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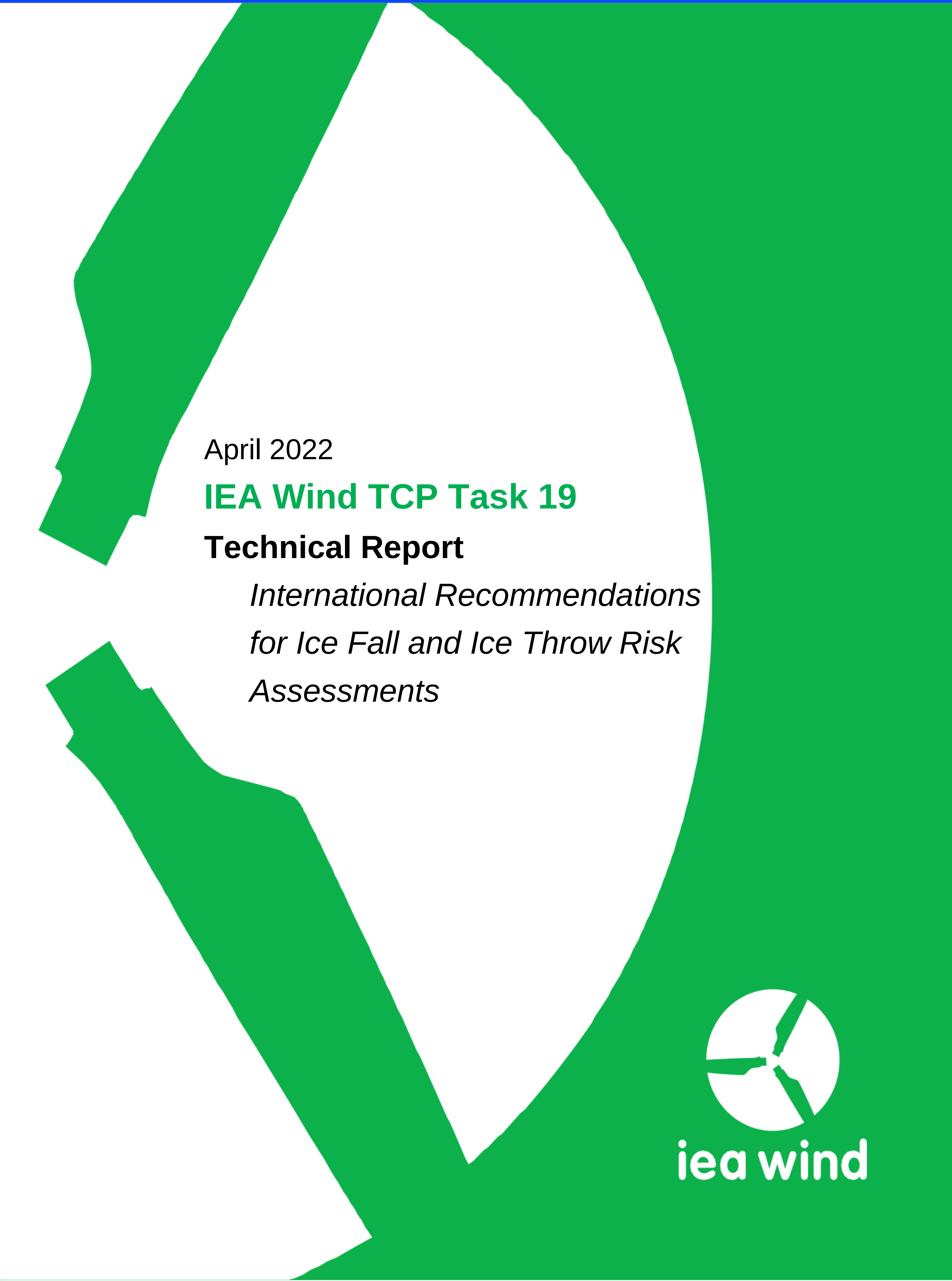

April 2022

IEA Wind TCP Task 19

Technical Report

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. The first edition was the result of a two-year creation process and intended to give answers regarding the selection and definition of the essential methodology and input parameters for ice throw / ice fall risk assessments. The second edition four years after refines this methodology according to the latest scientific findings and gives further guidance on selected topics. In this respect, the authors are confident that the guidelines presented in this document will again pave the way forward to more transparency and increase the quality of ice-risk assessments internationally.

The recommendations presented herein compile expert knowledge on risk assessment procedure and do not present any form of legal counsel. In particular risk reducing measures and their estimated effectivity must not be misconstrued to have any form of legal effect in juristic disputes. In general the national laws and standards regarding the assessment of ice throw / ice fall risk must 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 applicable.

Andreas Krenn

IEA Wind TCP, Task 19 Wind Energy in Cold Climates

April 2022

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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 119 GW at the end of 2020, with an expected growth rate of approximately 9 GW per year until 2025 (Karlsson, 2021). 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 utilization of general safety distances via rules of thumb. [See pages 50-53 in IEA Wind (2018).]

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 standstill and idling. While ice or snow falling from the tower or the nacelle (e.g. snow accumulation on the nacelle

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

roof or ice formation near the heat exchangers) 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. Ice or snow coming from the tower or the nacelle might nevertheless be an important consideration for occupational health and safety.

This document is solely concerned with the health and safety aspect of ice fall and ice throw, i.e. the threat to life and limb of people in the vicinity of wind turbines. Ice pieces from wind turbine can also cause material damage to vehicles, buildings and other infrastructure. Methods and data from Sections 2 and 3 can be used to compute the likelihood of such damages. The assessment of risks of material damage is, however, not covered by the present document.

Beyond ice fall/throw, there are other scenarios, such as tower collapse or blade throw, where a wind turbine may cause harm to people in its vicinity. To some degree, the assessment of such threats would use similar methods and similar acceptance criteria than outlined in this document. The scope of the present recommendations is nevertheless restricted to ice fall and ice throw.

