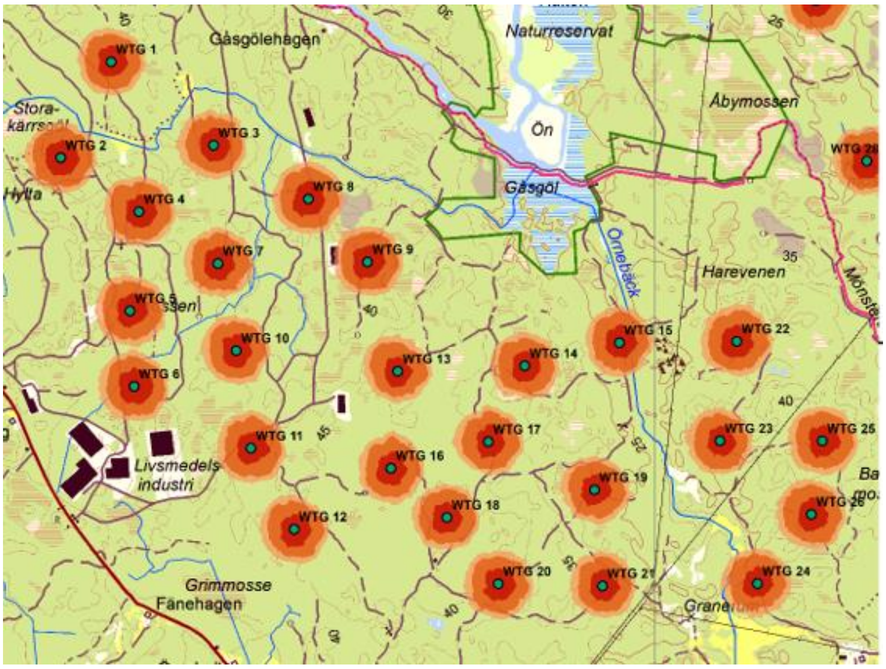
Åby Alebo wind farm, Mönsterås municipality, Sweden

Risk assessment of ice throw from wind turbines.

Rapport: KVT/BB/2020/R004



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Objectives

This report present IceRisk calculations for the wind farm Åby Alebo in the municipality of Mönsterås in Sweden. The calculations are carried out by Kjeller Vindteknikk on request by Stena Renewable.

The aim of the analysis is to assess the likelihood of ice throw and ice fall in the wind farm, assess the risk, and give recommendations for risk mitigation actions. A summary is given in Chapter 1. Safety distances are given in a separate chapter for the turbine types for wind farm Åby Alebo.

This report has been subject to comprehensive quality control according to Kjeller Vindteknikk's quality assessment system.

Notice

Revision history

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Content

1 Summary and conclusions

Kjeller Vindteknikk has carried out an IceRisk study in order to assess the frequency and probability of ice fall and ice throw from wind turbines, power lines, and masts (Bredesen 2015, IWAIS). The tool, IceRisk, is used for mapping the risk of ice throw and ice fall to carry out a risk analysis.

Analyses of the frequency of atmospheric icing have been carried out for the wind farm Åby Alebo in the municipality of Mönsterås. The aim is to calculate the likelihood of ice throw and ice fall within and in the vicinity of the wind farm. The wind farm consists of 36 Vestas V150 4.3 MW turbines. The turbines are located 19 – 47 m above sea level (ASL). The hub heights are 125 m and the rotor diameters are 150 m causing the turbine blade tips to reach up to 247 m ASL for the highest positioned turbines.

The calculations show that blade ice is expected to occur in 2.0 % of the time for the wind farm. with the potential to cause dangerous ice throw or ice fall in 0.2 % of the time. There are, on average, one icing episode each winter in the wind farm. The highest and lowest turbine will experience an equal amount of icing since the height variation is small. The wind farm Åby Alebo is in class 2 according to the IEA ice classification (light icing).

The calculated probabilities that harmful ice pieces[1] from the turbines will hit an area a given distance away are shown in Table 1-1. A probability of 10^{-4} [hits/square meter/year] means that an ice piece will hit a given area of 1 m^2 with a return period of 10,000 years.

Table 1-1 Relation between return period for hits per square meter and the probability of hits per square meter for dangerous ice pieces. The third column gives the distance for which the given probability will occur in mean of all sectors around the mean positioned turbine ASL in the wind farm with Vestas V150 4.3 MW. The distances are calculated for a mean icing year.

Return Period	Probability	Distance
100 years	10^{-2}	30 m
1,000 years	10^{-3}	100 m
10,000 years	10^{-4}	190 m
100,000 years	10^{-5}	220 m
1,000,000 years	10^{-6}	280 m

Risks for ice throw and ice fall have been evaluated for the surrounding area of the wind farm. It is recommended at all access roads to the wind farm to have signs which warn of the risk of ice fall with and informs about a safety distance of 200 m. Safety routines for personnel in the wind farm and for the personnel in the nearby food industry should be implemented. Further actions to mitigate the risk can be assessed. Suggested risk mitigation measures are given in Chapter 7.

[1] Calculated as freely rotating ice cubes with an impact energy above 40 J following the methodology in Bredesen (2015, IWAIS).

2 Introduction

Kjeller Vindteknikk has carried out a study of the icing conditions at Åby Alebo wind farm in Mönsterås municipality, Sweden.

Certain combinations of temperature, moisture, and wind speed will imply ice accretion on wind turbines. Icing is likely at temperatures below zero (˚C) combined with fog or low clouds. The most common form of icing is supercooled cloud droplets which will freeze when in contact with cold surfaces. Furthermore, supercooled rain and heavy snow fall can imply icing at temperatures around 0 to 1 ˚C.

Figure 2-1 Icing on the leading edge of a wind turbine blade in Finland. The picture is shown with permission from the Finish Meteorological Institute.

The frequency and amount of icing is closely linked to the height above sea level (ASL). A high mountaintop will often be covered by clouds, and if the temperature is below 0 ˚C, ice will likely accumulate on constructions.

Ice will also accumulate on a wind turbine in such weather conditions. Usually, the ice will accumulate on the leading edge of the blade when the turbine is operating (rotating) in icing conditions as shown in Figure 2-1. The accumulated ice on the blade may reduce production or in worst case cause a stop of the turbine.

Ice on the blade usually falls off in pieces of different sizes. The ice will often fragment into smaller pieces before it hits the ground (Seifert, Westerhellweg, & Krönig, 2003).

The aim of this study is to determine how often ice will accumulate on turbines at Åby Alebo and how far the ice will be thrown. A detailed model of trajectories is used as a foundation to generate statistics on dangerous ice throw and ice fall from the turbines. Further, risk for persons in the vicinity of the wind farm is assessed and measures which mitigates the risk are suggested.

3 Wind farm information

A map of the area of the wind farm with 36 V150 4.3 MW is shown in Figure 3-1. The planned Åby Alebo wind farm is located northwest of Mönsterås in the municipality of Mönsterås. The turbine blades of the highest positioned turbines will reach 247 m ASL since the hub heights are 125 m and the rotor diameters are 150 m. The height of terrain at the lowest and highest positioned turbine is 19 m and 47 m ASL, respectively. The terrain is rather flat in a forested landscape, see Figure 3-1.

The V150 4.3 MW turbines can be delivered with technologies that has the potential to influence the amount of ice throw. One such technology is the Vestas Anti-Icing System (VAS) which is an active blade heating system designed to heat the blade during icing situations. The purpose for such a system is mainly to optimize the production and longevity of the turbines during icing conditions. With such a system it is expected that less ice will build up on the blades thus reducing the overall challenges related to ice throw in the wind farm. It must however be noted that such a system cannot eliminate the risk for ice fall and ice throw.

In this report the calculation of IceRisk has been carried out with the assumption that no blade heating system are installed on the turbines.

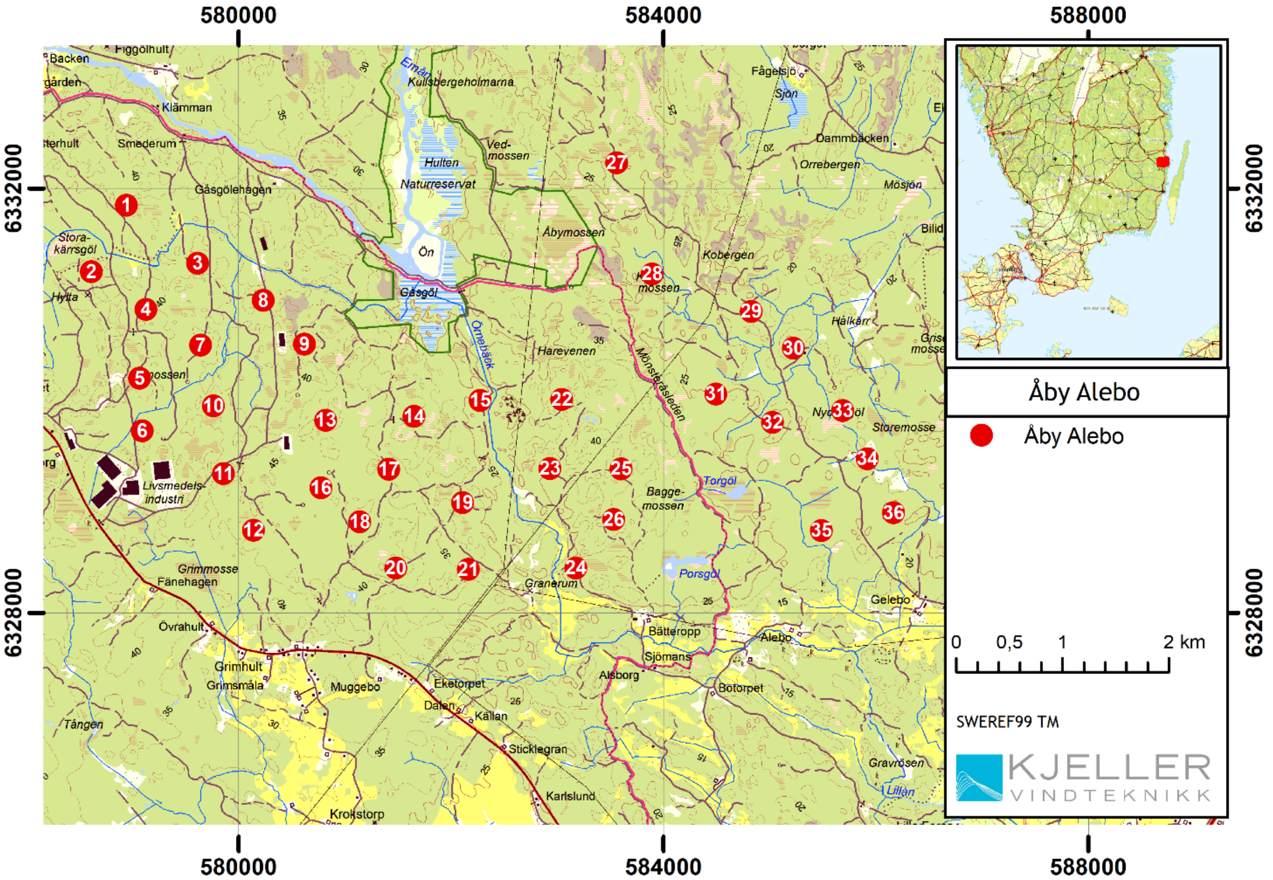


Figure 3-1 Map of the area surrounding the Åby Alebo wind farm. Red dots indicate turbine positions.

