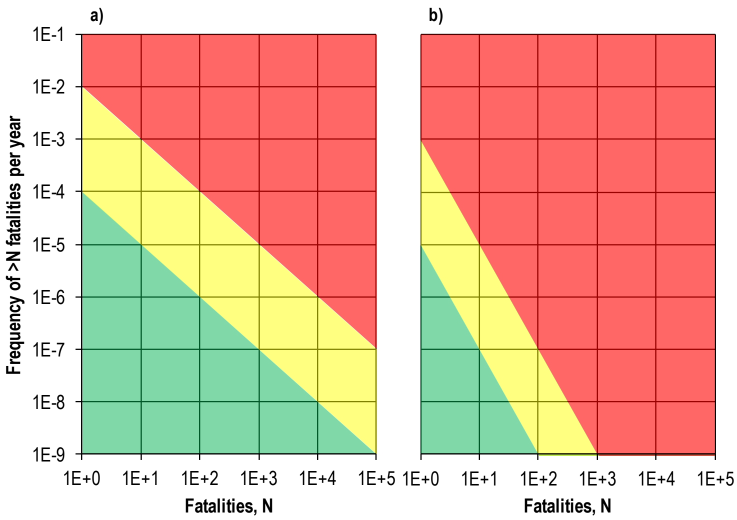

Figure 8: Examples for societal risk criteria in a) United Kingdom and b) the Netherlands (Floyd & Ball, 1998)

It should be noted that no risk aversion is taken into account in the UK, whereas in the Netherlands a risk aversion factor of two is used. In our opinion, there is definitely a risk aversion in the society. However, to simplify the procedure and with respect to the relatively low amount of harmed people per event, in the present case risk aversion can be ignored. According to (Trbojevic, 2015) for societal risks a combination of both approaches shown in Figure 9 should be used (see Table 6).

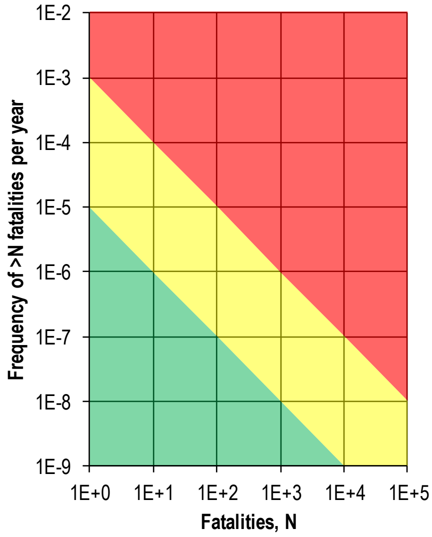

Figure 9: Simplified compromise for societal risk

4.2.3. Summary: Risk Acceptance Criteria to be Used

The following summary gives an exemplarily advice when to use individual risk as a benchmark and when societal risk has to be used instead. In general, the individual and the societal risk shall be considered and the relevant one(s) should be taken into account for defining measures.

Individual risk:

- Ways, paths, and small roads which are used by a small amount of people.
- Objects like barns, huts…, which are used regularly by the owner or by a small amount of by-passers.

Societal risk:

- State roads, federal roads, highways. Municipal roads if they are frequently used.
- Objects like barns, huts which are of general interest for the public (e.g. if they are a famous sight), official parking areas, industrial sites.

The numbers of Figure 8 and Figure 9 are no fixed values as certain circumstances may increase benchmarks for the individual or the societal risk. Figure 8 and Figure 9 can be understood as follows:

Risk value [1/a]		Evaluation
Societal risk (without risk aversion)	**Individual risk**	
> 10^{-3}	> 10^{-5}	The risk is unacceptable high. Risk reduction measures shall be initiated.
10^{-4} to 10^{-3}	10^{-6} to 10^{-5}	The risk is high and it is located in the upper ALARP region. Well-known risk-reducing measures shall be implemented and it is advised to look for additional risk-reducing measures.
10^{-5} to 10^{-4}	10^{-7} to 10^{-6}	The risk is tolerable and in the lower ALARP region. If further common measures to reduce the risk are known, they should be examined under cost-benefit aspects. A recommendation to implement such measures is not pronounced.

