Ice Throw Hazard

Experiences and Recent Developments in Germany

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Summary

In many regions of the world ice throw from wind turbines can be a serious hazard to the environment. The experiences made in Germany during the last years may serve as a contribution for future standardization of ice throw from wind turbines.

The assessment of ice throw risk from wind turbines can be split into several steps. The easiest, most determined step is the calculation of the trajectories of ice fragments. The main driving parameters for the calculation of the trajectories of ice fragments and their impact location on the ground are the rotational speed of the turbine and the topography of the terrain.

The more difficult and controversial steps are the number of icing days and the risk criteria to be applied. The number of icing days show a very high interannual variation. Long term measurements are needed which in Germany typically are only available at few meteorological stations at 2m height. A high uncertainty arises from extrapolating this data to the wind farm location and to hub height. Germany's National Meteorological Service (DWD) has recently published an icing map for Germany. The DWD correlates the number of icing days to the elevation above sea level. This approach gives good results for many locations and may be useful in other European countries. Concerning the risk criteria the concept of minimum endogenous mortality has been used in Germany for many years and has become well established. It is consistent with other approaches to determine a socially accepted risk level.

Abstract

Ice throw from wind turbines is a serious hazard. Especially close to traffic ways there is a demand of an individual risk analysis. No national or international standards exist, but are urgently needed. The aim of this paper is to give an overview over the critical points which should be assessed in a future guideline based on experiences from the German market.

Keywords

Ice throw, risk assessment, icing, icing days, minimum endogenous mortality, MEM

1. Introduction

Wind energy in regions with low temperatures or icing conditions requires special attendance regarding material and yield losses due to icing of the wind turbine. Hence several publications considering this topic exist. Besides the WECO Report [1], which was partially financed by the European Commission, the International Energy Agency IEA created a working group on this topic which published a report at the end of 2012 [2]. Both reports address the topic of hazards from ice throw, but propose only few solutions. One recommendation in the WECO report is a minimum distance of the wind turbine of 1.5 * (hub height + rotor diameter) to objects in regions with severe icing conditions. Alternatively it is suggested to switch off the wind turbine.

In high populated areas like Germany frequented traffic ways are often closer to the wind turbines than this minimum distance, which leads to an increasing demand for independent assessments of the related risks. As there is currently no international and no German standard for the assessments of ice throw, there is some uncertainty about the correct methods and assessment criteria. The wind industry has to meet this challenge by developing guidelines and standards to gain more acceptance for projects in icing climate and populated areas.

Based on the experiences, accepted procedures and methods from the German market, the paper will give an overview of the critical points, which need to be addressed and solved both in the discussions with authorities and in the more technical part of the assessment. This shall serve as a contribution for future standardization of ice throw from wind turbines.

2. Overview of the Situation in Germany

In Germany the suggested minimum distance of 1.5 * (hub height + rotor diameter) to close objects has become part of the "Muster-Liste der technischen Baubestimmungen" [3], a binding model list of technical building rules that contains technical rules for the planning, design and building for construction works and their parts in Germany. If the existing distance falls below this threshold value or the wind turbines are located in a region which is at very high risk for icing an assessment report for the specific wind turbine site is needed.

According to the "Muster-Liste der technischen Baubestimmungen" [3] an additional assessment report about the functionality of the ice detection system of the wind turbine is required as well. This document has to assure that icing is detected correctly and the wind turbine is switched off, if the minimum distance to other objects falls below the above described criteria.

Even if an ice detection system is installed and the wind turbines are switched off ice fragments can fall off the idling wind turbine. Ice falling from an idling wind turbine is defined as ice fall. Hence site specific assessment reports are needed in these cases to assess the hazards of ice fall as well.

To determine the risk of ice throw or ice fall five steps are necessary:

1. Define the number of icing events.

2. Define the type and number of ice fragments that are detached from the wind turbine during an icing event.
3. Calculate the trajectories of the ice fragments.
4. Calculate the probability and the extent of damage.
5. Evaluate the risk.

A validation of the boundary conditions and methods is quite difficult. Several years of icing measurements and knowledge of the actual number of detached ice fragments and their impact locations would be necessary for an accurate model validation. Especially the number of detached ice fragments has not been a subject for research, except for a single measurement campaign in Switzerland [2]. This measurement campaign took place in high mountain regions where an ENERCON E-40 is installed. A validation with this one campaign is of course not possible. But it can be used to prove, if the described approaches are conservative for this specific site in Switzerland.