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 characterizing 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

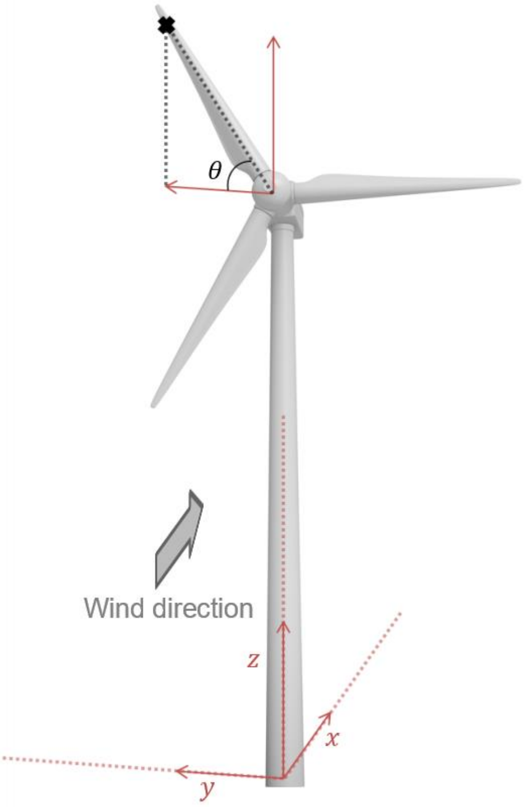

Figure 1: Illustration of the (x, y, z) reference coordinates

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.

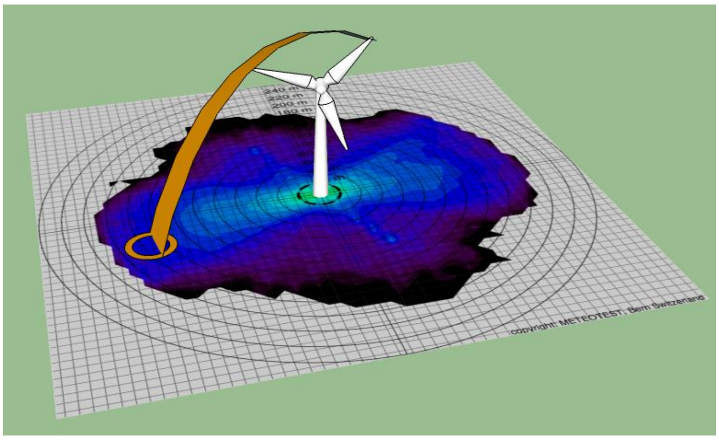

Figure 2: From one trajectory to a probability distribution (Source: courtesy of Meteotest)

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 characterization 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 center, 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. Wind data can be clipped above a certain wind speed (strong wind / storm conditions) if the presence of people at the given location can be reasonably excluded under such conditions.

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.

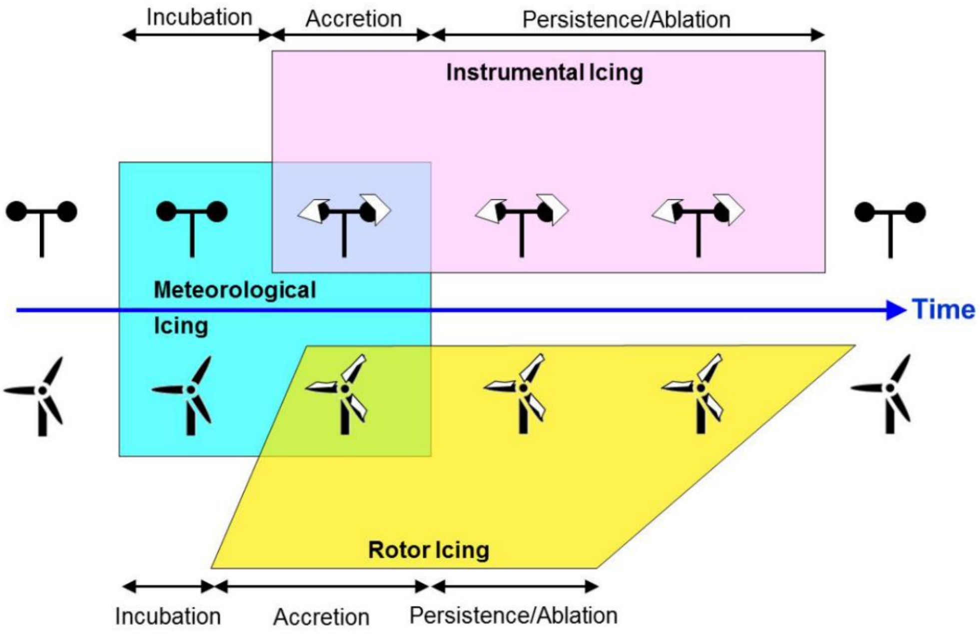

Figure 3: Definition of Meteorological Icing, Instrumental Icing, Rotor Icing, Incubation, Accretion, Persistence, and Ablation (IEA Wind, 2017)

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.

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

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.

There are two basic assumptions relations that can be used for the estimation of the scaling factor for the rotor size (sf_{rotor}), namely:

- The total surface of the rotor blade goes with the square of the rotor radius. Assuming a uniform ice accumulation on the surface of different size rotor blades would thus give an ice mass that increases with the square of the radius.
- The collision efficiency of water droplets on the leading edge of a rotor blade depends on the balance of inertial forces and aerodynamic forces on the droplets and decreases for larger leading edge radii (Makkonen (2000); Finstead, Lozowski & Gates (1988)). Rime ice growth – calculated as the product of collision efficiency times cross section – is thus small both for very small and very large leading edge radii and has a maximum at some 10 cm radius, depending on droplet size. According to this argumentation, the main robust dependency of rime ice mass accumulation is on the length of the leading edge, i.e. scaling linearly with the radius of the rotor.

These two assumptions are however simplifications of the actual icing processes and the actual dependency on the rotor size will in many cases lie in between a linear and a square dependency. Overall, one can thus use an intermediate scaling law in the form of:

$$sf_{\text{rotor}} = const. \cdot R^{\sqrt{2}}$$

Equation 4

Note that this is a rough estimate only, as there is insufficient data available to test the suggested form of scaling law, and even less so, for an ab-initio derivation of such a scaling law.