4 Icing Conditions at Åby Alebo wind farm

To calculate the risk of ice throw and ice fall in the wind farm, it is important to know the amount of ice growth on each turbine, and the frequency of the icing events. This chapter discusses the icing and wind conditions, in addition to the icing classification of the wind farm.

4.1 Methodology

To calculate the icing conditions, a time series with 20 years of data from the weather model WRF (Appendix A) for the wind farm was used. The icing conditions were calculated by using a standard cylinder as given by ISO 12494. The corresponding amount of ice which is accumulated on the blade at 67 % blade length may be in the order of 10–20 times more.

Since icing increases with height above ground level (AGL) the amount of icing is dependent of hub height and blade length of the turbine. In order to take into account how icing influences the turbine, calculation of ice growth for a turbine is usually made at a representative height AGL which is denoted rotor icing height (see Figure 4-1 below). The rotor icing height for the turbines at Åby Alebo is 175 m AGL.

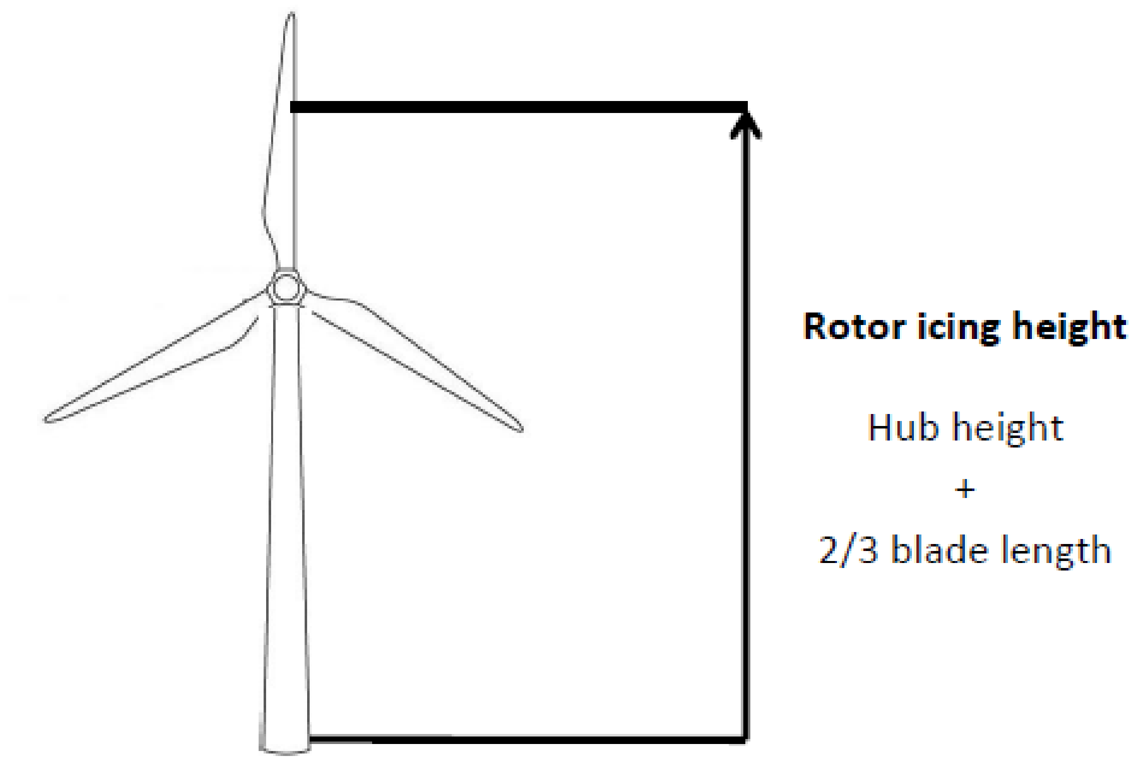


Figure 4-1 Definition of rotor icing height (IEA Wind TCP).

Several factors are important for icing and ice throw, including temperature, wind speed, cloud water content and air humidity. Sublimation (evaporation) is expected in midwinter and contributes to removal of ice on the blades in dry and cold conditions. Sublimation can be efficient in reducing the amount of ice on the blades since the ventilation is high due to the blades moving at high speed. This has been taken into consideration in the calculations.

4.2 Classification of icing conditions at Åby Alebo

IEA wind task 19 (2012) defines the periods when ice accumulates on objects as periods of “meteorological icing”, while periods when ice is expected to be present on the turbine blades as “rotor icing”. At Åby Alebo meteorological icing is found to occur at 0.7 % of the time (61 hours per year), while rotor icing is expected 2.0 % of the time or 172 hours per year.

Considering the classification used by IEA Wind (2012) for wind power (see Table 4-1) the turbines at Åby Alebo belong to ice class 2, which corresponds to light icing.

The height difference across the site is small, and we expect no variation in icing conditions across the site.

Table 4-1 IEA Wind icing classification (2012). When the criteria give different classification then it is recommended to use the highest rated class.

IEA Wind ice class	Meteorological icing [% of year]	Instrumental icing [% of year]	Production loss [% of yearly production]
5	>10	>20	>20
4	5-10	10-30	10-25
3	3-5	6-15	3-12
2	0.5-3	1-9	0.5-5
1	0-0.5	<1.5	0-0.5

4.3 Wind distribution at meteorological icing, blade icing and melting

A wind rose for the winter months (November to April) for an average turbine in the Åby Alebo wind farm is shown on the top left in Figure 4-2. The wind direction is distributed across the sectors with main wind directions from SSW to NNW. The wind rose on the upper right shows the wind conditions during the periods when ice accumulates on the turbine blades (meteorological icing). The build-up of ice is most frequent from the western sectors, but also wind from the north east can cause icing at the site. On the bottom left, the wind rose for rotor icing is shown, i.e. when ice is expected to be present on the blades. Winds in the northwestern sectors are most common during rotor icing. On the bottom right, the wind rose for the melting periods are shown, which are most common in the southwestern sectors. It is expected that the risk of ice throw will be increased during the periods with ice on the blades and the melting periods. Thus, it is expected that most ice throw events occur when winds are from directions from SSW to NNW.

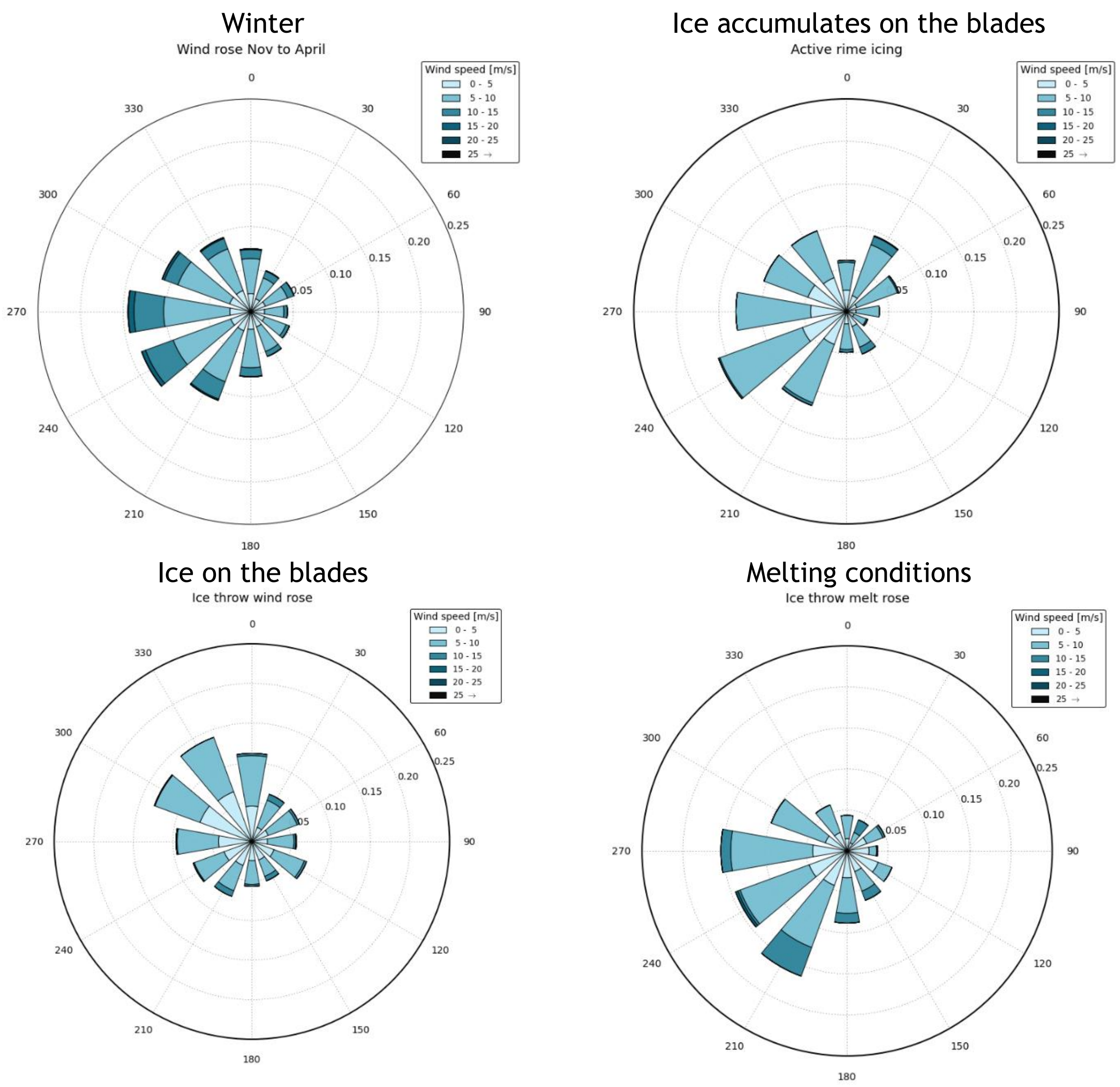


Figure 4-2 Wind roses showing wind direction and strength for different icing situations.