3. Annual Icing Events

The determination of the annual icing events is one of the most important, yet one of the most difficult tasks. Several years of measurements at the specific site, preferably at hub height, would be necessary to detect the exact number of icing events. Even then a distinction between meteorological icing of the instruments and icing of the rotor blades has to be made. Meteorological icing occurs earlier than icing of the rotor blades while icing on the rotor blades can under certain circumstances last longer.

There is a large variation in the number of icing events from year to year. Hence a climatological period of 30 years of measurements would be necessary for a good estimation of the typical number of icing events at a specific site. In Germany long-term measurements are only available at the climate stations of the German Weather Service (DWD). As the measurements are at 2m height they are strongly influenced by local effects and may not even be representative for sites in 100m distance. These local effects are negligible at hub height. However, an accurate interpolation of the measurements at 2m height for a site that is several kilometres away and for a hub height of 100m or more is almost not possible and associated with very high uncertainties.

Another source for the number of icing events are icing maps, as presented e.g. in the WECO report [1] or the IEA report [2]. The number of icing events in these maps are interpolated over large distances and can only give trends. The IEA report points out that while the maps show a smooth distribution of ice events, in reality the icing events can vary significantly over small distances due to the topography.

The DWD recently introduced an icing map for Germany [9] that is based on the data of more than 70 climate stations. According to the analysis of the DWD an exponential connection exists between the number of icing events and the elevation of the site above sea level. Currently this icing map represents the best data basis for icing events in Germany. Figure 1 shows the annual icing events in Germany according to [9]. It is up to further investigation to prove, if this approach can be applied to other countries as well.

Depending on the icing conditions, the icing of the rotor blades can become so extensive that ice fragments detach and become a hazard to the environment. Icing occurs when super cooled water droplets fall on the rotor blades or the temperature of the blade surface is beneath the dew point temperature and water vapour sublimates into rime ice. Between 0°C and -10°C icing from water droplets on rotor blades occurs. From 0°C to -4°C the icing is delayed and large crystal ice fragments form. Beneath -4°C rime ice with a less adhesive surface grows. Below -10°C extensive rime ice evolves on the rotor blade edges. Icing for even lower temperatures does not play a significant role in terms of ice throw or ice fall.

A distinction between extensive ice plates, which form along the chord of the blade, and smaller ice fragments at the blade edges has to be made. Further information on the weight and shape of ice fragments can be found e.g. in the WECO report [1].

The number of ice fragments per ice event and the number of ice events per year define the site specific annual number of ice fragments.

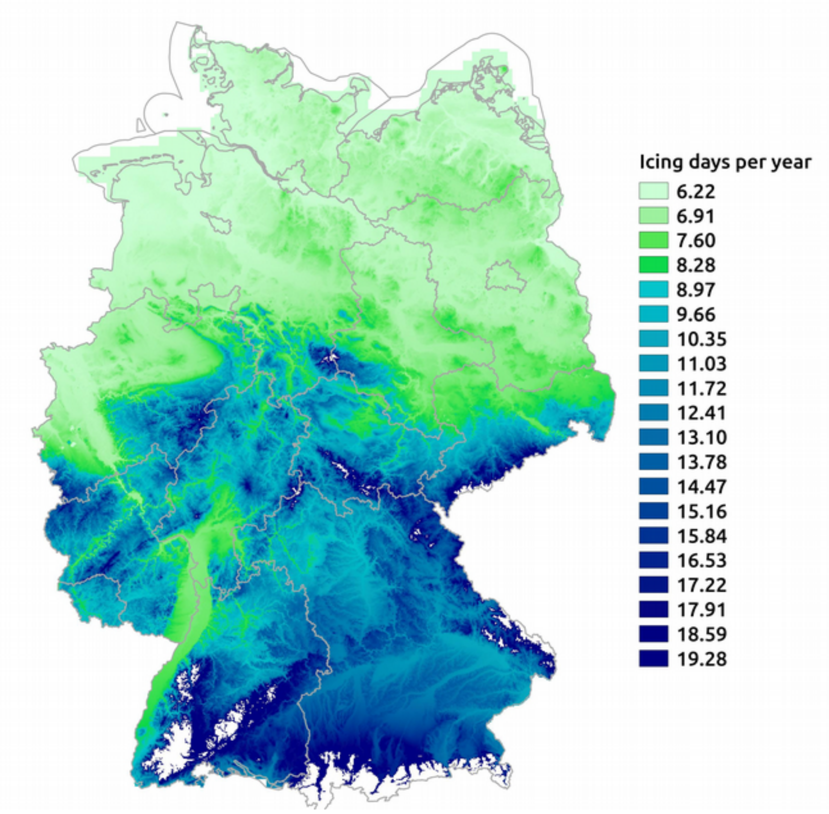

Figure 1: Icing days calculated according to [9] for heights up to 700m asl.