The ice load distribution from IEC 61400-1 (International Electrotechnical Commission (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:

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

Equation 5

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). This blade ice mass distribution is meant to be used for the computation of extreme and fatigue structural loads of the wind turbine and therefore does not correspond to the typical ice mass to be expected on a particular site. Hence, 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:

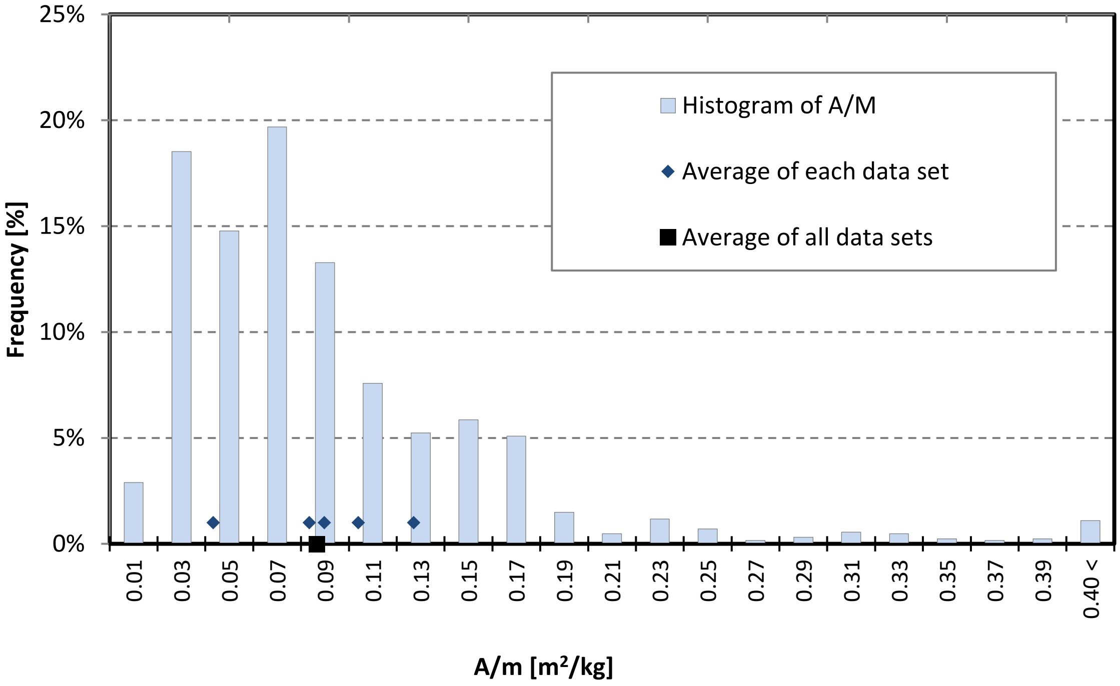

Figure 4: A/m histogram (columns) and average values for merged data set and individual data sets (cross).

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 IEA Wind (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 IEA Wind (2018)), 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 (IPS, e.g. a rotor blade heating 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 active IPS in anti-icing operational mode (activated during operation) or de-icing operational mode (activated after shut-down when idling or at standstill) (see Godreau et al. (2020)). 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.

Ice piece number as effected by different IPS and operational modes

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)**			
				Idling No active IPS (a)	**Idling IPS de-icing (b)**	**Operational No active IPS (c)**	**Operational IPS anti-icing (d)**
5	> 10	> 20	> 20	> 3200	> 8800	> 9600	> 8000
4	5 – 10	10 – 30	10 – 25	1600	4400	4800	4000
3	3 – 5	6 – 15	3 – 12	800	2200	2400	2000
2	0.5 – 3	1 – 9	0.5 – 5	400	1100	1200	1000
1	0 – 0.5	0 – 1.5	0 – 0.5	80	220	240	200

Table 2: IEA icing class and corresponding yearly number of ice pieces per wind turbine, based on manual site measurements of ENERCON E-82 turbines (78 m HH) with and without active IPS, respectively in anti- or de-icing operational mode (column (a), (b) and (d)), and an extrapolation from the values of column (a) to the operational state without active IPS (column (c), see paragraph below).

Measurement campaign (column (a), (b) and (d))

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% for each of the columns (a), (b) and (d) 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 for (a), (b), and (d).

Extrapolation (column (c))

The numbers of ice pieces were extrapolated by calculations based on long-term mesoscale climatic data of the site. Ice accretion was modelled for the idling not heated wind turbine (column (a)) and for the operating not heated wind turbine (column (c)). Both simulations result in different average total ice masses per year on the rotor due to the different apparent wind speeds along the rotor blades. The increase in ice mass was directly used as a factor for the increase in ice pieces falling from the operating not heated wind turbine. This means it was assumed that the mass distribution of ice pieces falling from the idling and operating wind turbine remains unchanged. The numbers of ice pieces as given in column (c) are not directly comparable to the data in columns (a), (b) and (d) as the numbers in column (c) are not directly based on measurements but were calculated using simplifying assumptions and thus have higher uncertainties.

Ice piece weight as effected by different IPS and operational modes

Based on manual site measurements of ENERCON E-82 turbines at an IEA icing class 4 site and using an idling turbine without active IPS as reference (Table 2, column (a)), following observations can be enunciated:

- Expected average piece weight for an idling turbine with active IPS in de-icing mode is up to 50% smaller than reference.
- Expected average piece weight for an operational turbine with active IPS in anti-icing mode is up to 40% smaller than reference.

The order of magnitude of ice pieces fallen/thrown for different icing classes, as well as the decrease in expected average ice piece weight for different IPS operational modes, may be used as informative guideline but cannot serve as normative references, as these numbers/factors are specific to the mentioned turbine type and its respective sub-systems, such as ice detection system and IPS, as well as to the meteorological conditions at the measurement and verification site. Furthermore, the data are subject to uncertainties of unknown magnitude, e.g. with respect to collection efficiency. It is also important to note that icing is a phenomenon considered to have a high inter-annual variability (Cattin, Koller, & Heikkilä, 2016).

Both expected icing properties described above (number of pieces and piece weight) are based on an ENERCON E-82 turbine in an ice-prevention-setup with the following characteristics,

- Ice detection by means of power curve deviation method.
- Equipped with hot-air circulation system inside blades.
- Automatic heating when ice detected:
    - Operational-heated mode: at least 1-hour heating; Turbine goes in idling-heated mode if operational heating is not sufficient to remove icing.
    - Idling-heated mode: 1-hour heating cycle[2]; Turbine returns to idling-heated mode if ice still detected after cycle.
- Automatic turbine restart after icing events.

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[2] Heating cycle duration used for testing purposes in an idling/ heated turbine at an IEA icing class 4 site. Current cycle standard is 4-hour for idling/ heated, which could be assumed to produce less ice throw/ more ice fall.

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 (International Organization for Standardization (ISO), 2010) 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.

