# RISK ANALYSIS OF ICE THROW FROM WIND TURBINES

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## 1. Introduction

Wind turbines are normally erected far away from houses, industry, etc., as the wind conditions are not favourable in the vicinity of large obstacles. Furthermore, with regard to acoustic noise emission and shadow flicker certain distances are required by national regulations, when wind farms are planned in the neighbourhood of residential areas. Thus, wind turbines should not cause risks as far as ice throw is concerned. However, the turbines are erected close to roads or agricultural infrastructure in order to avoid long and expensive access roads for erection and maintenance. This induces a risk for persons passing by the wind turbines, cars passing the streets if ice fragments fall down from a turbine.

Especially in the mountainous sites or in the northern areas icing may occur frequently and any exposed structure - also wind turbines - will be covered by ice under special meteorological conditions. This is also true if today's Multi Megawatt turbines with heights from ground to the top rotor blade tip of more than 150 m can easily reach lower clouds with supercooled rain in the cold season, causing icing if it hits the leading edge.

Figure 1 Nice view, but the rime ice accretion on the grass and the fence signalises danger of ice throw in the neighbourhood of the wind turbines.

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If a wind turbine operates in icing conditions which are described in [1], two types of risks may occur if the rotor blades collect ice. The fragments from the rotor are thrown off from the operating turbine due to aerodynamic and centrifugal forces or they fall down from the turbine when it is shut down or idling without power production. It depends upon the weather and especially the wind conditions, on the instrumentation of the wind turbine's control system, and on the strategy of the control system itself.

In the IEC Standard [2] icing is defined as an extreme external condition. Following the philosophy of this Standard a design load case, combining external and operation conditions, never combines extreme external conditions with faults. Regarding icing as an extreme external condition, only situations at normal operation are to be considered. This is important for the assumption how the control system is reacting under icing conditions.

## 2. Icing during operation

When the turbine is operating it is assumed that the leading edge of the rotor blade collects ice and drops it off regularly, due to aerodynamic and centrifugal forces [3]. Depending on the rotor azimuth, the rotor speed, the local radius, and the wind speed, the throwing distance of the ice fragments varies. Also, the geometry of the ice fragments and its mass will affect the flight trajectory. Typical ice fragments have been investigated in a wind tunnel in order to assess the aerodynamic properties of such a body [4]. Taking into account the experience gained from the research project WECO, Wind Energy production in COld climate [1] and the wind tunnel tests [4] typical ice accretion at the rotor blade's leading edge can be estimated and its flight trajectory calculated. The results of the calculations have been validated against the results of an inquiry among operators of wind turbines where the masses and throwing distances of ice fragments in wind farms have been investigated. The comparison proved the calculation to be conservative.

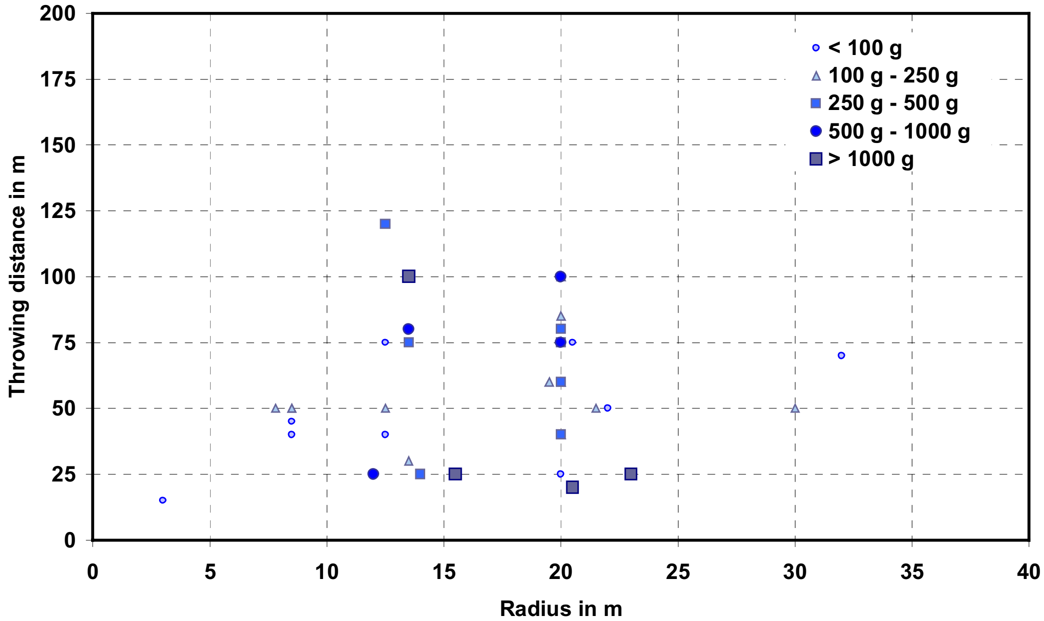


Figure 2 Observed ice fragments from the WECO data base [1] and own additional data.