The ice mass that grows on the blade differs from ice event to ice event and is difficult to estimate. A simple approach is to take the ice loading conditions from the current draft of the IEC 61400-1 Edition 4 [10]. In this standard the overall ice mass is defined depending on the specific blade geometry. Considering the average weight of an ice fragment the number of ice fragments can be calculated. The number of ice fragments is assumed to be independent of the rotational speed of the wind turbine. Therefore the number of ice fragments is the same for ice throw and ice fall.

Depending on the site and size of the wind turbine this approach results in a range of 50 to 50 000 ice fragments per year for Germany. In the Swiss report [2] a maximum of 92 ice fragments has been found close to the turbine. A direct comparison between the Swiss site and the German sites is not possible, because the alpine altitudes are not covered by the icing map according to [9]. For the same wind turbine type in the low mountain landscape of central Germany approximately 500 ice fragments per year would be estimated. This number exceeds the experimental data from Switzerland considerably and thus is a hint that the described methods seem to be conservative

4. Methods for Ice Throw Calculation

If the boundary conditions such as wind direction and wind speed, ice geometry and ice density, the drag coefficient of the ice fragment, the position of the ice fragment on the rotor blade, the position and rotational speed of the blade and the topography are known, the calculation of realistic trajectories of the ice fragments is straight forward and results in a reliable distribution of ice hits on the ground.

Adequate results are achieved if the full geometry and inertia moment of the ice fragment is considered rather than a simplified point mass and this three-dimensional ice fragment is tracked during the whole flight. In contrast to ballistic trajectories for point masses, this approach leads to more realistic result of flight distances. Additionally very high flight distances due to lift effects are captured as well.

As it is unknown under which circumstances the ice fragment detaches from the blade and whether it breaks up during the flight, a simplified approach is taken where all ice fragments detach without any loss of energy and stay intact during the flight.

In order to get reliable results a huge number of trajectories has to be calculated. A possible method to achieve this is e.g. a Monte-Carlo-Simulation.

Three of the mentioned boundary conditions have a distinct influence on the distribution of ice hits around the wind turbine and their effect typically becomes visible in the results:

- the distribution of wind direction and wind speed
- the topography
- the rotational speed of the wind turbine

Large flight distances for ice throw and ice fall occur in combination with high wind speeds. The main storm direction is therefore almost always visible in the results. The effect of the wind distribution can be overlapped by the influence of the topography when large flight distances occur along distinct slopes of the terrain. Figure 2 and 3 illustrate the differences in the results in case the topography is not considered and in the case that it is considered.