4.4 Distribution of ice piece size

In Figure 4-3 the distribution of ice amounts for an average positioned turbine in Åby Alebo wind farm is shown. The ice amounts and associated ice pieces are divided into 5 categories, corresponding to the categories from TechnoCenter Éolien (now Nergica) shown in Figure 4-4. The largest amount of ice during the 20 years data series is calculated to be around 0.7 kg/m which corresponds to category 2 in Figure 4-4.

An amount of ice of around 0.5 kg/m on a reference body could result in a piece of ice of about 5 cm (cube) with a mass of 100 g on a turbine blade (separated in cubes of ice). An example ice piece of this size is shown on the top right of Figure 4-4 (Wadham-Gagnon, 2013). Examples of ice pieces found for other situations under varying icing conditions is also shown in Figure 4-6.

Approximately 22 % of the ice pieces are expected to be dangerous (above 0.5 kg/m) according to Figure 4-3. At the effective icing height, the threshold of 0.5 kg/m is reached 0.2 % of the time and in average once (1 time) per year. There is no variation across the site of these numbers since the height difference is small.

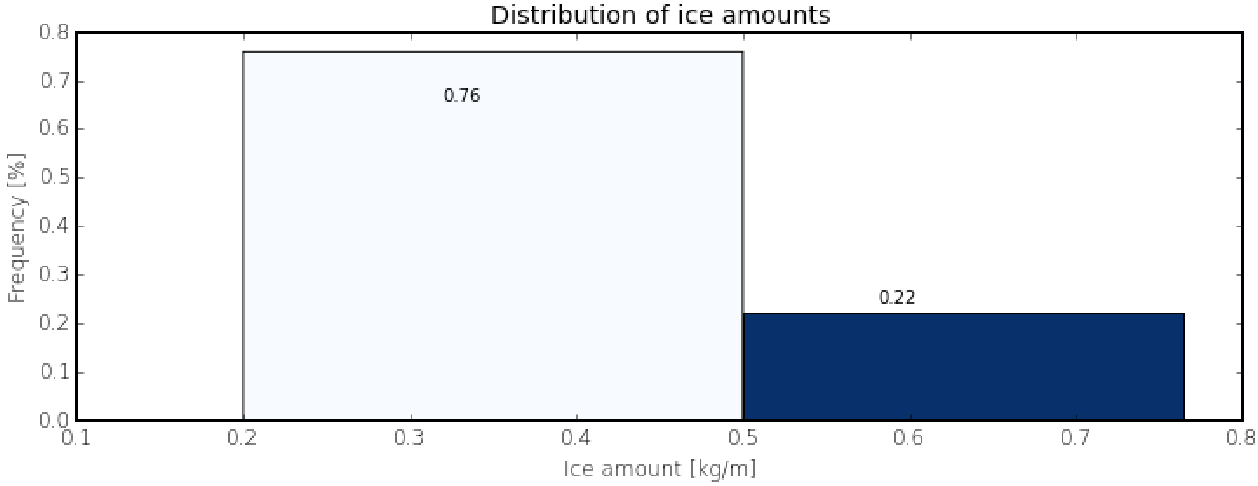
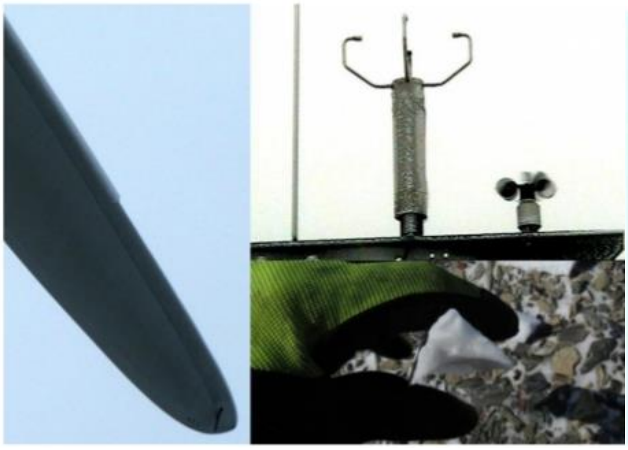


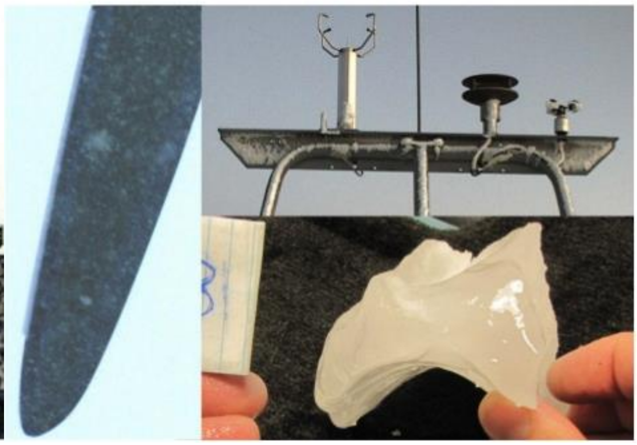
Figure 4-3 Distributions of ice amounts on a standard body for an average positioned turbine. The bins correspond to the categories 1 (light blue) and 2 (dark blue) in Figure 4-4.

TechnoCentre éolien
Wind Energy TechnoCentre

Cat. 1: ISO 12494 ice load up to 0.5 kg/m



Cat. 2: ISO 12494 ice load between 0.5 and 0.9 kg/m



Cat. 3: ISO 12494 ice load between 0.9 and 1.6 kg/m

Cat. 4: ISO 12494 ice load between 1.6 and 2.8 kg/m

Cat. 5: ISO 12494 ice load between 2.8 and 5.0 kg/m

Figure 4-4 Relationship between ice load on the reference body (ISO 12494) at hub height and accumulated ice on a turbine blade divided into 5 categories. The pictures are reprinted with the permission of Wadham-Gagnon at TechnoCentre éolien (now Nergica).

4.5 Monthly and yearly distributions of icing

Icing has a large variation throughout the year, and from year to year. This is an important aspect when considering which measures are suitable for the site. Figure 4-5 and Figure 4-6 show average icing hours through the year and the distribution of rotor icing hours per year for the last 20 winters.

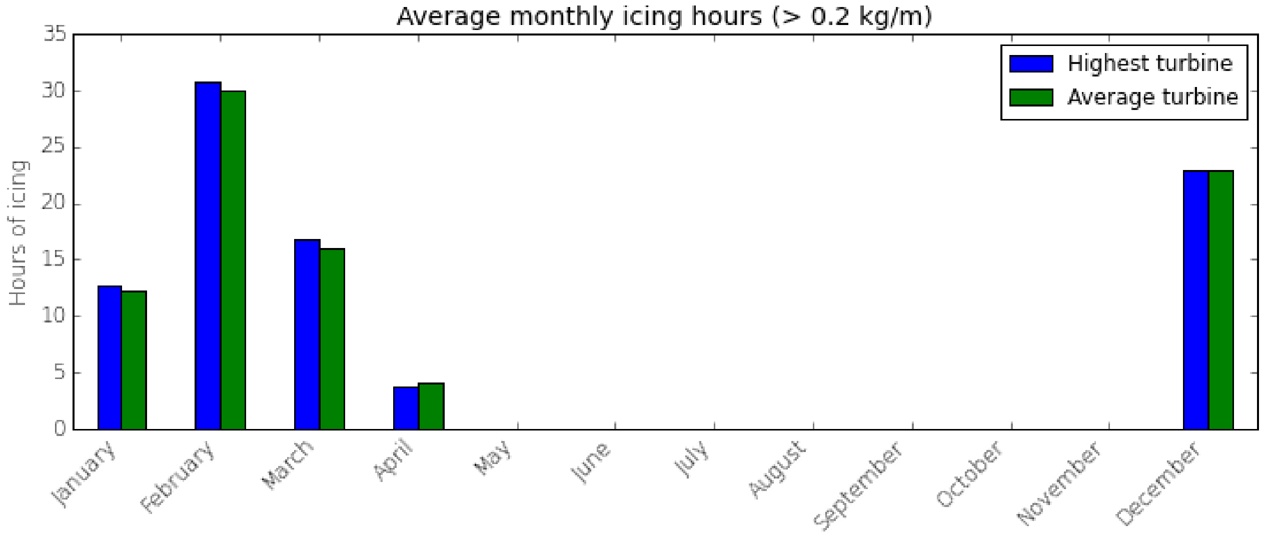


Figure 4-5 Monthly variation of rotor icing hours on a standard body for the highest positioned turbine.

Icing is mainly distributed across the months of December to March at Åby Alebo (Figure 4-5), but in some cases, icing can also be present in April. February is the month with the highest amount of icing.

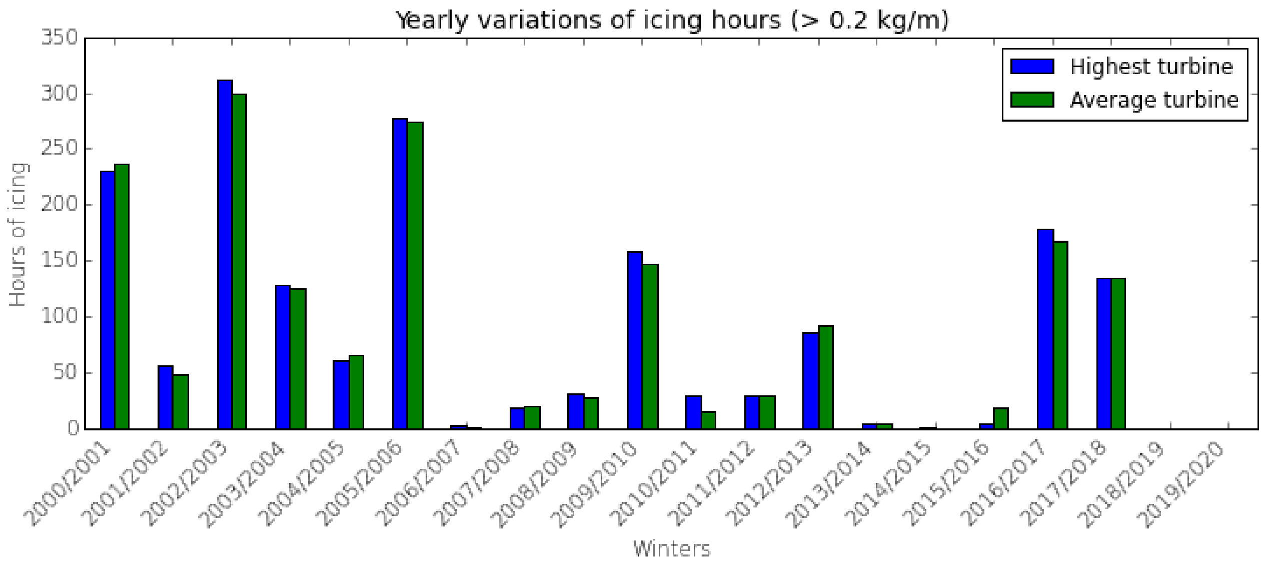


Figure 4-6 Yearly variation of rotor icing hours on a standard body for the highest positioned turbine.