Table 6 Example for individual and societal risk criteria

As can be seen from Table 6, the risk values between societal and individual risk differ by two orders of magnitude. There are no strict risk acceptance criteria as limit given, as there are sometimes boundaries, like special public interest, which can be an argument for accepting higher risks in a designated area. However, the following thresholds can been identified clearly in Table 6:

- If the calculated risks are lower than 10^{-7} (individual) and 10^{-5} (societal), they are lower than risks people are exposed in normal life.
- If the calculated risks are higher than 10^{-5} (individual) and 10^{-3} (societal) the risk is unacceptable. Extensive risk reduction measures (e.g. relocation or change of turbine specifications, see Table 8) can be initiated to re-assess whether the risk can be sufficiently reduced.
- In the region between these thresholds (ALARP region) the residual risk can usually be reduced with different measures, a relocation of the wind turbine is not necessary.

4.3. Effect of Risk Reducing Measures to the Result

Once a risk is calculated, it should be decided whether a risk reduction is necessary or not. Which sort of measures can be implemented is different from country to country due to legal requirements and within countries there are sometimes regional differences. In some countries for example, it is possible that the public right of way does not accept to close a path or a road during ice fall conditions, whereas in other regions this is acceptable, also site-specific demands shall be considered.

In its simplest form the required warning system for the ice throw hazard for the public are suitably located signs. This may be enough for remote areas that are rarely visited during the weather conditions associated with icing events. 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 in order 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 ALARP principle (As low as reasonably practicable, associated with acceptable cost). So, in this section, different sorts of measures are listed and discussed. Which measures are useful and practicable in a given situation shall be decided site-specific.

4.3.1. Global Quantitative Measures

The term “quantitative measure” means that an effectivity can be allocated to the measure. This can be expressed by a risk reduction factor (RRF), by which the risk is reduced. In this terminology, a RRF of, e.g., 10 means that a safety measure reduces the risk by a factor of 10. In the following table, the most common quantitative measures are listed with a suggested range for the RRF.

Category	Safety measures	Risk reduction (RRF)	Appropriate for
Reduction of likelihood of presence	Warning signs of ice fall conditions	1 to 10	Minor roads and paths
	Warning light connected to the ice detection system on the turbine in combination with warning signs	10 to 100	Minor roads and paths
	Physical barrier (official road closure) and signs	10 to 100	Roads and official frequently used hiking paths

Table 7: Quantitative measures for the risk reduction

The maximum achievable risk reduction in Table 7 is 100. The next order of magnitude (1000) is not reachable whenever human errors have to be considered. Consequently, a risk in the unacceptable area from Table 6 cannot be reduced into the acceptable area with the common measures discussed in Table 6. Therefore, other measures have to be taken into account.

4.3.2. Measures That Require Recalculation

If closure of roads, paths or other areas is not possible or does not lead to the desired effect, other measures, that mean mostly hardware adaption and/or structural measures and mostly require recalculation of the project, are possible (see Table 8).

Category	Safety measures	Remark
Adopting hardware and / or structural measures	Fixed nacelle yaw angle (Optimized for the protected object)	A recalculation is necessary. Fixing the nacelle yaw angle can also increase the risk, this is dependent on the local conditions
	New turbine dimensions (Reducing the rotor diameter or the hub height)	A recalculation is necessary.
	Relocating the wind turbine	
	Rerouting the road / path	A recalculation is necessary in most cases. Sometimes, e.g. when the original risk profile shows that a new route is not hit by an ice fragment, no new calculation is necessary.
	Rerouting the road / path in winter	
	Adaption of operational strategies	For example, ice-detection methods or restart procedures after shut-down.

Table 8: Measures that require recalculation

Technical solutions like blade-heating have not predominantly been developed to reduce the risk, but they may change the risk depending on the system and configuration.

4.3.3. Qualitative Measures

Additional measures, which have an effect but cannot be assessed quantitatively, should be considered independent from the measures discussed above. (see Table 9).

Category	Safety measures	Remark
Awareness of residents	Communication strategy	Independent from the calculated risk, these measures should be taken to inform the residents and – as a long term strategy – change their behaviour.
	Regular education to change behaviour of people.	

Table 9: Qualitative measures

5. Uncertainties of Ice Fall / Ice Throw Risk Assessments

As any attempt to model natural phenomena, also the assessment of risk due to ice throw / ice fall from wind turbines is linked with uncertainties.