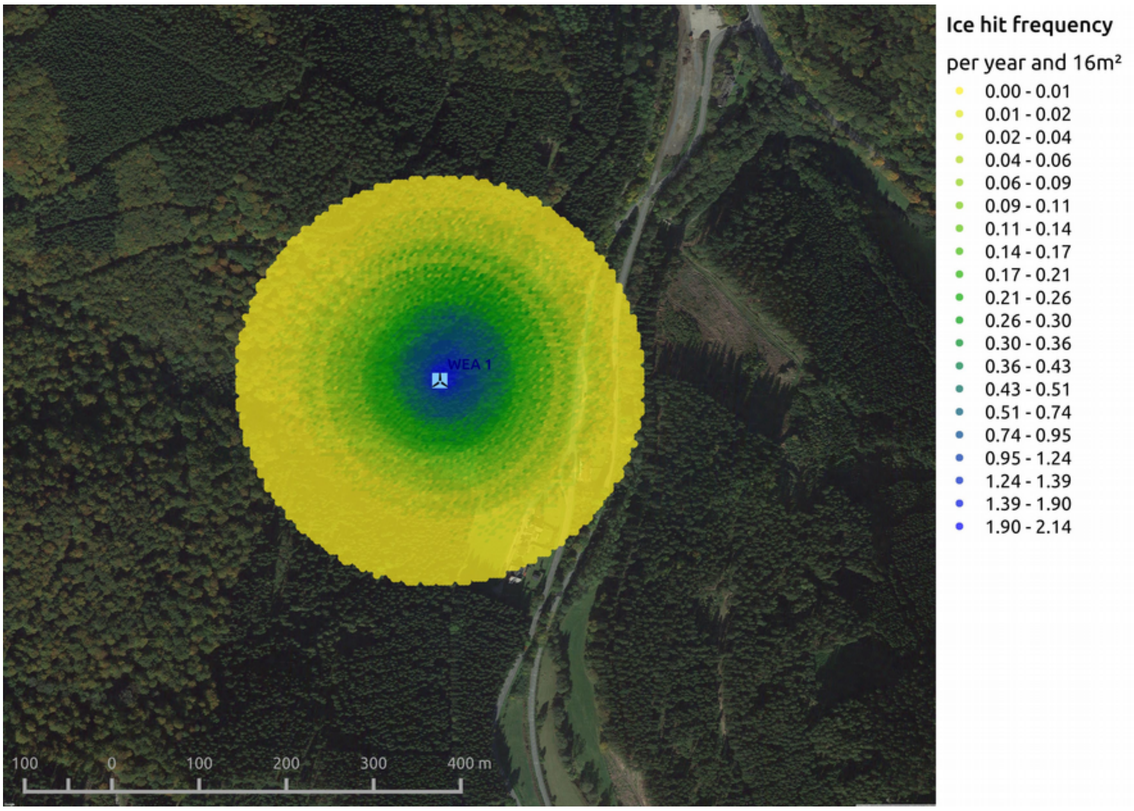

Figure 2: Ice hit distribution without terrain influence.

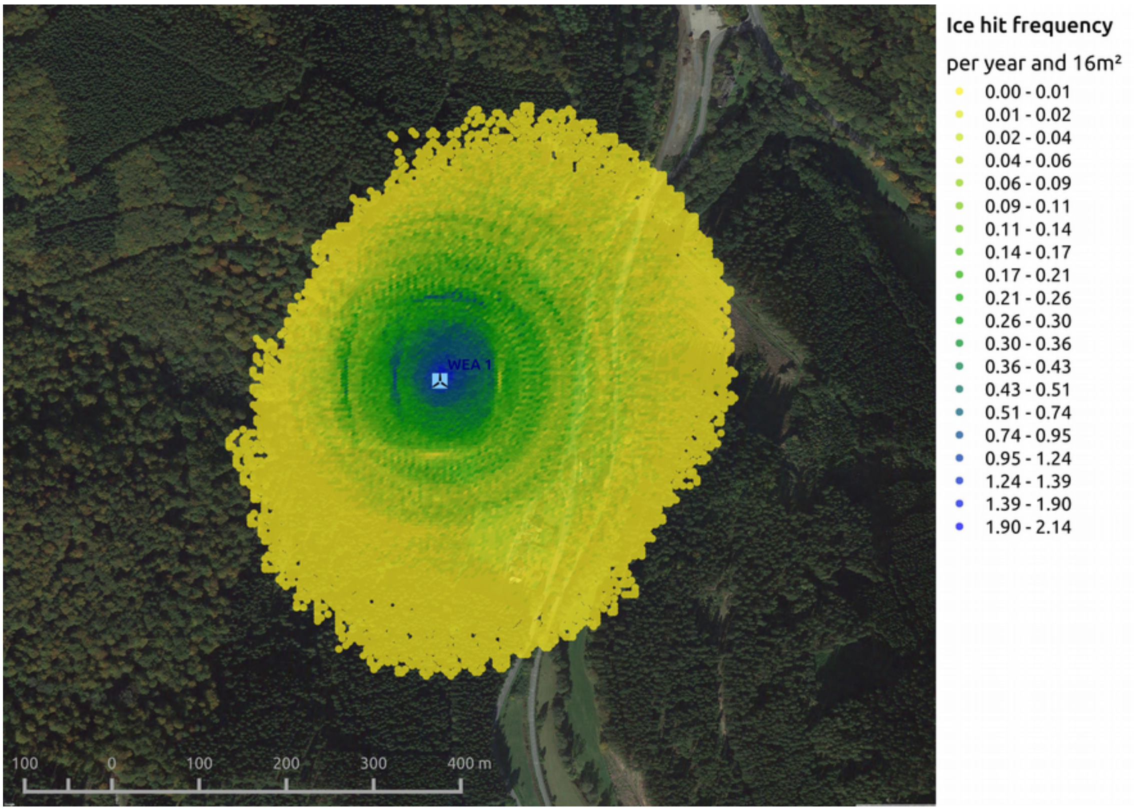

Figure 3: Ice hit distribution with terrain influence.