The calculation needs the following inputs, which are partly known exactly, but some of them still have to be estimated on the knowledge available at present. Input parameters from the wind turbine are the rotor diameter, the hub height and the blade shape - most important the chord length at the tip of the blade - and the rotor speed range.

The size of the ice fragments is estimated according to the recommendations given in [1,4]. Observations show that the ice fragments don't hit the ground as long slender parts but break off immediately after detaching from the blade into small fragments. For the worst case scenario several assumptions can be made in order to reduce the extent of calculations. Smaller ice fragments or the smaller area produce less aerodynamic drag and thus increase the throwing distance. Large or long ice fragments experience more aerodynamic drag and will hit the ground in a closer radius around the turbine. The wind tunnel test showed a typical drag coefficient of $c_d = 1.2$. In the throw calculations $c_d = 1.0$ has been chosen for conservative assumptions. Possible lift of the fragments has been neglected. For the calculation of the ice fragment's mass the ice density given in [5] with 700 kg/m³ has been used. The steps of rotor azimuth were chosen to two degrees. The air density is automatically corrected according to the ICAO atmosphere to the altitude of the site plus hub height at an ambient air temperature of 0°C. Higher temperatures will increase the throwing width, but no icing will occur at temperatures with more than a few degrees above the freezing point. Wind gradients have been neglected.

The result of such a typical ice throw calculation for an operating turbine is a table of numbers and for better understanding a graphic has been plotted directly on the topographical map of the site concerned. Ellipsoidal curves representing the possible hits on the ground in steps of wind speed demonstrate the risk area on the map.

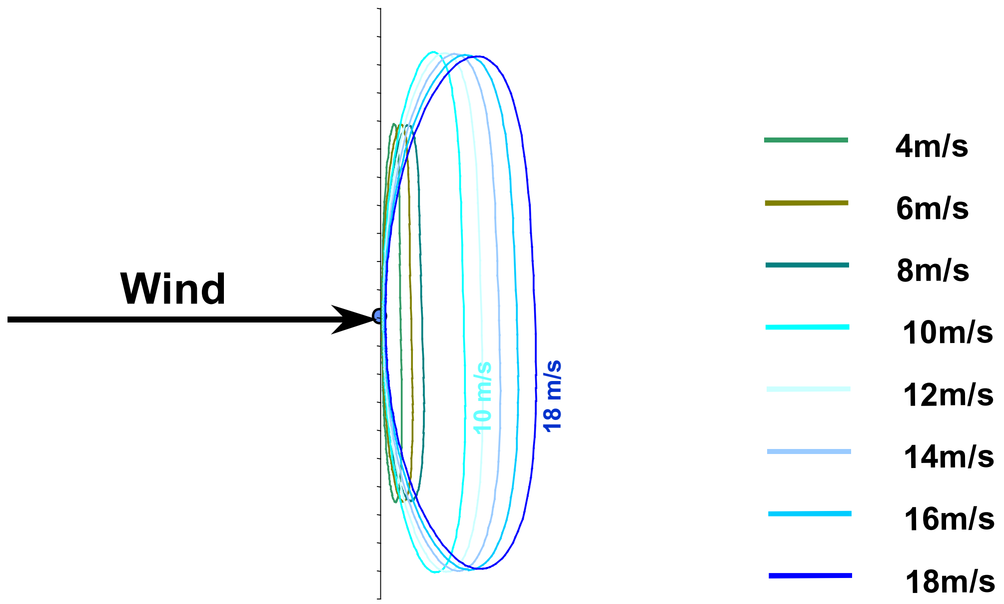


Figure 3 Result of the ice throw calculation. The curves represent the worst case width per wind speed.

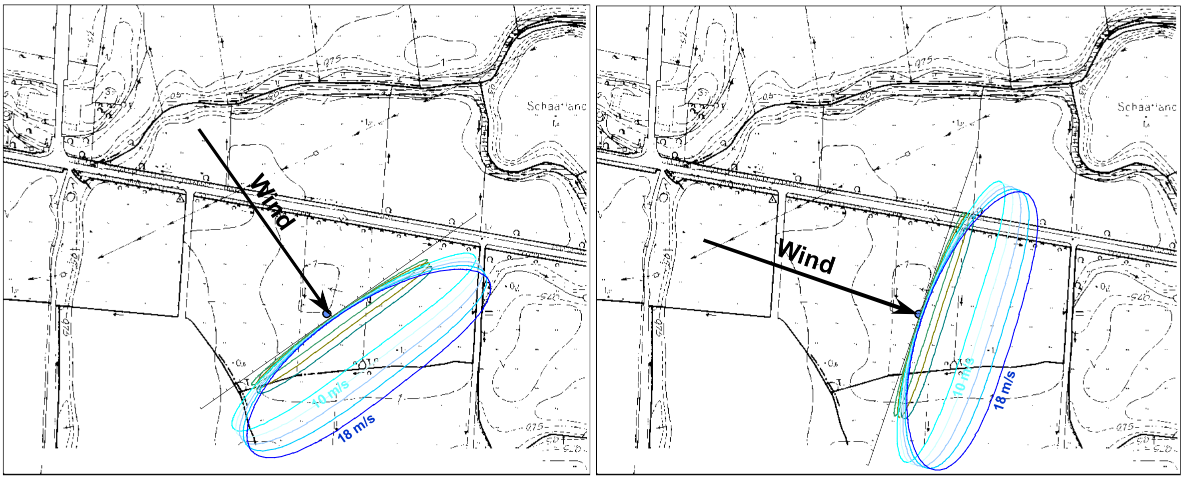


Figure 4 Combination of the ice throw calculation and the topographical map. In the right side the wind direction causes risky operation during icing conditions for the road, whereas the situation in the left side is not critical.