A simplified risk assessment often delivers a singular value R_0 for the risk (e.g. $R_0 = 10^{-7}$ fatalities per year). However, this singular value often represents a mean value or an expected value for the risk and the actual risk cannot be calculated with any desired precision, as many factors or influence have an impact on the uncertainty of the result (e.g. lack of knowledge, inaccuracy of underlying databases or environmental boundaries). These factors may exemplarily be:

- Number of icing days per year
- Mass of the ice fragments considered
- Relevant impact area
- Number of affected people or probability of presence
- Assumed consequence
- …[9]

The uncertainties of the individual factors of influence lead to an overall uncertainty in the end result of the risk analysis (see Section 4). Yet, no concrete recommendations can be given regarding the values of uncertainties or safety margins for ice throw / ice fall risk assessments, as the individual uncertainties vary depending on the given task, the quality of data basis, the chosen methodology and the site-specific situation. 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. There is a good background knowledge related to ice throw and ice fall and there is consensus among experts on where the large uncertainties lie. However, it has to be pointed out that there is also a general agreement amongst the experts that additional research work is necessary before definitive answers regarding the treatment of uncertainties can be given.

From a more general perspective, it is important to distinguish between factors of influence that have an effect on the landing positions of the ice fragments and those that have a direct effect on the calculated risk level.

On the one hand, for the former set of factors of influence, a conservative approach in the selection of the values does not necessarily lead to a more conservative (i.e. careful) result of the risk assessment. This applies to all parameters that have an impact on the landing positions of the ice fragments next to the wind turbine, e.g. the physical parameters of the used ice fragments, data for wind speed and wind direction, etc.. Selecting conservative values for those parameters might for example lead to a conservative estimation of the maximum distances of falling ice fragments, but at the same time result in an underestimation of the likelihood of being hit in the closer vicinity of the wind turbine. Hence, those parameters and values shall be selected as realistic as possible. For example, calibrating the mathematical model with field observation results significantly reduces the uncertainty of the impact positions of the ice fragments.

On the other hand, there are factors of influence that have a more direct effect on the conservativeness of the results. Examples for such parameters are the number of considered ice fragments, estimations of the effectivity of measures, the assumptions for the size of the hit area, or the selection of thresholds to the

[9] The more detailed the risk model is, the more factors of influence need to be considered.

acceptable risk level. Therefore, safety margins and conservative values respectively shall be applied for those aspects.

Since no definitive recommendations regarding the treatment of uncertainty factors can be given, the approach used for handling of uncertainties shall be clearly motivated and described in the assessment.

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7. Appendix

7.1. Terminology

The following definitions are derived from the *ISO Guide 73 - Risk management — Vocabulary* (International Organization for Standardization, 2009), which defines the internationally acknowledged binding terminology for the terms of risk. Some definitions have been omitted, as they are not relevant for the purpose, others have been added or changed. In these cases, the discrepancy to (International Organization for Standardization, 2009) has been noted.

Risk: (from DIN ISO 12100 **(International Organization for Standardization, 2010)**)

Risk = Likelihood (probability of occurrence) · Consequence (impact of occurrence)

Risk assessment:

Overall process of risk analysis and risk evaluation (Risk identification is part of the risk analysis)

Risk analysis:

Process to comprehend the nature of risk and to determine the level of risk

NOTE 1 Risk analysis provides the basis for risk evaluation and decisions about risk treatment

NOTE 2 Risk analysis includes the risk identification and risk estimation.

Risk evaluation:

Process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable

NOTE Risk evaluation assists in the decision about risk treatment.

Hazard:

Source of potential harm

NOTE Hazard can be a risk source

Likelihood: (shortened in relation to ISO Guide 73)

Chance of something happening

Probability:

Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty. NOTE: See definition of “Likelihood”

Frequency:

Number of events or outcomes per defined unit of time

NOTE Frequency can be applied to past events or to potential future events, where it can be used as a measure of likelihood/probability.

Consequence:

Outcome of an event affecting objectives

NOTE 1 An event can lead to a range of consequences.

NOTE 2 A consequence can be certain or uncertain and can have positive or negative effects on objectives.

NOTE 3 Consequences can be expressed qualitatively or quantitatively.

NOTE 4 Initial consequences can escalate through knock-on effects.

Risk level:

Magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood

Risk categories: (additional to ISO Guide 73)

Categories of resulting and residual risk, often displayed in the risk matrix with different colours. Common categories are:

- acceptable
- tolerable
- high
- unacceptable

Risk acceptance:

Informed decision to take a particular risk (can be different for different group of people) / Socially accepted risk, even if not everyone is always aware of the exact risk

NOTE 1 Risk acceptance can occur without risk treatment or during the process of risk treatment.