Especially close to the wind turbine the ice hit frequency displays the main wind direction (green and blue areas in figure 2 and 3). The maximum flight distance is dominated by the topography as can be seen in figure 3. Without the topography the critical area for ice hits would simply be estimated wrong as is easily visible from the comparison of figure 2 and 3.

The rotational speed of the wind turbine effects the distance of ice hits as well. A significant difference can be seen between ice throw and ice fall. For ice throw the rotational speed of the wind turbine during operation is considered whereas for ice throw it is the smaller rational speed for the idling turbine. In figure 4 it can be seen that high frequencies are shifted towards larger flight distances in the case of ice throw. The maximum flight distance for ice throw however is only slightly larger than for ice fall, because it is mainly dominated by storm events and the topography.

In figure 4 the flight distance is normalized with the sum of hub height and rotor diameter. It can be seen that the maximum flight distance is below the threshold distance for the wind turbine of 1.5 * (hub height + rotor diameter) as demanded in [3].

Maximum flight distances in the range of the single sum of hub height and rotor diameter as shown in figure 4 are typical for sites with moderate slopes in the terrain. In these cases approximately 50% of the ice fragments resulting from ice fall hit the ground directly underneath the rotor, i.e. they have a maximum flight distance equal to the rotor radius. In case of ice throw approximately 30% of all ice fragments hit the ground underneath the rotor. According to the Swiss report [2] 40% of the ice fragments were found underneath the rotor, while the maximum flight distance was 1.02 * (hub height + rotor diameter). This supports the calculation method and boundary conditions used here to calculate the flight trajectories of the ice fragments.

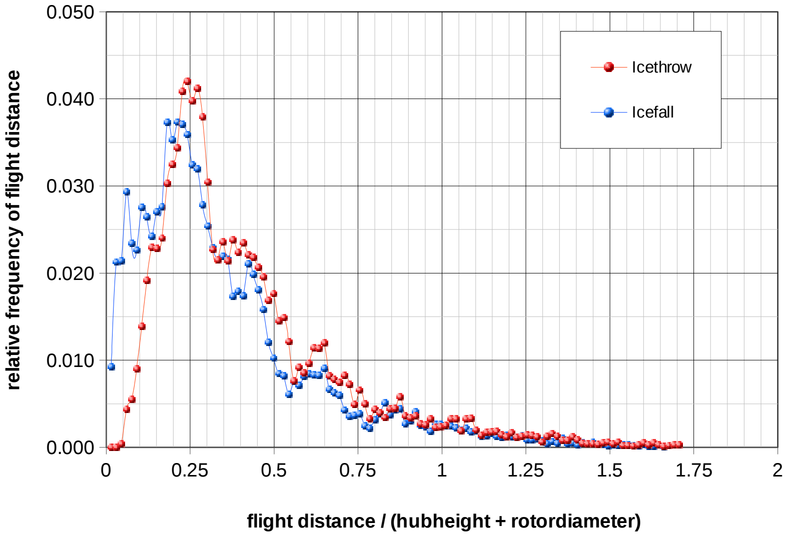

Figure 4: Distribution of ice hits for ice fall and ice throw in complex terrain.

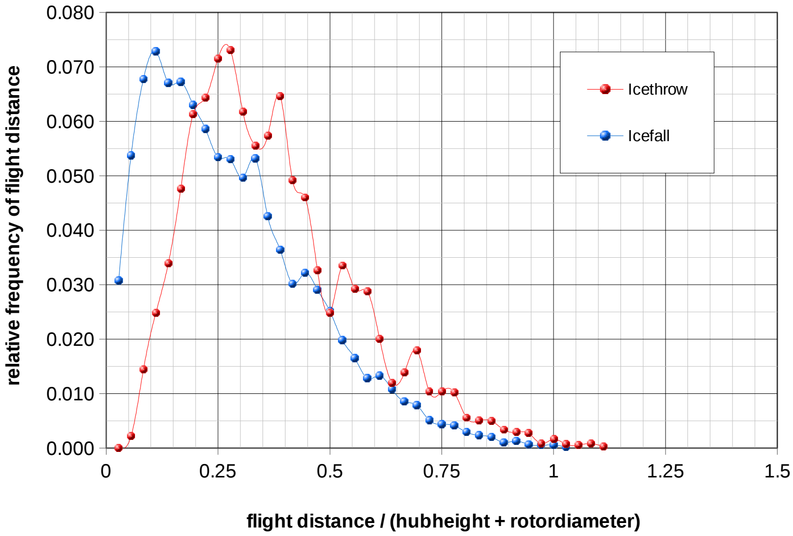

Figure 5: Distribution of ice hits for ice fall and ice throw in non complex terrain.