As shown in Figure 4-6, there was a high amount of icing during the winter of 2002/2003, whereas in the winter of e.g. 2014/2015 there were only smaller amounts of icing. In general, the variation is large, spreading from close to no hours to over 250 hours of icing for individual winters.

5 Calculations of ice throw

In the previous chapter, the icing conditions for the wind farm were presented. In this chapter, this information is used to calculate the risk of ice throw around each turbine. In Section 5.1, the calculations of an ice throw database for the turbine type considered in this report is described. In Section 5.2, a spatial probability distribution of ice throw from an arbitrary turbine in the wind farm is calculated by using four scenarios of operation.

5.1 Calculations of an ice throw database for the turbine type

In-cloud icing is expected to cause icing on the turbines at Åby Alebo. This type of icing accumulates on the leading edge of the blade when liquid cloud droplets from low clouds (fog) freezes on the surface of the blade during winter. Rime typically has a density of 500 kg/m^3. When the temperature is close to 0 °C or when drizzle is involved in the icing process, the density can increase to between 700 and 800 kg/m^3. An inspection of the thrown ice pieces at the Swiss site, Gütsch (Cattin 2007), showed an even distribution of porous rime ice of low density and glace ice of high density. Densities of 500, 800 and 850 kg/m^3 are used in the calculations.

The calculations have been performed for a Vestas V150 turbine with 125 m hub height and a rotor diameter of 150 m. The highest rotational speed for the turbine is 10.4 rpm. Calculations using a trajectory model (Biswas 2012) show expected throw length for ice pieces of different sizes during different weather conditions. In Figure 5-1 the throw lengths are shown for large ice pieces at the right (5.2 kg) and for smaller ice pieces (150g) at the left. Smaller ice pieces (less than 150 g) are not regarded as dangerous. The proposed safety distance at Åby Alebo wind farm is dependent on how far dangerous ice pieces can be thrown from the blade during operation. Shape, size and density of the thrown pieces are important for this calculation. The calculations are performed using assumptions for a selection of ice piece shapes based on different CdAoM-factors,[2] with varying throw positions across the turbine blade. From the calculated distances shown in Figure 5-1 it is evident that the proposed safety distance is smaller than the 413 m given by the general Seifert safety rule[3].

[2] CdAoM describes the relationship between effective area (A) and mass (M) for an ice piece. CdAoM=C_dA/M, where C_d is the drag coefficient of the ice piece.
[3] The general safety rule: (H+D) * 1.5, where H is the hub height and D is the rotor diameter.

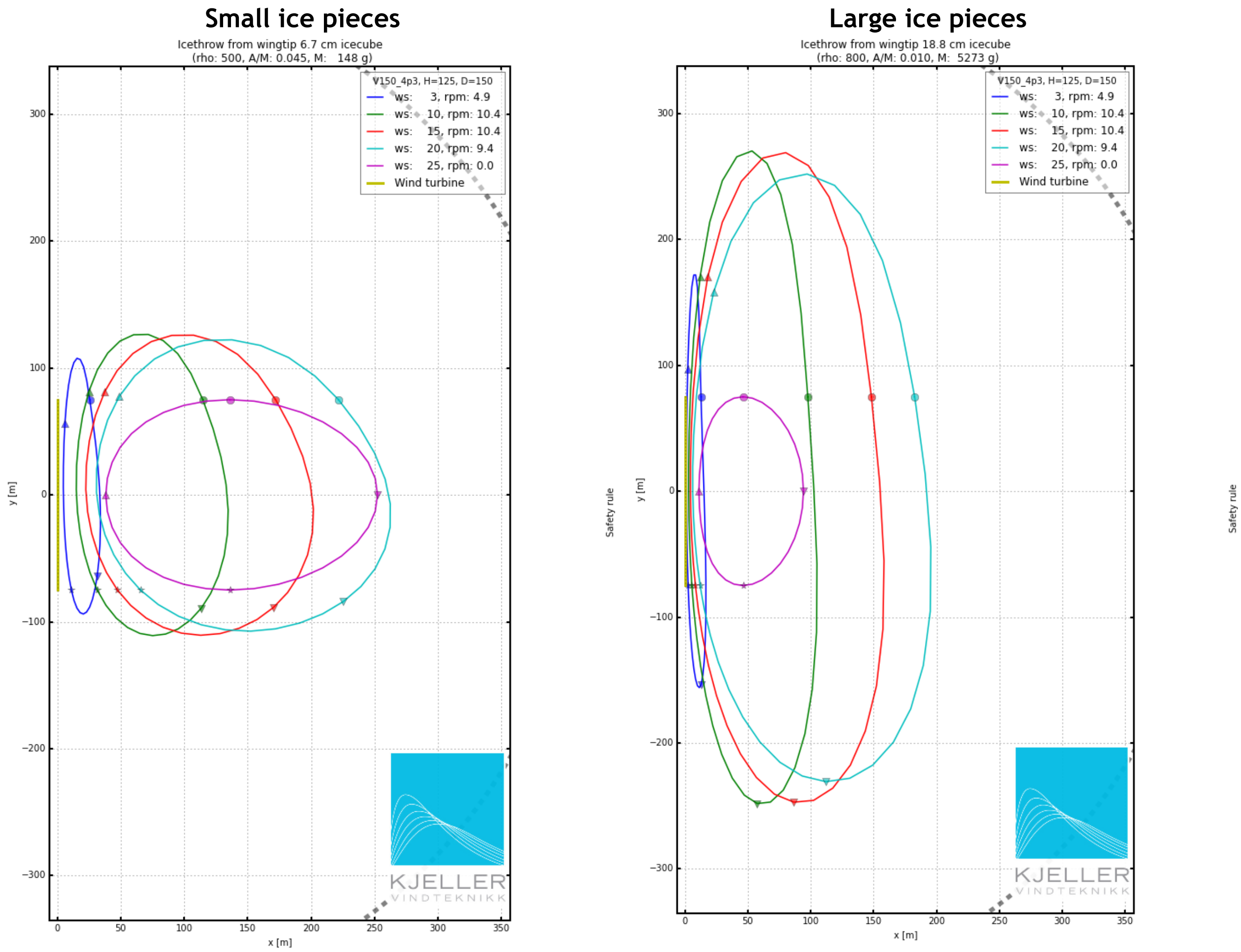


Figure 5-1 Calculated zones for ice throw with small and large ice pieces from the blade tip of a V150 4.3 MW turbine, with a rotor diameter of 150 m and a hub height of 125 m. The wind direction is left towards right. The different colors correspond to different wind speeds. The purple line shows a stopped turbine at 25 m/s, the rest of the lines show turbines during operation.

5.2 Probability distribution for ice throw in Åby Alebo wind farm

In this section, a probability map is presented for an average turbine in the wind farm (Figure 5-2). The map is calculated by combining the wind statistic and the size distribution presented in the previous chapter with detailed calculations using a trajectory model. This map shows the ice throw risk around the turbine, depending on the directional sector. In addition, the model is used to separate between dangerous and non-dangerous ice throw and ice fall based on the calculated impact energy for each ice piece (see Bredesen 2015/2016). The separation between dangerous and non-dangerous ice pieces is justified below.

We assume that the probability for ice throw from a rotating turbine blade grows linearly with the radial position on the turbine blade, as the build-up of ice grows along the blade with a larger swept area. In addition, the distribution of the detachment angle for the turbine blade is assumed as given by Battisti (2005). Shortly summarized, the combination of gravity and the centripetal acceleration of an ice piece on a turbine blade will most likely cause detachment of the ice when the blade points down, and least likely when the blade points up.

Calculations of ice throw is performed for 4 scenarios where ice throw is expected:

1. Ice on the blade and the turbine rotates at full speed

2. Ice on the blade and the turbine rotates at reduced RPM due to the presence of ice on the blades
3. Ice on the blade, melting conditions and the turbine rotates at full speed
4. Ice on the blade, melting conditions and the turbine rotates at reduced RPM due to the presence of ice on the blades

Ice pieces with an energy of impact of above 40 J can be regarded as dangerous for humans (see Bredesen (2015, IWAIS), Bredesen (2014), Refsum (2015), and TNO Greenbook). In this calculation we thus regard the ice throw of fragments with an impact energy of more than 40 J as dangerous while the fragments with lower impact energy as non-dangerous. The risk of ice throw is calculated using 10 million different landing positions for dangerous ice pieces depending on the wind conditions, turbine performance, size of the ice pieces and the detachment position on the rotating turbine blade.

The combined statistics from all 4 scenarios are shown in Figure 5-2 for a turbine at average elevation at Åby Alebo. The probability of a dangerous ice throw or fall is distributed fairly even across the sectors, though the risk of ice throw is slightly higher on the east side of the turbines compared to the west. At one square meter, throws with a return period of 100 years will land 30 m from the turbine, 1000 year at 100 m from the turbine, 10 000 years 190 m from the turbine, 100 000 years 220 m from the turbine and 1 000 000 years 280 m from the turbine. Terrain variations have not been included in Figure 5-2. The ice can be thrown further down-hill and shorter up-hill, though in this wind farm the terrain variations are quite small. This effect is, however, taken into consideration in the end results and for the risk map presented in Chapter 6.