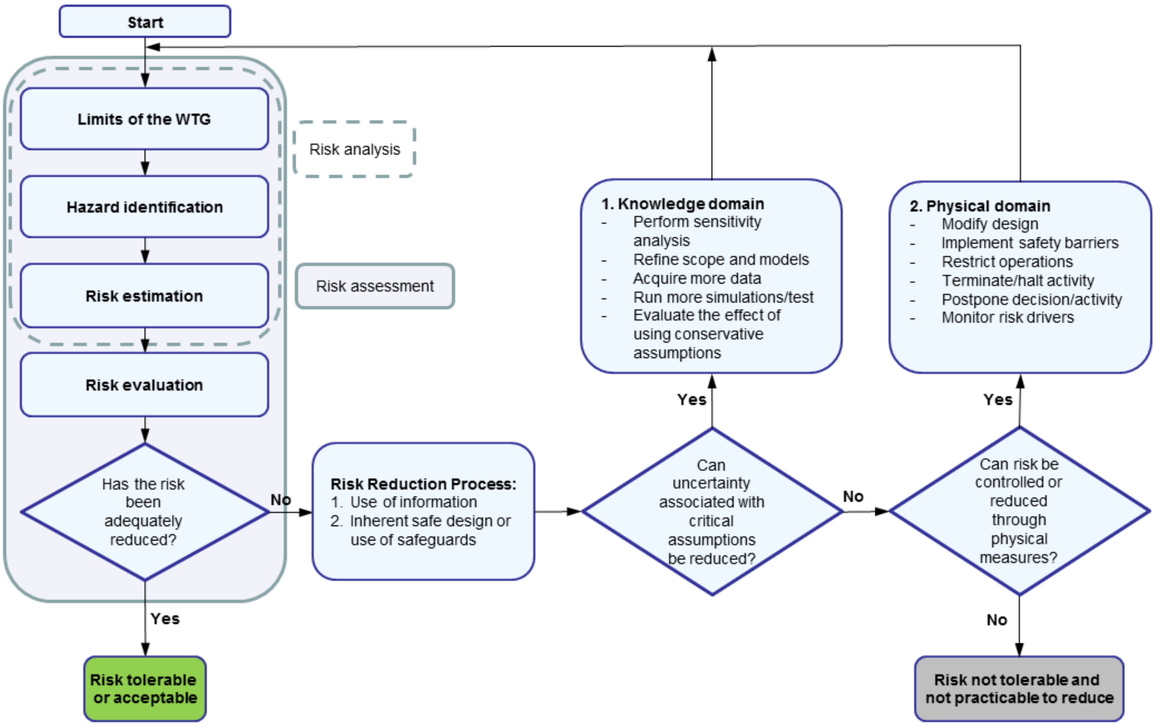

Figure 5: Risk assessment following DIN ISO 12100 as a tool to gain risk understanding, which is necessary to manage and keep the risk under control. The risk management process in the knowledge and physical domain enables sufficient understanding and confident decision-making (Source: courtesy of TÜV 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[3].

For using the correct terminology in risk assessments and for a better understanding of this section, the most relevant terminology is summarized in the appendix of this document (see Appendix A: Terminology).

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

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 5), 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 2 and 3). For further treatment, the results shall be normalized to a realistic number of ice fragments per year as shown exemplarily in Table 2.

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 5 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). (Cf. 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."*

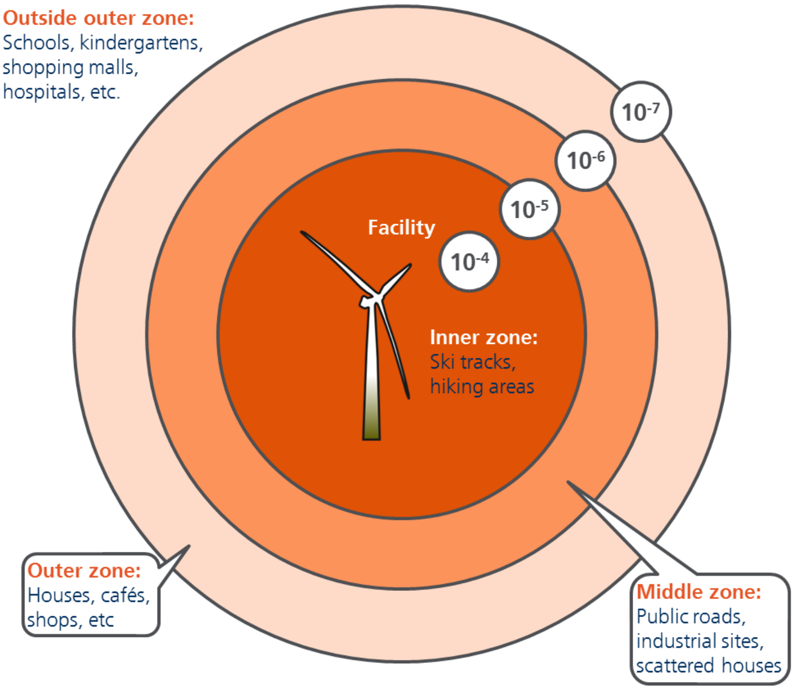

Figure 6: Suggested safety zones around installation that may cause risk of ice throw or ice fall. The numbers indicate the iso-risk contours for localized individual risk (LIRA), the probability that an average unprotected person, permanently present at a specified location, is killed during one year due to ice fall or throw from the facility.[4] *(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

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.

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[4] 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.

Probability of lethal consequences

The estimation of the likelihood of lethal consequences of unprotected persons from the impact of ice pieces is, because of the diversity of possible circumstances and the scarceness of data, difficult to assess. One useful reference is CPR 16E (Committee for the Prevention of Disasters caused by dangerous substances, 1992), where three different ranges of projectile masses are discussed: 0,001 to 0.1 kg, 0.1 kg to 4.5 kg, and above 4.5 kg. For the case of ice fall, the intermediate mass range is relevant and in this range a lethality rate P_{lethal} is given in the form of a probit function[5]

$$P_{\mathrm{lethal}} = \mathrm{Pr}(-17.56 + 5.3 \cdot \ln S)$$

Equation 6

where S is the kinetic energy (in units of [kg m^2 s^{-2}]) of a projectile with a mass m and an impact velocity u

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

Equation 7

An illustration of the resulting lethality versus impact energy curve energy for projectiles with a mass between 0.1 and 4.5 kg is given in Figure 7. The limits of this mass range do not affect the applicability of this curve to the scenario of ice fall / throw from wind turbines: Ice pieces with masses smaller than about 100 g can hardly exceed the threshold of potentially lethal impact energies; and ice pieces with masses above 4.5 kg in an ice fall scenario would be considered to be 100% lethal anyway.