5. Risk Analysis

In principle a distinction between material damage and personal damage has to be made. In case of traffic ways and the surrounding of buildings it is usually sufficient to concentrate on the personal damage as material damage is insignificant compared to personal damage.

For the damage frequency on traffic ways the federal states of Germany usually provide statistical data from road traffic censuses. If road traffic censuses do not exist the traffic volume has to be estimated. Roads without road traffic censuses are mostly minor roads or small tracks and it is therefore in most cases possible to work with conservatively estimated values.

The amount of personal damage can range from minor injuries to major injuries and death. Established evaluation criteria can be found for the case of death. A common practice is to limit the evaluation to the cases of death and include the major injuries in this assessment. The following assumptions may be made:

- An ice piece hitting an unprotected person always leads to major injuries or death.
- An ice piece hitting the road within the area of the emergency stopping distance of the car or hitting the car directly always causes an accident. The average number of people in a car [8] and the frequency of major injuries and death due to a car accident [7] are known so that the number of affected people can be estimated.

Obviously neglecting the minor injuries, not differentiating between major injuries and death and assuming that every ice hit results in an accident is a very conservative approach. However, a further distinction is very difficult and is not supported by sufficient statistical data.

In order to evaluate personal damages the concept of minimum endogenous mortality (MEM) [6] can be used. The minimum endogenous mortality captures the death risk by technology, e. g. in sports, do-it-yourself activities, working accidents or traffic. Diseases etc. are not considered.

In developed countries the minimal endogenous mortality can be found amongst the group of five to fifteen year old people and amounts to $2*10^{-4}$ death per person and year. A new technology should not increase this values significantly. Hence the mortality caused by a new technology should not exceed $1*10^{-5}$ death per person and year.

Alternatively the accepted death risk is regarded to depend on the amount of voluntariness and the amount of possible personal influence associated with the activity [6]. If the possibility to avoid a risk approaches zero or if the risk is not taken voluntary, the acceptance decreases. Here the minimum accepted risk reaches $1*10^{-5}$ death per person and year in the worst case, which is similar to the minimal endogenous mortality defined before (figure 6).

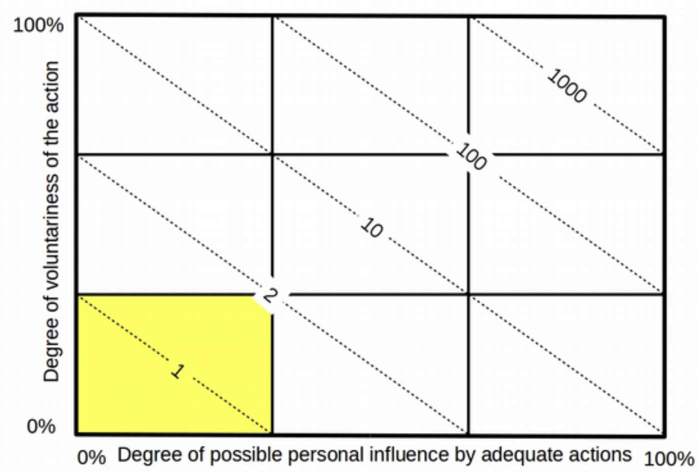

Figure 6: Accepted risks of death per 100 000 persons per year according to [6]. The yellow field highlights the accepted risk based on the MEM concept.

In case of the risk of dying due to ice throw or ice fall from a wind turbine a person typically neither stays voluntarily close to a wind turbine nor is the person able to lower the risk by appropriate behaviour. Therefore the minimal endogenous mortality is a justified and reasonable approach.

6. Summary and outlook

The demand for risk assessments of ice throw from wind turbines has increased in the German market during the last few years. The technical part of calculating the trajectories of ice fragments can be solved quite accurately and the driving parameters which determine the results are known and have been presented.

There is much more uncertainty in the assessment of icing days and the risk threshold that can be applied. During the last years approaches and methods have been developed within the German market to solve the mentioned uncertainties and discussions. Some of these approaches are specific for Germany but others may easily be adopted by other countries.

There is a strong need for the development and standardization of methods to assess the risk due to ice throw from wind turbines. Without this, the acceptance by the society and authorities for wind projects in areas with risk potential may be affected negatively in the future.

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