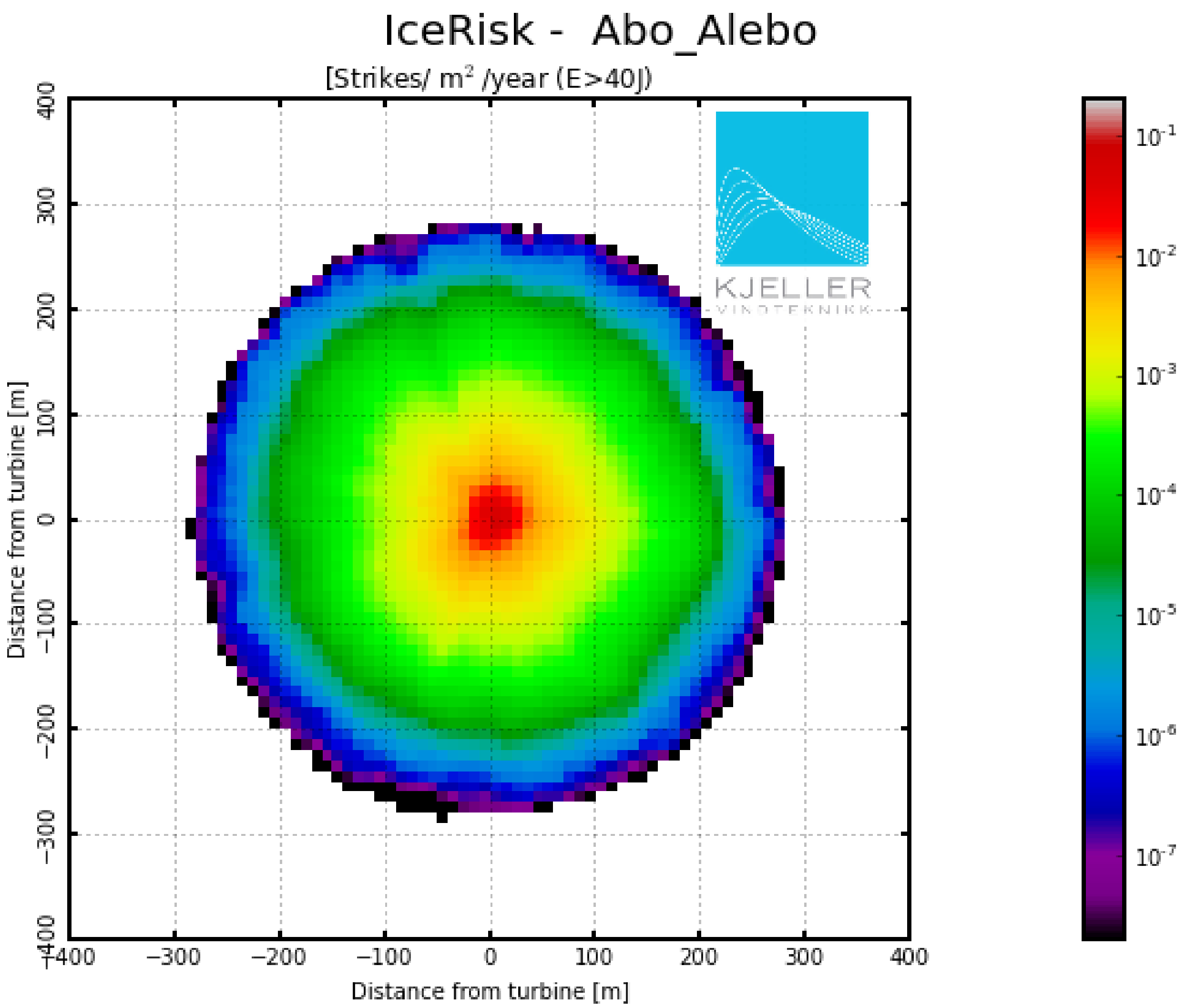


Figure 5-2 Number of strikes by dangerous ice pieces per square meter each year as a function of distance from the turbine. The statistics from the four scenarios described above are combined in the figure to represent a turbine in operation.

6 Risk evaluation of the surrounding area

After the calculation of the icing conditions, we can draw the risk of ice throw as LIRA contours (Localized Individual Risk per Annum) on a map, which are then interpreted and compared to defined thresholds. The definitions for risk (LIRA, IRPA, PLL) are given in Appendix B.2. These definitions are used in the following analysis, and it is important to understand the difference between them. Two different sources for suggested risk mitigation strategies and acceptable risk levels are used in this evaluation. The Norwegian Water Resource and Energy Directorate (NVE) published their national guidelines for ice throw for wind turbines in 2018 (NVE, 2018). International guidelines for ice throw and ice fall was published in 2018 as well by IEA wind (IEA Wind, 2018). The risk acceptance criteria from both sources are presented in Appendix B (Table B-2 and Table B-3). The process to decide which mitigation measures are necessary are shown in Appendix B.5.

In this chapter, the risk assessment for the wind farm is performed. In Section 6.1, the risk map of ice fall and ice throw for Åby Alebo farm is presented. In Section 6.2, an identification of risks is evaluated for the wind farm. Suggested risk mitigation measures will be presented in Chapter 7.

6.1 Risk map (LIRA)

Figure 6-1 and Figure 6-2 show the risk contours for LIRA in the Åby Alebo wind farm. In general icing occurs seldom in the wind farm and the risk of ice throw is considered to be low.

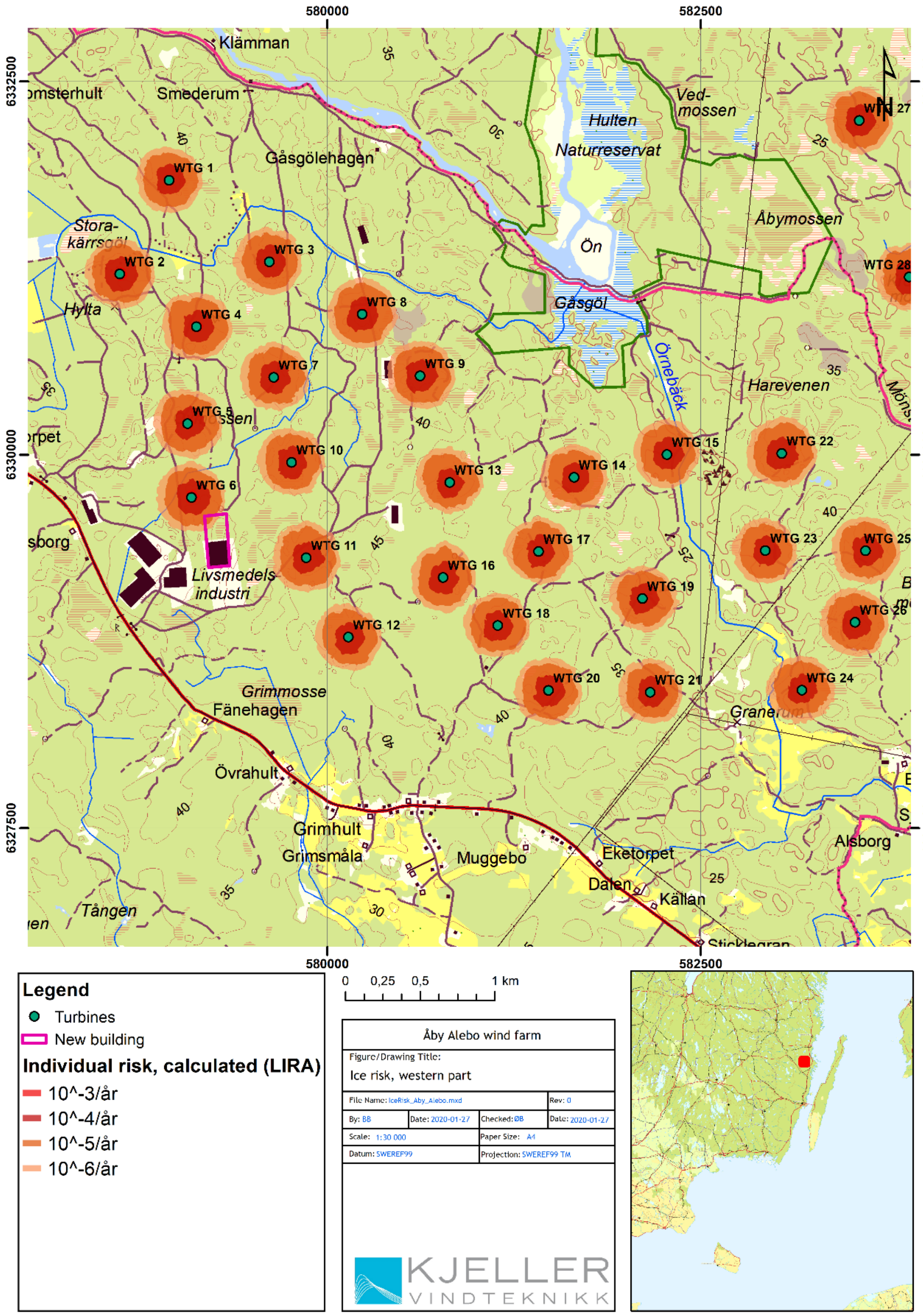


Figure 6-1 A map of the western part of the Åby Alebo wind farm showing the risk contours for an unprotected person who is permanently present in the wind farm (LIRA contours, red color). The darker color, the higher LIRA. For more information on LIRA, see Appendix B.