NOTE 2 Accepted risks are subject to monitoring and review.

NOTE 3 Acceptance criteria may vary between different countries, cultures and situations

Risk treatment:

Process to modify risks

NOTE 1 Risk treatment can involve:

- avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk;
- taking or increasing risk in order to pursue an opportunity;
- removing the risk source;
- changing the likelihood;
- changing the consequences;
- sharing the risk with another party or parties [including contracts and risk financing]; and
- retaining the risk by informed decision.

NOTE 2 Risk treatments that deal with negative consequences are sometimes referred to as “risk mitigation”, “risk elimination”, “risk prevention” and “risk reduction”.

NOTE 3 Risk treatment can create new risks or modify existing risks.

Risk reduction factor (RRF): (additional to ISO Guide 73)

The factor by which a calculated quantified risk can be reduced by implementing a measure.

Residual risk:

Risk remaining after risk treatment

NOTE 1 Residual risk can contain unidentified risk.

NOTE 2 Residual risk can also be known as “retained risk”.

NOTE 3 Residual Risks are not always quantifiable

Risk profile / Risk area: (differing from ISO Guide 73)

Subsequent areas on the ground near to a windturbine which can be allocated to different risk categories under given scenarios or circumstances, seperated by iso-risk lines (in reality the risk continuously rising the lower the distance is).

As the actual risk is a product of the likelihood of ice fragments coming down and the likelihood of people present in the surrounding of the wind turbine, the term danger/risk zone (often defined by rules of thumb) has to be used with due care in risk assessments.

LIRA (Localized individual risk): (additional to ISO Guide 73)

The probability that an average unprotected person, permanently present at a specific location, is killed during a period of one year due to a hazardous event.

IRPA (Individual risk per annum): (additional to ISO Guide 73)

The probability that a specific or hypothetic individual will be killed due to exposure to the hazards or activities durung a period of one year.

NOTE Individual risk [fatalities/person and year]

PLL (Potential Loss of Life): (additional to ISO Guide 73)

The expected number of fatalities within a specific population per year

NOTE 1 PLL = n · IRPA (n=number of people in the population)

NOTE 2 Societal risk [fatalities/year]

Minimum endogenous mortality (MEM): (additional to ISO Guide 73)

Mortality due to internal causes such as genetic constitution, injuries connected with birth, or degenerative diseases. By contrast, exogenous mortality is connected to external causes such as infectious diseases or accidental injuries.

ALARP: (additional to ISO Guide 73)

As low as reasonably practicable, i.e. associated with acceptable cost. Equivalent to the abbreviation ALARA for "as low as reasonably achievable".

ALARP principle: (additional to ISO Guide 73)

Means that the residual risk shall be reduced as far as reasonably practicable.

7.2. List of Symbols

Symbol	Description	Units
x, y, z	Along-wind, lateral and vertical components of position vector of the ice fragment	[m]
t	Time	[s]
m	Mass of the ice fragment	[kg]
A	Frontal area of the ice fragment in the direction motion relative to the air	[m^2]
a, b, c	Three main spatial dimensions of the ice piece	[m]
$V(z)$	Wind speed at height z	[$m\ s^{-1}$]
u_x, u_y, u_z	x, y, and z components of velocity of the ice particle in space	[$m\ s^{-1}$]
$\|U\|$	Magnitude of velocity of the ice particle relative to the air	[$m\ s^{-1}$]
g	Gravitational acceleration	[$m\ s^{-2}$]
ρ	Air density	[$kg\ m^{-3}$]
C_D	Coefficient of drag	
$M(r)$	Ice mass distribution on the leading edge	[$kg\ m^{-1}$]
r	Radial position from rotor axis	[m]
$Ch_{85\%}$	Chord length at 85% of the rotor radius	[m]
N_{site}	Amount of ice for the wind turbine on the site of interest	
N_{obs}	Amount of ice from site measurements	
sf_{ice}	Scaling factors for site icing conditions	
sf_{rotor}	Scaling factors for rotor dimensions	
sf_{op}	Scaling factors for operational mode	

Pr	Probit function	
S	Kinetic energy of the ice fragment	[kg m^2 s^{-2}]
u	Velocity of the ice particle in space	[m s^{-1}]
$F(N)$	Frequency with a number of N or more fatalities	[yr^{-1}]
C	Constant factor defining the overall position of the F-N curve for $N = 1$	[yr^{-1}]
α	Risk aversion factor allows to represent the fact that an event with many victims is socially less accepted	