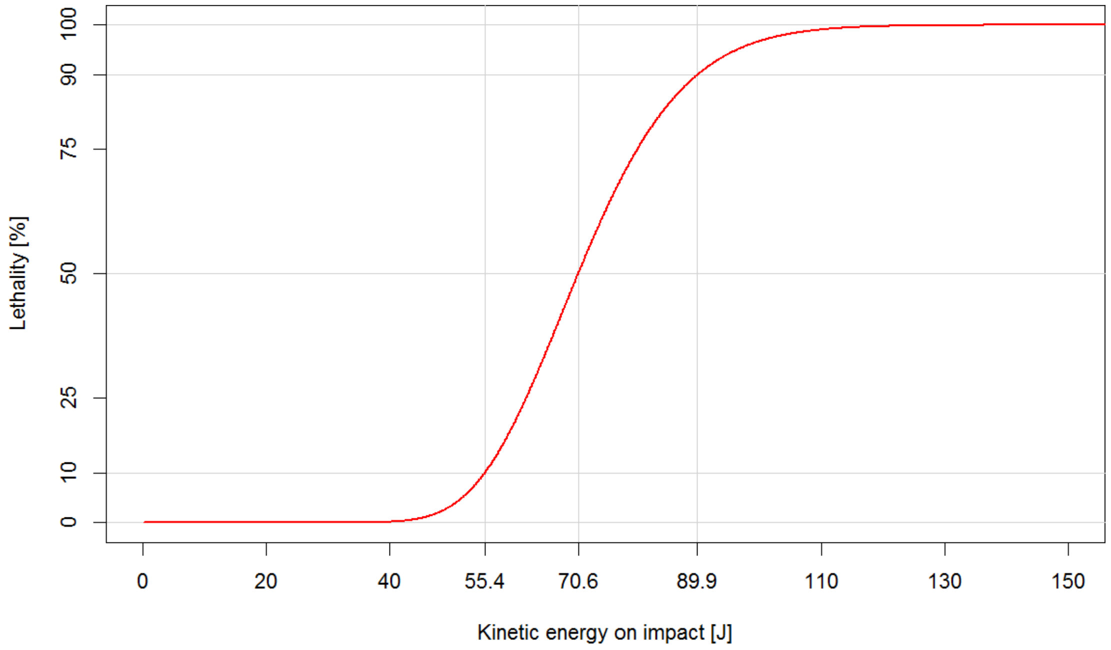

Figure 7: Correlation according to CPR 16E between lethality rate and the impact energy for projectiles with a mass between 0.1 and 4.5 kg.

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[5] Cumulated normal distribution with $\mathrm{Pr}(x) = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right)$. The location and the width of the distribution are given by the mean ($\mu = 5$) and the variance ($\sigma^2 = 1$), respectively. erf is the error function.

Another useful source of data is (Feinstein, Heugel, Kardatzke, & Weinstock, 1968). This study is focused on military causalities but also contains data on two scenarios that are relevant for ice fall / throw from wind turbines, namely:

- Skull fracture by the impact of a blunt object on the head (cross section 0,03 m^2) with a probability of lethality of 10%/50%/90% for impact energies of 90J/127J/179J.
- Fracture of large bones of the limbs (cross section 0,14 m^2) with a probability of lethality of 10%/50%/90% for impact energies of 288J/418J/613J.

These numbers for lethal impact energies are significantly higher than those from CPR 16E and thus confirm that Equation 6 and Figure 7 are conservative estimates. It is thus recommended, to use the energy limits from CPR 16E (Equation 6 and Figure 7) for ice fall / throw risk assessments.

Another factor adding to the conservativeness is that both studies refer to impacts of objects of very low deformability and thus, the results should only be related to high-density ice. For other ice types (brittle, lower density) the consequences of impacts will be less severe, but not exclusive of minor injuries.

Consequences to persons in vehicles

A fatality of a person in a vehicle as a direct consequence of an ice piece impact is theoretically possible, depending on a sufficiently high impact energy. Based on a United Nations agreement (United Nations, 2015), first met in Geneva in 1958, car windshields are required to sustain impact energies of minimum 89 J. A study concerned with the consequences of items falling / being thrown from overpasses has shown, that commercially available wind shields generally sustain impact energies of up to 140 J (Spathonis, 2001). An ice piece with a residual energy of 90 J after breaking through a wind shield could directly cause a fatality with a probability of 90% according to Figure 7. The probability of a respective combination of ice piece weight, consistency, trajectory and relative speed to the car being hit is nonetheless very low. Conversely, the established necessary impact energy of minimum 180 J can serve as a threshold up to which a respective ice piece is highly unlikely to directly cause a fatality.

The indirect consequences of an ice piece impacting on a vehicle or very close-by (e.g. on the road directly in front of the vehicle) also need to be taken into account, for instance loss of control over the vehicle and/or a crash into an obstacle or another vehicle. Multiple factors influence the possible outcomes of such a scenario that in most cases cannot be calculated/simulated exhaustively by a reasonable effort. Hence, conservative assumptions need to be made where necessary. An overall conservative approach is to assume every ice piece or a non-negligible fraction impacting on a vehicle to cause a fatality. A typical ratio between accidents with fatal and non-fatal consequences can be established as 1 to 10. A similar ratio can also established between near-miss and minor accidents (Herry, Sedlacek, & Steinacher, 2011).

A factor that however can be considered and entered into an assessment, is the crash protection that is offered by the current generation of vehicles. Crash tests according to Euro NCAP (Euro NCAP, 2021) require a car's design to absorb the impact energy of a head-on collision with a mobile progressive deformable barrier[6], where both the car and the barrier move at a speed of 50 km/h towards each other. The impact energy absorption must be to an extent that, in conjunction with safety equipment such as airbags, restraints etc., severe trauma is averted for all passengers. Hence, if the speed of vehicles is below this threshold of 50 km/h (e.g. on a road section where a speed limit is in force), lethal consequences for the occupants in an ice-impact triggered road accident can be excluded with high certainty, even for the

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[6] A mass of 1.400 kg mounted onto a chassis.

worst case scenario of a head-on collision. Imposing a speed limit of 50 km/h on affected roads in times of ice fall conditions or in winter times in general is thus a viable risk reducing measure (see Table 8).

Severe trauma and death can possibly occur in case of an impact velocity higher than 50 km/h in a crash as described above. In that case, one can employ a velocity-dependent scaling law for the consequence of a head-on collision. The expected consequence is proportional to the kinetic energy of the impact, which is in turn proportional to the square of the velocity. Furthermore, considering the reaction time of the driver as well as the effect of any driver reactions onto the vehicle dynamics adds two additional powers of the velocity. This suggests a scaling law proportional to the velocity to the power of four for the probability of a fatal accident as indirect consequence of an ice-piece-impact on a car windshield.