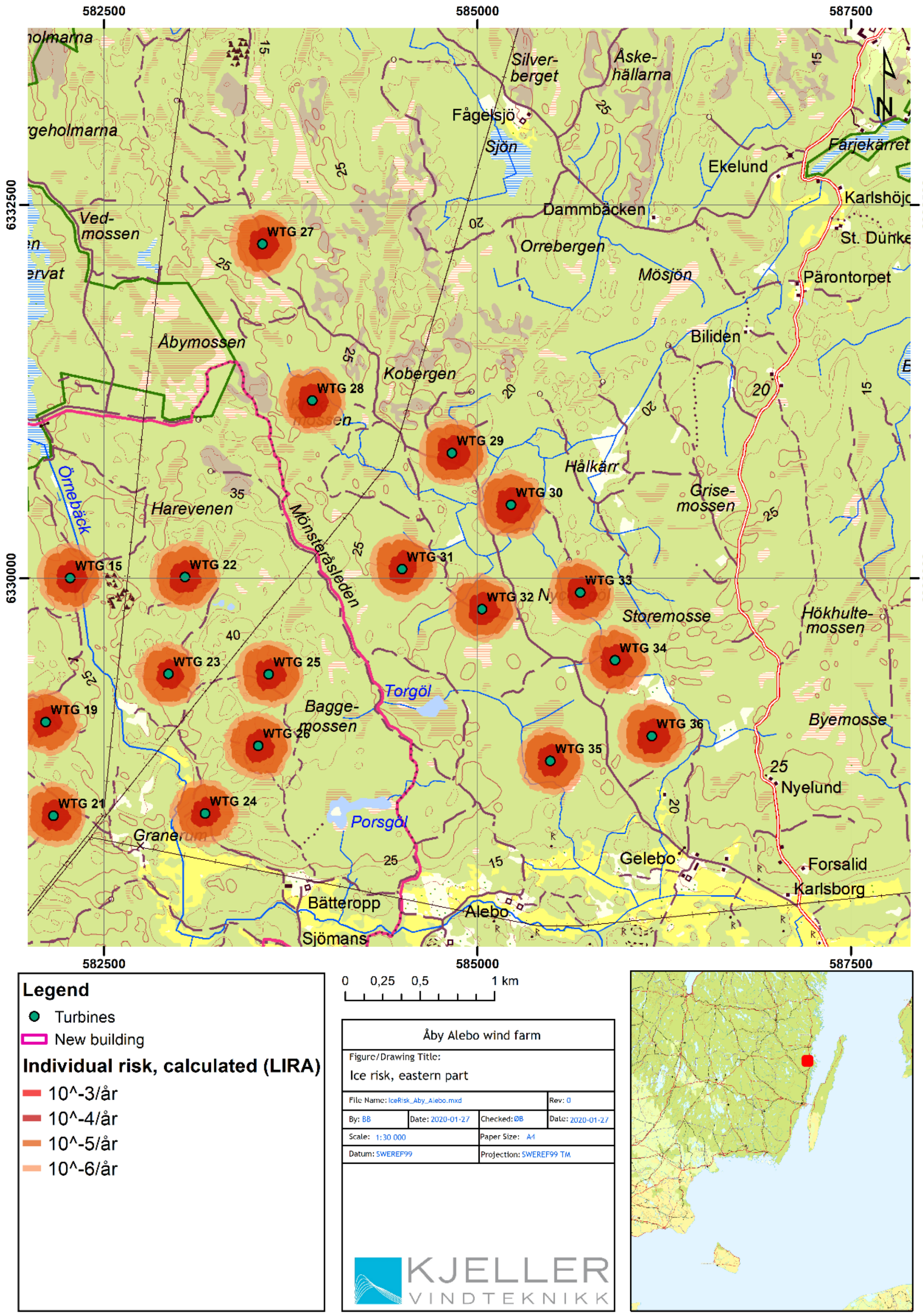


Figure 6-2 A map of the eastern part of the Åby Alebo wind farm showing the risk contours for an unprotected person who is permanently present in the wind farm (LIRA contours, red color). The darker color, the higher LIRA. For more information on LIRA, see Appendix B.

6.2 Objects at risk

The following sections 6.2.1 to 6.2.8 describe the risk for objects at or on which risk of human damage is present. The section 6.2.9 is concerning objects where the risk of material damage is present.

6.2.1 Internal roads

There is a risk associated with travelling on the internal roads and for approaching and entering the turbines.

6.2.2 Nearby roads

The road passing the wind farm to the south will not be influenced.

6.2.3 Hiking trails

The hiking trail Mönsteråsleden goes through the wind farm. The risk is negligible on the hiking trail.

6.2.4 Skiing tracks

There is no information about skiing activities in the wind farm area.

6.2.5 Snowmobile tracks

There is no information about such activities in the wind farm area.

6.2.6 Buildings

The existing buildings close to WTG 6 are not in risk for ice throw. However, it is planned to expand the building SSE of WTG 6 as shown in Figure 6-1. The northwestern part of the expanded building will be subject to risk at a level which is evaluated as acceptable for industry according to Appendix B.3.

The building just west of WTG 9 is subject to risk at a level which is evaluated as acceptable for industry according to Appendix B.3. But as shown in Figure 6-1 the risk increases on the east side of the building.

6.2.7 Hunting and fishing areas

There is no information about hunting and fishing areas inside the wind farm.

6.2.8 Forestry

The area is assumed to be used actively for forestry. There will be a risk inside the LIRA zones shown in Figure 6-1 and Figure 6-2.

6.2.9 Power lines

There are existing power lines crossing the wind farm, which are outside the risk zones, however, a power line may be built to connect the wind farm to the power grid. Such a power line is recommended to be built outside of the LIRA risk zones shown in Figure 6-1 and Figure 6-2.

7 Recommendations to mitigate ice risks

The risk in the wind farm has been mapped out and challenges have been identified. Based on evaluation of risk scenarios, suitable risk mitigation measures can be chosen. This chapter discusses and proposes a few possible measures for the Åby Alebo wind farm. Chapter 7.1-Chapter 7.3 presents some general risk mitigation actions that can be taken. Chapter 7.4 presents the specific risk mitigation measures suggested for this wind farm with regards to the general risk level presented in the previous chapter.

For a good overview of possible mitigation measures, please consult the view of Svensk Vindenergi as presented by Göransson and Haaheim at Winterwind (2016) (see appendix C) and the Norwegian guidelines on ice throw and ice fall from wind turbines from NVE (2018). For more details on risk analysis, see e.g. the Norwegian standard (NS 5814)[4].

7.1 Knowledge

In order to manage the risk in your own wind farm, knowledge is a prerequisite. Appropriate measures could be professional communication (for employees and the public), signs, employee routines, training and warning systems. It is expected that the use of signs can reduce the risk by a factor of 1-10 (IEA 2018).

7.2 Warnings

During icing or expected icing, different warning systems can be installed. This can be sounds and/or light, or other information. Typically, a warning system could be driven by a combination of sensors on the turbine, weather predictions, and turbine inspection. It is expected that the use of an active monitoring of warning system can reduce the risk with a factor of 10-100 (IEA 2018).

7.3 Design solutions

In and around the turbine there are several possibilities to reduce the risk; ice measuring sensors, web cams on the nacelle, defining specific risk zones, communication procedures, secure vehicles, and roofs. In addition, the turbine can react to the ice measurements, either by stopping, starting a blade heater, or reducing the rpm. It is also possible to do individual settings for each turbine in the wind farm. In addition, physical safety measures can be put up, such as blocking of internal roads.

For employees, routines can help to manage the risk which is not managed through design; sensors, web cameras, communication procedures, ice warnings and specific risk zones, secure vehicles, and roofs.

[4] Norsk standard NS 5814:2008, Demands for risk assessments.

7.4 Specific risk mitigation measures

Suggested risk mitigation measures:

There should be signs at all natural access paths informing about the risk of ice throw with a recommended safety distance of 200 m to the turbines during icing conditions.

Safety routines to be used during icing conditions should be established and implemented for the service personnel and for the personnel working in the food production facilities close to and inside the wind farm.

On the northern side of the building SSE of WTG 6 as well as on the eastern side of the building close to WTG 9 extra caution needs to be taken. Depending on the usage of the building it can be recommended installing signs warning of increased risk at the entrance of the building.

Additionally a safety course regarding the risk of ice throw can be performed to inform the involved personnel about the risk and knowledge on how to handle/reduce their own risk when working close to or in the wind farm in order to establish the safety routines needed.

8 Bibliography

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Appendiks A Meso-Scale Model WRF

A.1 Meso-Scale Model WRF

The Weather Research and Forecast (WRF) model is a state-of-the-art meso-scale numerical weather prediction system, aiming at both operational forecasting and atmospheric research needs. A description of the modelling system can be found at the home page http://www.wrfmodel.org/. The model version used in this work is v3.2.1 described in Skamarock et al. (2008)[5]. Details about the modelling structure, numerical routines and physical packages available can be found in for example Klemp et al. (2000)[6] and Michalakes et al. (2001)[7]. The development of the WRF-model is supported by a strong scientific and administrative community in U.S.A. The number of users is large, and it is growing rapidly. In addition, the code is accessible for the public.

The meso-scale model WRF solves coupled equations for all important physical processes (such as winds, temperatures, stability, clouds, radiation etc.) in the atmosphere based on the initial fields and the lateral boundary values derived from the global data.

A.2 Input data

The most important input data are geographical data and meteorological data. The geographical data is from the National Oceanic and Atmospheric Administration (NOAA). The data includes topography, surface data, albedo and vegetation. These parameters have high influence for the wind speed in the layers close to the ground. For the entire domain except for Sweden and Norway, the model uses land use data input from NOAA. The land use data for Sweden is retrieved from the Geografiska Sverigedata (GSD)-Land Cover which is classified in accordance with the European Union's CORINE Land Cover mapping project[8]. For Norway, the model input uses the N50 land use data provided by the Norwegian Mapping Authority[9].

For the solving of the model equations it requires boundary conditions of the area considered. Such lateral boundary data is available from the National Centres for Environmental Protection (NCEP). The data originates from the Final Global Data Assimilation System (FNL)[10] and is available as global data with 1 degree resolution every 6 hours. FNL is an operational assimilation model that incorporates all available observation data globally and uses this data to create a global analysis dataset, or a snapshot of the atmosphere, four times every day. The assimilation model incorporates data from several thousand ground-based observation stations, vertical profiles from radiosondes, aircrafts, and satellites.

Similar lateral boundary data is also available from the European Centre for Medium range Weather Forecasting (ECMWF). The reanalysis data ERA Interim[11,12] is available with a spatial resolution of approximately 0.7 degrees globally. Data is available every 6 hours. The ERA interim dataset does also assimilate observational data. For weather forecasting the datasets from ECMWF is usually accepted to have higher quality compared to NCEP datasets, in particular for the European region.

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[6] Klemp JB., Skamarock WC. and Dudhia J., 2000: Conservative split-explicit time integration methods for the compressible non-hydrostatic equations (http://www.wrf-model.org/)

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[8] http://www.eea.europa.eu/publications/COR0-landcover

[9] http://www.kartverket.no/eng/Norwegian_Mapping_Authority/

[10] http://www.emc.ncep.noaa.gov/gmb/para/parabout.html

[11] Dee, D. P., et al. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q.J.R. Meteorol. Soc., 137: 553–597. doi: 10.1002/qj.828

[12] http://www.ecmwf.int/research/era/do/get/era-interim

A.3 Model setup

The model setups used in these analyses are shown in Figure A-1. The simulations of the northern European region have been performed for 20 and 12 years covering the periods of 1992-2011 and 2000-2011, respectively. The model has in each case been set up with 2 nested domains. The horizontal resolutions are 16 km x 16 km and 4 km x 4 km for the shorter period, and 18 km x 18 km and 6 km x 6 km for the longer period. To describe Sweden in greater detail the model has also been set up with several 1 km x 1 km simulations that cover the period 01.10.2009 – 30.09.2011.