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 3[7].

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[7] 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.

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 3: Categories of routes in the analysis (example)

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[8].

Relevant impact area

In the determination of impact probabilities, in principle both the cross section of the projectile and the cross section of the impact area need to be taken into account. In general, however, the relevant cross section of ice pieces from wind turbines will be small enough that they can be considered as point masses. The impact probability is then only a linear function of the vulnerable impact area.

Another effect, which should be taken into account when calculating impact probabilities, is the projection of the impact area in the direction of the ice piece’s trajectory. In many instances, this distinction will not have any practical consequences, because, either projection does not make a big difference in the first place (e.g. a person’s head), or, the impact area’s orientation will be variable as well (e.g. a vehicle’s windscreen). Projection, however, can be an important consideration when calculating and interpreting the

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[8] 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.

impact density of ice pieces on the ground, the latter usually being a horizontal plane. For ice piece trajectories that are strongly inclined from the vertical, projection can thus have a sizeable effect. As the angle of an ice piece's trajectory is essentially given from the ratio of the free-fall velocity (vertical component) to the wind speed (horizontal component is wind drift), shallow impact angles occur predominantly for high wind speeds and at large distances from the turbine.

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 0.18 m² (torso[9] impact is additionally taken into account).

Accumulation of risks

Risk assessment in general requires, that all relevant risks an individual is exposed to by the matter at hand, are taken into account. There are two aspects to this: (1) multiple risks posed by one risk source (e.g. for a wind turbine: the risk of turbine collapse and the risk of ice fall), and (2) multiple risk sources of the same kind within the assessment's reach (e.g. several pre-existing wind turbines along an access road to a planned wind farm).

The first aspect is not in the scope of these recommendations, which is solely the risk posed by ice fall and throw. The latter aspect however needs to be incorporated when analyzing the exposure of individuals. Only if the risk added by the matter at hand is not significantly increasing the existing risk or, respectively, is insignificant compared to the relevant risk acceptance criteria, the accumulation with other (pre-existing) risk sources can be neglected. If other relevant (pre-existing) risk sources are neglected, although significant, a respective delimitation shall be included in the scope of the assessment.

For state roads, federal roads and highways, where the societal risk becomes relevant, the risk of a car accident per kilometer of the road is typically significantly higher (German Federal Highway Research Institute, 2017) than the herein defined risk acceptance criteria for the societal risk (Section 4.2.2). Therefore, it can be argued that an accumulation of risks from wind turbines along these roads need not be considered unless several wind turbines impose a risk at the very same point along the road.

On small local roads, paths and ways like farm tracks and trails, where the individual risks becomes the relevant risk, a critical individual may be defined. The critical individual is the individual for whom the risk is assumed to be the highest. It may e.g. be a jogger passing the wind farm weekly or a local person walking its dog daily. The accumulation of risks can then be restricted to the wind turbines which impose a risk along the assumed route of the critical individual.

The accumulation of several calculated risk values has to be treated as a propagation of probabilities resulting in terms of higher order. Due to risk values in general being much smaller than 1, terms of higher order can be neglected in most cases. The total risk is then calculated as the sum of the individual risks.

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[9] The dimensions of a 50th percentile male crash test dummy suggest a cross section of the torso of 0.14 m².

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 (ISO), 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 (ISO), 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. In risk assessment standardization, a tolerable risk is defined as a risk which is accepted in a given context based on current values of society (International Organization for Standardization (ISO) / International Electrotechnical Commission (IEC), 2014).

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

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

Equation 8

According to the EN 50126 (European Committee for Electrotechnical Standardization (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[10].

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 8).

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[10] 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.

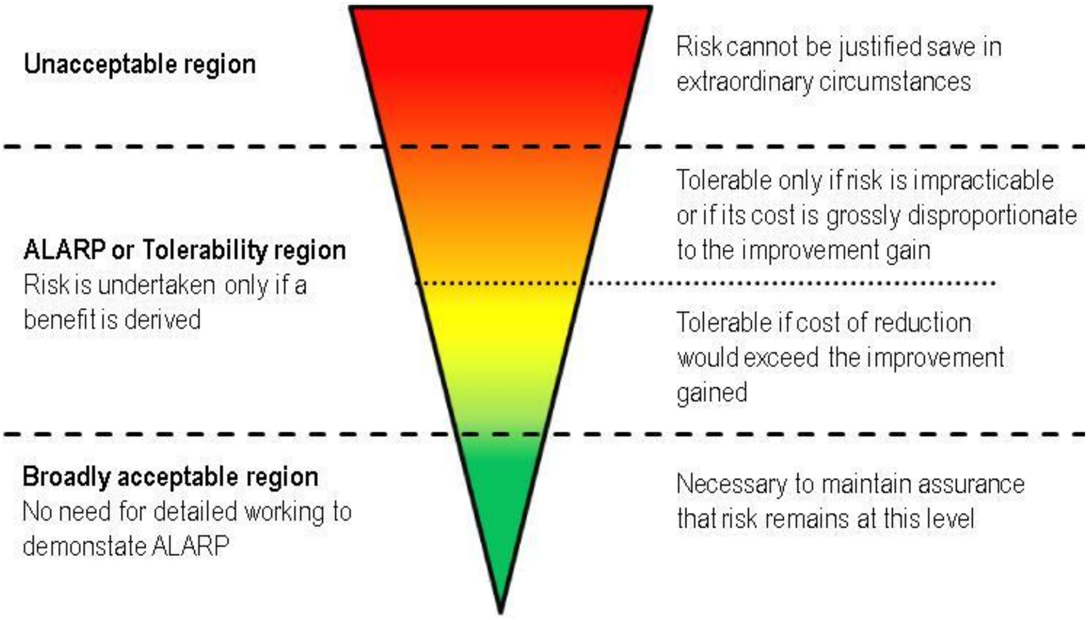

Figure 8: ALARP principle (Health & Safety Executive (HSE))

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.”

The region of concern is identical with the tolerability region of the UK Health and Safety Executive in Figure 8.

“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 … 15 · 10^{-6} / year
	car drivers	2.0 … 2.2 · 10^{-4}/ year[11]
	Aircraft (passengers)	0.67 … 1.2 · 10^{-4}/ year
Leisure activities	Mountain climbing	1.0 … 2.7 · 10^{-3}/ year
	Parachuting (USA)	2.0 · 10^{-3}/ year
	Holiday (UK 1990)	1.0 · 10^{-4}/ year
Everyday life	Fire in buildings	8.0 · 10^{-6}/ year
	Household activities	1.0 · 10^{-4}/ year
	Lightning (UK, USA)	1.0 … 5.0 · 10^{-7}/ year

Table 4: 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 4, if there are no other meaningful statistics.[12] The actual risk must not rise significantly compared to these. This results in the upper limit for the individual/collective risk in question.

Traffic risk, for instance, is as a risk accepted by society and can be used as background risk for the definition of acceptance criteria based on it. Any technology – in this case wind turbines – must not increase the accepted risk by a significant amount (e.g. 5% as established for the MEM by the EN 50126 (European Committee for Electrotechnical Standardization (CENELEC), 2017)). Note, that this comparison with pre-existing risks refers to a public location, and not to an individual with pre-existing risks. Pre-existing, socially accepted risks of individuals (e.g. smoking) must not be used to construe higher permissible risk levels for these individuals.

If there are established country specific regulations concerning the risk level for certain installations or situations (e.g. for landslides/avalanches on public roads in Norway (Norwegian Public Roads Administration, 2021)) these can be used to derive risk acceptance criteria.

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[11] 2.0 · 10^{-5}/year is the current best performance index (achieved for Norway 2017).

[12] 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 9 shows two representative examples of F-N-curves from the UK and the Netherlands. The transition area (or ALARP region, see Figure 8) between acceptable and tolerable risk covers two orders of magnitude.

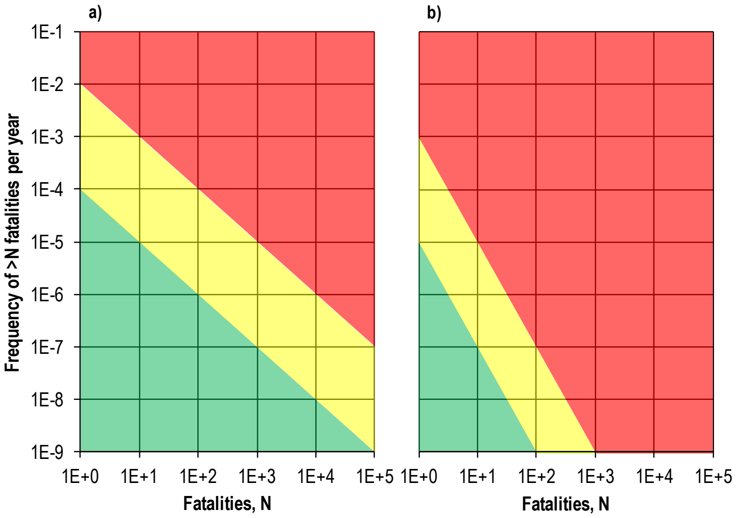

Figure 9: Examples for societal risk criteria in a) United Kingdom and b) the Netherlands (Floyd & Ball, 1998)

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 10 should be used (see Table 5).

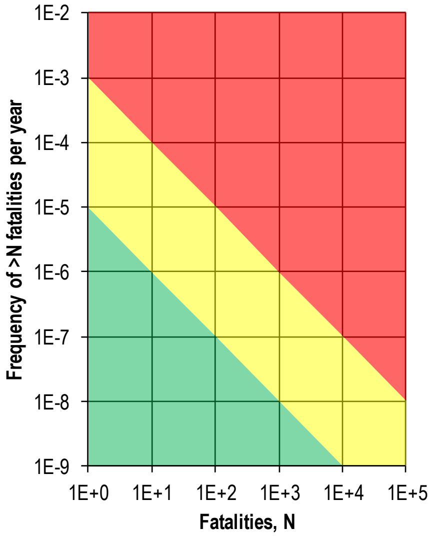

Figure 10: Simplified compromise for societal risk

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 9 and Figure 10 are no fixed values as certain circumstances may increase benchmarks for the individual or the societal risk. Figure 9 and Figure 10 can be understood as follows:

Risk value [1/year]		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 5: Example for individual and societal risk criteria

As can be seen from Table 5, 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 5:

- 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 7) 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.

Risk acceptance dependent on familiarity and benefit

People and society in general are willing to accept higher risks the more familiar they are with them, the more voluntarily they take them, and the greater and more direct the perception of benefit from the risky activity is (Swiss Federal Office for Civil Protection, 2008). This allows for a distinction between different groups of persons for which different risk acceptance criteria can be stipulated:

First persons: People directly familiar to or benefitting from the risk (source), e.g. operating personnel fully aware of the risk.

Second persons: People indirectly familiar to or benefitting from the risk (source), e.g. other workers on the premises being informed and warned about the risk.

Third persons: People ignorant to and not benefitting from the risk (source), i.e. the general public.

The risk acceptance criteria for the latter category are the same as established for the individual/societal risk above. For the first category it is generally accepted practice to increase these by one order of magnitude.

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
	Rerouting supervised by security guard for high risk events	10 to 100[13]	Minor roads and paths
	Physical barrier (official road closure) and signs	10 to 100	Roads and official frequently used hiking paths

Table 6: Quantitative measures for the risk reduction

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[13] Cf. (Swart, Kristiansen, & Bredesen, 2019)

The maximum achievable risk reduction in Table 6 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 5 cannot be reduced into the acceptable area with the common measures discussed in Table 5. Therefore, other measures have to be taken into account.

Warning signs

An important factor for the effectivity of warning signs is the placement at all relevant entry points to the area around a turbine being affected by ice piece impacts. There are numerous rules of thumb defining this area by a fixed distance from the turbine. In Norwegian regulation (Norwegian Water Res.&Energy Directorate, 2022) a safety distance of hub height (HH) plus rotor diameter (RD) is recommended at which to place warning signs. In Austria it is common practice to place warning signs at a distance of 1,2 times tip height (TH). The German Technical Building Regulations (Deutsches Institut für Bautechnik, 2022) states that buildings and roads are unaffected by ice fall and throw above a distance of 1,5 * (HH + RD) (unless the site is prone to severe icing), which can be used for the placement of warning signs. Such rules of thumb can be applied in absence of detailed analyses of site-specific icing conditions and calculations of trajectories and impact probabilities.