The ERA Interim dataset is used as lateral boundary conditions for the 6 km simulation, while the NCEP-FNL dataset is used as input for the 4 km and 1 km simulations.

Each of the simulations has 32 layers in the vertical with four layers in the lower 200 m. We have used the Thompson microphysics scheme and the YSU scheme for boundary layer mixing.

With the current setup, the WRF-model calculates the change in the meteorological fields for each grid-cell for a time step from 5 to 108 seconds in the different domains with increasing time step for lower horizontal resolution. In this way a realistic temporal development of the meteorological variables is achieved. Data is stored to disk every 1 hours of simulation.

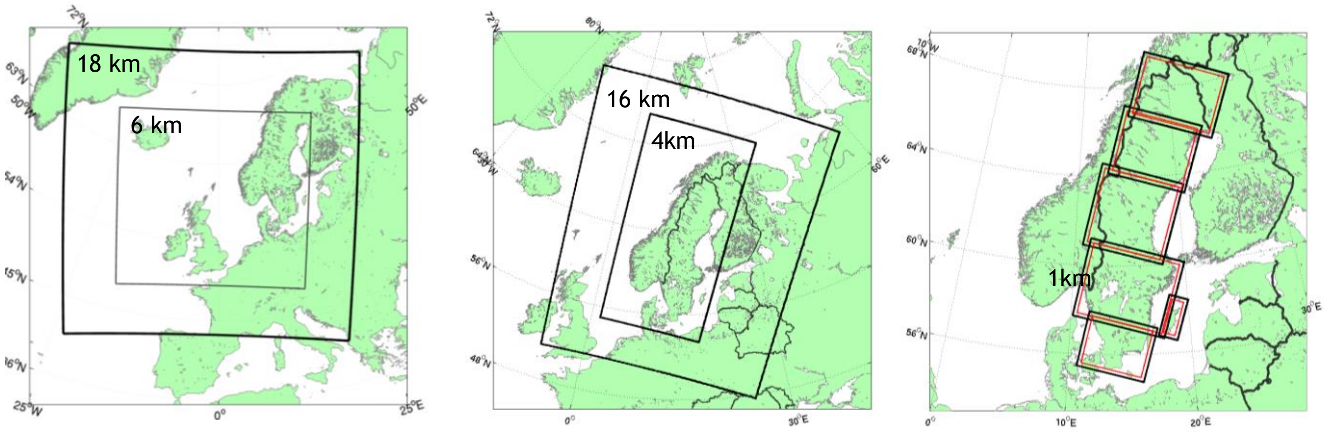

Figure A-1 Model set up for WRF simulations. Left: 6 km (and 18 km), middle: 4 km (and 16 km), right: several 1 km domains covering Sweden.

A.4 Ice load calculations

According to the standard ISO 12494 (ISO/TC98/SC3/WG6 2000)[13] icing has been calculated from

$$\frac{dM}{dt} = \alpha_1\alpha_2\alpha_3 \cdot w \cdot A \cdot V \tag{1}$$

Here *dM/dt* is the icing rate on a standard cylindrical icing collector (defined by ISO 12494 as a cylinder of 1 m length and 30 mm diameter), *w* is the liquid water content, and *A* is the collision area of the exposed object. *V* is the wind speed and a_1, a_2 and a_3 are the collision efficiency, sticking efficiency and accretion efficiency, respectively.

Periods of active meteorological icing is identified from the model data when the icing rate (*dM/dt*) exceeds 10 g/hour. The number of hours where active icing is identified is reported as “icing hours”. 10 g of ice on the standard cylindrical icing collector is equivalent to a 0.5 mm layer of ice on the cylinder.

Accumulated over time (1) gives M as the mass of ice on a standard cylindrical icing collector. Icing is calculated at a specific height equivalent to the elevation of the turbine hub. The ice will often prevail sometime after the period with active icing, until it is removed by melting, sublimation or mechanically as ice shedding. The time periods when ice is present on the cylinder, are defined as periods with instrumental icing. Wind speed measurements are typically influenced by icing during these periods. In these periods there will also typically be ice on the blades of the wind turbines resulting in a reduced power production. We have defined the periods with instrumental icing as the periods when the ice mass, *M*, exceeds 10 g/m.

There are several sources of uncertainty in the model data. The cloud processes are simplified and calculated by using parameterizations. Uncertainties therefore exist in the total amounts of cloud water available in the air masses, and in the distribution of cloud water vs. cloud ice in the air masses. The model setup is using a sophisticated microphysics scheme.[14] This is the scheme that gives the most accurate calculations of liquid water content[15] and is thus recommended for icing calculations. Uncertainties are also related to the vertical distribution of the moist air and choice of parameterization scheme for the boundary layer mixing processes.

In the simulations also the topography is represented by a grid and does not reflect the real height of the mountain peaks. This means that the mountain tops in the model are lower than in the real world. This discrepancy can lead to an underestimation of the icing amounts particularly for coarse model grids. We correct for the discrepancy in height between the model grid and the actual elevation of the sites. This correction is done by lifting the air in the model to the correct terrain height. This lifting will contribute to lower the pressure and temperature in the air, allowing for an increased amount of cloud water, or it will lead to condensation in the cases when the air will reach the water vapor saturation pressure. The lifting is performed according to the vertical profile of temperature and moisture locally in the model.

[13] ISO 12494 2000: Atmospheric Icing of structures, International Standard, ISO/TC98/SC3/WG6.

[14] Thompson G., P.R. Field, W.D. Hall and R Rasmussen, 2006: A new bulk Microphysical Parameterization Scheme for WRF (and MM5)

[15] Nygaard B.E.K., J.E. Kristjansson and L. Makkonen, 2011: Simulations vs. observations of supercooled cloud liquid water at ground level; sensitivity to model resolution and cloud microphysics parameterizations. Winterwind 2011, Umeå, 9-10. February 2011.

A.5 Removal of ice

Ice melting is calculated by evaluating the energy balance model, given by

$$Q = Q_h + Q_e + Q_n, \quad (2)$$

where Q_h and Q_e are the sensible and latent heat fluxes. Q_n is the net radiation term. There are also other terms which will come into the total energy balance model; however, they are assumed to be of negligible size in this context. A detailed description of the melting terms is given in Harstveit (2009).[16]

When Q becomes positive, melting will start. Often during melting episodes, the ice does not melt gradually away such as described by the energy balance model. When the melting is initialized the ice will often be removed more quickly by shedding, particularly from a rotating blade. This ice shedding is a stochastic process which makes it difficult to estimate the time when all ice is removed. In this work no ice shedding is assumed in relation to melting of the ice. This implies that the ice load can be overestimated at some periods during melting. The melting process does however happen quite fast, so only shorter periods of time will be affected.

Sublimation is a process for ice removal that is found to be important, in particular for dry inland sites where the temperature can stay below freezing for several months continuously during the winter. At such sites the accumulated ice will not melt. Sublimation is defined as the transfer of ice from solid state directly to water vapor. This will happen in situations with dry air. The sublimation rate increases with wind speed when the ventilation of the iced object is high. This can allow for faster ice removal of a rotating turbine blade compared to a fixed object. The sublimation rate is calculated by evaluating the energy balance between outgoing long wave radiation and latent heat release from the sublimation process. Sublimation has been included in the icing calculations. During the process of sublimation, we have observed that the ice becomes brittle and that small pieces of ice continuously fall off the cylinder. This shedding is included by multiplying the sublimation rate with a factor of 2.5.

[16] Harstveit K, Byrkjedal Ø. and E. Berge 2009: Validation of Regional In-Cloud Icing Maps in Norway, IWAIS, Andermatt 2009.

Appendiks B Risk assessment

B.1 Risk definition

The risk is usually taken as the probability of an event multiplied with an associated consequence. Here the probability is given in Table B-1 and the potential consequence is a severe injury or fatal accident. 40 J is considered a kinetic energy limit than can cause a fatality for an unprotected person. When a person is protected by the wind shield of a car, we consider the energy limit as 180 J for the same consequence.

Table B-1 Relation between energy limit strike area, and consequence of an ice piece strike (Bredesen & Refsum, 2015) and (Bredesen,2019)

Energy Limit	Strike area	Consequence
15 J	0.1 m^2	Casualty (serious injury protection limit)
40 J	0.1 m^2	Fatality (death) unprotected person
180 J	0.01 m^2	Fatality person protected by windshield of a car

B.2 Definitions of LIRA, IRPA and PLL

LIRA (Localized Individual Risk per Annum) gives the risk at a given position for an unprotected person, who is continuously present (100 % unprotected exposure). The individual risk, LIRA-contours, is calculated by combining possible events of accidents with the respective risk of death. The risk contours show the geographical distribution of individual risk, by showing the expected frequency of incidents capable of causing casualties at a given position, independent of whether there are any persons present at the position. Suggested acceptance criteria are shown in Figure B-1.

IRPA (Individual Risk per annum) [17] describes the risk for a given pattern of movement for a person. There are separate suggested risk acceptance limits for IRPA. The risk should typically be negligible compared to the background risk in society. As an example, this could be done by comparing an average position in the park for 1 hour to the risk of death in traffic. If the risk is acceptable using the LIRA-value, it is not necessary to calculate IRPA.

PLL (Potential Loss of Life) describes the risk for a given pattern of movements for a group of persons, also called a group risk.

To better understand the definitions and the link between them, we use an example. At a given position in the park, the LIRA value is $1x10^{-4}$. If an unprotected person spends 3 minutes every day at this position (0.2 % of the time), the IRPA for this person is $2x10^{-7}$. If 500 persons spend 3 minutes every day at this position, the group risk (PLL) is $1x10^{-4}$. For comparison, 109 people got killed in traffic in Norway in 2017, which corresponds to an IRPA of $2.1x10^{-5}$.

B.3 LIRA methodology

The chosen Individual Risk (IR) metric is LIRA. It is recommended to provide IR contours in a risk assessment (IEA Wind, 2018)

Risk is the product of probability and consequence. Here, the probability is the inverse of the average recurrence period for a possible fatal ice piece striking an area of 1 square meter. The impact kinetic energy limit for considering a possibly fatal ice piece is taken as 40 J corresponding to a 200 g ice piece falling at 20 m/s (72 km/h).