If site-specific analyses and calculations have been done, the positions of warning signs can be based on iso-risk contours such as LIRA. A LIRA of 10^{-6} constitutes the threshold from negligible risk to possible risk. This means, outside of this contour around the turbine, no risk due to ice fall or throw is to be expected. The 10^{-6} LIRA contour corresponds to an impact probability contour of about 10^{-5} per square meter per year. Inside of this contour and up to an impact probability contour of 10^{-3} per square meter per year, the risk is not negligible but still small and does not lead to exceeding risk acceptance criteria for short exposure times per day, such as half an hour for a pedestrian or a car passing on a road twice a day. Hence, the 10^{-3} per square meter per year impact probability contour is a well-defined distance for the placement of warning signs. Depending on site-specific usage scenarios and frequencies, other limits and distance definitions can be favorable.

An example for an ice fall warning sign can be found in Appendix C: Warning Signs, along with explanations and further recommendations.

Personal protective equipment

Operating personnel and construction workers are required to use personal protective equipment, in particular helmets. Protective helmets are designed to absorb a certain range of impact energies, for instance up to 100 J in case of EN 14052 (European Committee for Electrotechnical Standardization (CENELEC), 2012). The risk reduction by use of such helmets can be incorporated by increasing the lower threshold of relevant impact energies of ice pieces accordingly.

Another useful reference for the level of protection offered by wearing helmets is the meta-study on bicycle injuries and helmet-use by Olivier & Creighton (2017). According to this study, an overall risk reduction factor of 3 can be assigned to bicycle helmets.

Finally, the guideline, requirement, or even the legal obligation to wear personal protective equipment does not guarantee its actual use. The observance of such requirements is likely to vary between companies, industries and countries as well as with the working conditions. Nonobservance, however, is an aspect that should be considered when assessing the effectivity of a risk reduction measure.

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 7).

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 or during operating periods with high risk expectancy	
	Imposing a speed limit on the road	Consequences of ice piece impacts and sequential crashes depend on the velocity of the vehicle
	Adaption of operational strategies	For example, ice-detection methods or restart procedures after shut-down.

Table 7: 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 8).

Category	Safety measures	Remark
Awareness of residents	Communication strategy[14]	Independent from the calculated risk, these measures should be taken to inform the residents and – as a long term strategy – change their behavior.
	Regular education to change behavior of people.	

Table 8: Qualitative measures

4.3.4. Conditional Measures

The results of the generally adopted risk analysis procedure as well as the common risk acceptance criteria are given as average values on a yearly basis. Yet, the sources of risk vary over time and in turn does the risk imposed on individuals. Depending on the context, it can thus be useful or necessary to assess the risk in reference to different time bases, in particular when risk reducing measures shall only be activated under certain conditions, for instance when ice accretion is detected by ice detection systems or forecasted by meteorological simulations. The process of risk analysis, including calculation of trajectories and impact probabilities, remains the same, aside from being referenced to a suitable time base, e.g. days or hours. For the process of risk evaluation it is however necessary to define reasonable action thresholds on the same time base to be used in place of the yearly-based risk acceptance criteria. One approach could be to define the action threshold per icing event as the yearly-based acceptance criterion (fatalities per year) divided by the expected number of icing events per year, arriving at an action threshold in units of fatalities per event. Such an action threshold is subject to high uncertainty though, as the number of icing events exhibits high inter-annual variability for any given location and can thus only be estimated. A different approach could be to reference the action threshold to LIRA contours. In that case, the considered period is extrapolated to a full year in order to calculate the LIRA contours. The activation of measures at distinct locations can then be based on the pathway of the contours.

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[14] Cf. (Jeuring & Sivle, 2021)

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 subject to 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 influences 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:

- Wind speed data
- Mass and shape of ice fragments
- Number of ice fragments
- Relevant impact area
- Probability of presence / exposure of people
- Assumed consequences / vulnerability
- Thresholds of risk acceptance criteria
- Effectivity of risk reduction measures
- …[15]

From a 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 values.

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, for which safety margins and conservative values should be applied accordingly. Examples for such parameters are the number of considered ice fragments, estimations of the effectivity of measures, the assumptions for the relevant cross-section when hitting pedestrians/vehicles, or the selection of thresholds for the acceptable risk criteria. For some of these factors it is easy and useful to define an upper bound or conservative limit, for others such an upper bound is hard to deduce.

A pragmatic approach to treat uncertainties within a risk assessment report is for example the Strength of Knowledge Index (Society for Risk Analysis, 2022). The following criteria can be applied to assess the strength of knowledge regarding a certain aspect:

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

- The reasonability of the assumptions made
- Amount and relevance of data used
- Agreement/consensus among experts on the aspect
- How well the phenomena involved are understood

A scale to classify the strength of knowledge can be of the following manner

- Poor background knowledge (red)
- Medium strong background knowledge (yellow)
- Strong background knowledge (green)

This approach enables also uninformed readers to easily understand the confidence in the results of a risk assessment report. Nonetheless, this or any other approach for the treatment of uncertainties shall be clearly motivated and described in the risk assessment report.

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Appendix A: Terminology

The following definitions are derived from the *ISO Guide 73 - Risk management — Vocabulary* (International Organization for Standardization (ISO), 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 (ISO), 2009) has been noted.

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

IPS (Ice protection system): (additional to ISO Guide 73)

Means for the removal of ice or the mitigation of ice buildup on the rotor blades of a wind turbine. Usually, the term IPS refers to a heating system for the rotor blade surface.

Appendix B: 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	

Appendix C: Warning Signs

In Figure 11 a compilation of examples for warning signs to denote the potential risk of ice fall and/or throw around wind turbines is depicted. These signs do not follow a particular standard, moreover, while focused on text and not visual communication, these signs could fail to convey the risk to individuals approaching the affected area when there is a language barrier and/or the risk is expressed as conditional (i.e. depending on specific weather conditions or time of year).

Figure 11: Compilation of warning signs informing about the potential risk of ice fall and/or ice throw (Source: courtesy of Thomas Hahm, Fluid & Energy Engineering GmbH & Co. KG)

Considering the above, a proposal for a general warning sign was developed, see Figure 12. The warning sign aims to convey the risk of ice fall around turbines in a simple but effective way. Several elements are included:

- Indication of turbine as the source of the risk for ice fall.
- Indication of ice fall risk both below and around the turbine.
- Indication of icing as icicles and snowflakes to convey the nature of the risk.
- Indication of a risk zone both visually and in written form. 'Zone' is a word common in many languages compared to area or range.

Figure 12: General warning sign for the risk of ice fall

An additional indication for a preventive action could also be included by an additional sign, see Figure 13. The form of preventive action depends on local regulations and could be for instance the prohibition of entering the wind farm area, the suggestion to keep a distance from the turbines or the statement of entry at own risk.

Figure 13: General warning sign for the risk of ice fall with an additional sign for a preventive action