In this analysis every ice piece with an impact kinetic energy above 40 J is considered 100 % fatal for an area of a person occupying the area of 0.1 square meters (potential critical hit). Hence, the LIRA contour 10^{-4} /year then corresponds to the millennium ice piece hitting a square meter with an impact kinetic

[17] IRPA=exposure*LIRA. One hour exposure per day gives IRPA=LIRA/24.

energy above 40 J. More details describing the methodology is given in (Bredesen & Refsum, 2015) *and* (Bredesen R. E., 2017).

In order to understand the ice throw risk margins at the site, the modelled risk levels are compared against the average risk from dying in a traffic accident in Norway 2017 as well as typical risk acceptance criteria for societal risk (potential for loss of life per annum, PLL) and individual risk (Individual Risk Per Annum, IRPA) used in Norway. We observe that the risk may exceeding the LIRA criteria while being tolerable and acceptable for the exposure scenarios.

Beware, that the responsibility of reducing the risk to a minimum should not be dependent on an opportunistic choice of the method yielding the lowest risk. High precision analyses can facilitate further cost-benefit analyses for the different risk mitigating measures (e.g. according to the ALARP (As Low As Reasonably Practicable) principle as used in the UK). Based on the given ALARP recommendation, it can clearly be communicated that the risks are managed properly by reducing the risk to a reasonably practicable minimum and an acceptable level.
We remark that a risk index such as individual risk (IRPA/LIRA) does not describe all aspects such as 1) Aspects of risk not covered within risk assessment scope. 2) Model errors and 3) Aspects of model predictions not conveyed by risk metrics. However, a risk analysis shall identify the relevant initiating events and develop the causal and consequence picture. How this is done depends on which method is used and how the results are to be used. However, the intent is always the same: to describe risk.

Figure B-1 is taken from the ice throw recommendation from IEA Task 19 (IEA Wind, 2018). It gives suggestions of which objects are accepted within which LIRA safety zone.

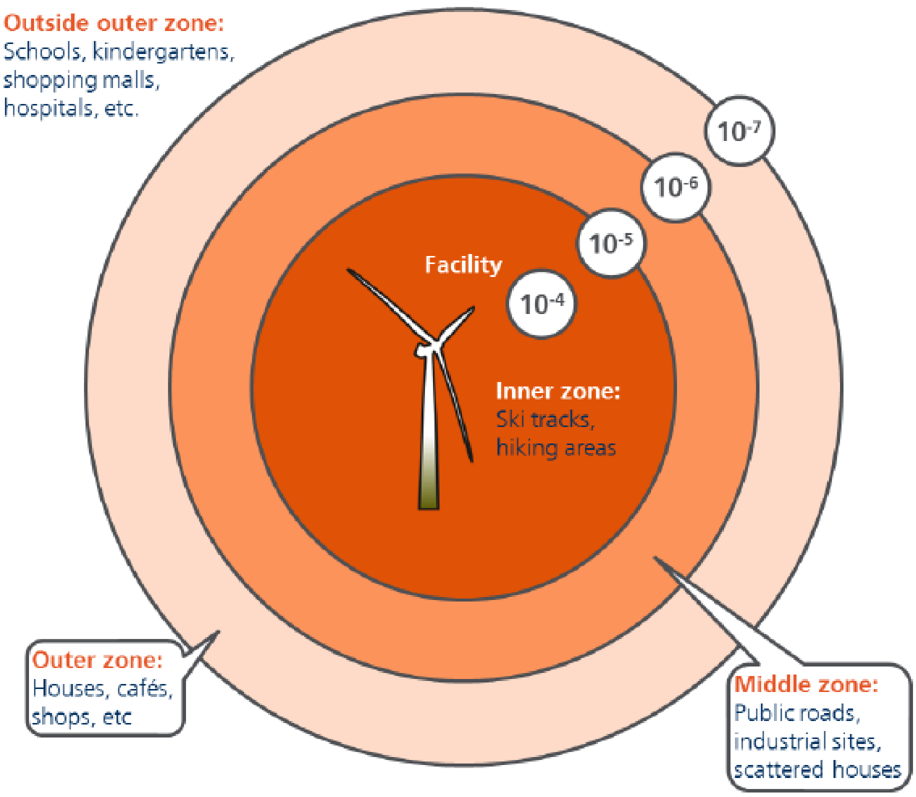

Figure B-1 Suggested safety zones around installation that may cause risk of ice throw or ice fall. The numbers indicate the iso-risk contours for localized individual risk (LIRA), the probability that an average unprotected person, permanently present at a specified location, is killed during one year due to ice fall or throw from the facility. (Source: courtesy of Lloyds Register / Kjeller Vindteknikk) (IEA Wind, 2018, s. 16)

B.4 Exposure scenarios

Beyond using the LIRA risk metric for calculating consultation distances and hazard zones for the risk of iced throw, the risk estimates may also be assessed for specified persons or groups. The following tables show standard interpretation of a more detailed risk assessment accounting for exposure scenarios. Note that the suggested acceptance criteria shall motivate further risk mitigating efforts and ALARP is recommended independent on risk acceptance criteria, see Table B-2 and Table B-3.

Table B-2 Comparable risk for driving a car in Norway and suggested acceptance criteria from the Norwegian Directorate for Civil Protection (DSB) combined from all sources at facility.

	Group Risk (PLL)	Individual Risk (IRPA)
Risk fatal road accident (Norway 2017)		2×10^{-5}
Suggested risk acceptance criteria Norway (DSB)		
3. person (public)	1×10^{-4}	2×10^{-7}
2. person (guests)		3×10^{-6}
1. person (trained service personnel)		4×10^{-5}

Table B-3 Example for individual and societal risk criteria (IEA Wind, 2018) and Norwegian Directorate for Civil Protection (DSB) (bottom line).

Risk value [1/a]		Evaluation
Societal risk (without risk aversion)	Individual risk (IRPA)	
$> 10^{-3}$	$> 10^{-5}$	The risk is unacceptable high. Risk reduction measures shall be initiated. Extensive risk reduction measures (e.g. relocation or change of turbine specifications, can be initiated to re-assess whether the risk can be sufficiently reduced.
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.
$<1 \times 10^{-5}$	$<1 \times 10^{-7}$	Risks are lower than risks people are exposed to in normal life.
$<1 \times 10^{-4}$	$< 2 \times 10^{-7}$	Typical risk acceptance criteria in Norway third person all sources (Norwegian Directorate for Civil Protection, DSB).

B.5 Are measures necessary?

The following procedure can be used to decide if risk reducing measures are necessary for the park (a similar overview can also be found in (IEA Wind, 2018, s. 14):

1. Is the LIRA-value at exposed places in the park (roads, buildings, ski tracks etc.) above the threshold values in Table B-3?
   - If no: No further measures are an official demand, but some measures, such as ice measurements, signs and good information, are both useful and wise
   - If yes: Continue to part 2

2. What is the exposure in the park?

- Some examples of questions to get this information:
    - Is there a public road nearby? How much traffic is there on this road?
    - Are there hiking trails nearby? How often are these used? How often are they used in the winter? How many people use the trails?
    - How often are the wind farm employees in the park during the winter?

3. Assumed exposure is used to calculate the IRPA- and PLL-values. Are these below the thresholds in Table B-3?
    - If no: No further measures are an official demand, but some measures, such as ice measurements, signs and good information, are both useful and wise
    - If yes: Continue to part 4

4. Now we know that measures in the wind farm are essential. each position where the threshold is crossed, an individual assessment of needed measures is necessary.

Appendiks C Risk mitigation strategies

The Swedish Wind Energy Association presented the following list of measures on Winterwind (2016).

C.1 List of risk mitigation strategies related to ice-throw and ice fall

The following lists of possible risk mitigating strategies originates from Statkraft and the Swedish Wind Energy Association. The presented guidelines for cold climate work include risk mitigating strategies on internal & external communication, turbine specific ice-mapping, turbine technical measures, and operational strategies:

Communication:

- ***Ice Statement:*** *Safety is one of our core values and in our H&S policy we state our commitment to prevent all incidents and control safety risk arising from our activities; Under certain cold climate weather conditions, ice can form on wind turbine structures and rotor blades in a variety of ways. This ice can affect production and also be a safety hazard; The purpose of this statement is to state the management's commitment to ensure safe and sound cold climate operations on our plants.*

- ***Belief:*** *Ice build-up on turbines is inevitable during cold climate conditions; Any unsafe condition due to ice formation on turbines must be controlled. Concessions to this will not be made in favour of business result; At the design stage of developments projects in cold climate areas, risk from falling ice must be assessed and mitigated. This might be means of, but not necessarily limited to, state of the art ice prevention or de-icing technology; For all operational sites, residual risk must be identified, assessed and controlled by site-specific procedures supported by local management approval. Rules stipulated by legislation or enforcement bodies must always be followed.*

Turbine specific ice-mapping: *Mapping of the likelihood of ice or snow build up for the area; Mapping of ice-trajectory; Critical mass based on an impact energy > 40J; Move away from risk area based on (H+D)x1.5; New risk area based on the prevailing wind direction during ice build-up and melting; Risk analysis and acceptance criteria.*

Turbine technical measures: *Ice detection instruments; Vibration detection; Power curve deviation; De-icing systems; Anti-icing systems; Barriers at entrance; Ice camera.*

Operational strategy: *Warning signs; Warning lights & horn; Road gates & barriers; Meteorological forecasts; Understanding the location-specific weather phenomena; Register ice-throws; Demand of weather-specific routines; Visual observation of ice on blades; Procedures for manual or remote stop of turbines; Safe start-up after ice events; visual check that the blades are free of ice; Minimize staff exposure inside and during transport through the risk area; Safe transport vehicles; Yaw turbine to minimize risk for ice throw/ falling ice hitting sensitive areas; Larger risk acceptance for employees than third parties where knowledge and routines are in place to manage the risk; Ad-hoc information to local stakeholders such as reindeer herders, local tourist associations, snowmobile organizations, snow clearance companies, skiers, hunters, etc.; Stop turbines before ice-event which is expected to be followed by a longer period of high air pressure and low temperatures; De-icing with helicopter or MEWP; Technical upgrading: De-icing, Deflect heat to the blades, Hydrophobic coating, Protective sleeve during periods of active icing*