What can be done with the result of such a calculation? If the wind speed and direction is known at the specific site as shown for example in Figure 4 the control system of the turbine can decide whether the turbine has to be shut down or keep in operation. The control system should base its decision upon the icing conditions, the wind speed and direction and the rotor speed. An unnecessary risk can be avoided in that way. Alternatively, a big circle around the turbine representing the overall risk area can be drawn. However, this will need much more space within the wind farms.

A simplified empirical equation has been introduced in [1] representing such a "risk circle" without detailed calculations.

$$d = (D + H) \cdot 1.5$$

*d* = maximum throwing distance in m

*D* = rotor diameter in m

*H* = hub height in m

This empirical and simplified equation can only be a "rough guess" and a help for a first shot in planning the position of a wind turbine close to streets or other objects, involving a certain risk. A more detailed calculation is recommended.

### 3. Ice fall from a wind turbine at standstill

Only the icing of the rotor blade is discussed here. During winter time it may occur that - depending on the shape of the nacelle housing - snow and ice adds up on the top. Due to the heating of generator and gearbox, the ice on the surface melts and results in a water film enabling the amount of ice or snow to slip down. As the rotor blade always represents the higher position, for the worst case scenario, ice from tower or nacelle can be neglected. However, close to the turbine the high masses of possibly falling large and heavy ice fragments may be extremely dangerous for maintenance staff. Precaution is necessary to avoid accidents resulting from that.

In principle, a shut down wind turbine does not differ from other structures like towers, antenna masts, masts of power lines, etc. concerning ice accretion. Depending on the rotor position of the braked or idling rotor different fall widths along the prevailing wind will result at the end of the icing event and increasing temperatures. The size, the mass and the aerodynamic properties are estimated in the same way as for operating turbines. It is recommended that - if operation during icing conditions is excluded - that the turbines shuts down if only a slight ice accretion builds up at the rotor's leading edge. Once the turbine is stopped, it may not restart automatically if it is not guaranteed that all ice is melted or removed from the surface. This is not necessary if the turbine can be started manually and it is sure that any risk for persons or objects in the vicinity of the turbine can be excluded.

For automatically detecting ice on the rotor blades, several methods can be recommended. However, at present all these methods or instruments have to be improved and further validated. At first, the power curve and the ambient air temperature should be checked continuously. If a defined deviation is detected which can be related to a beginning rotor blade icing, the turbine should be shut down. The rotor blades use highly sophisticated aerodynamics and thus will react rather sensitively to small roughnesses at the leading edge like ice. If the temperature is low as well, a drop in the power signal at a certain wind speed - even if related to the affected hub anemometer - can be an indicator for icing. An ice free anemometer is required as well as a heated wind vane in order to avoid an oblique inflow, which would increase the fatigue loads and decrease the power. A heated shaft of the anemometer alone cannot be recommended.

Observations reported in [1] show that an amount of ice accretion in the order of up to 40 per cent of the chord length leads to a throw-off situation during operation. However, the power loss caused by a much smaller amount of ice will indicate icing much earlier. If the turbine is shut down, the ice built up during idling or standstill as described in [3] has to be considered.

The fragments falling down - released during the dewing period - will only be accelerated by the wind speed. The rotor is assumed to be positioned in the typical stand still or parked situation. The maximum wind speed has to be predicted according to the site specific report, connected additionally to the temperature.

For the calculations the following data are required: The altitude of the site, the hub height and the rotor blade radius of the turbine and the rotor blade geometry. The last one is needed for the estimation of the ice fragment's size.

Observation showed that ice fragments which fall from a stopped rotor break into smaller parts on the way down to the ground. In the worst case - large ice fragments reach longer distances from the still standing rotor - two meter long fragments have been investigated. The other dimensions of the ice fragments depend on the geometry of rotor blade. For the calculations it is assumed that the fragments start at the blade tip. The volume of the ice piece multiplied with the ice density from [5] results in the fragment's mass. Contrary to the rotating rotor the drag coefficient of the ice fragment from the stopped rotor is assumed to be 1.2, as this produces greater falling distances and is thus a conservative assumption. The air density is gained from the site altitude plus hub height at an air temperature of 0° C which also leads to conservative results.

The overall falling trajectories for different ice fragment's masses, wind speeds and rotor positions is demonstrated in Figure 5.

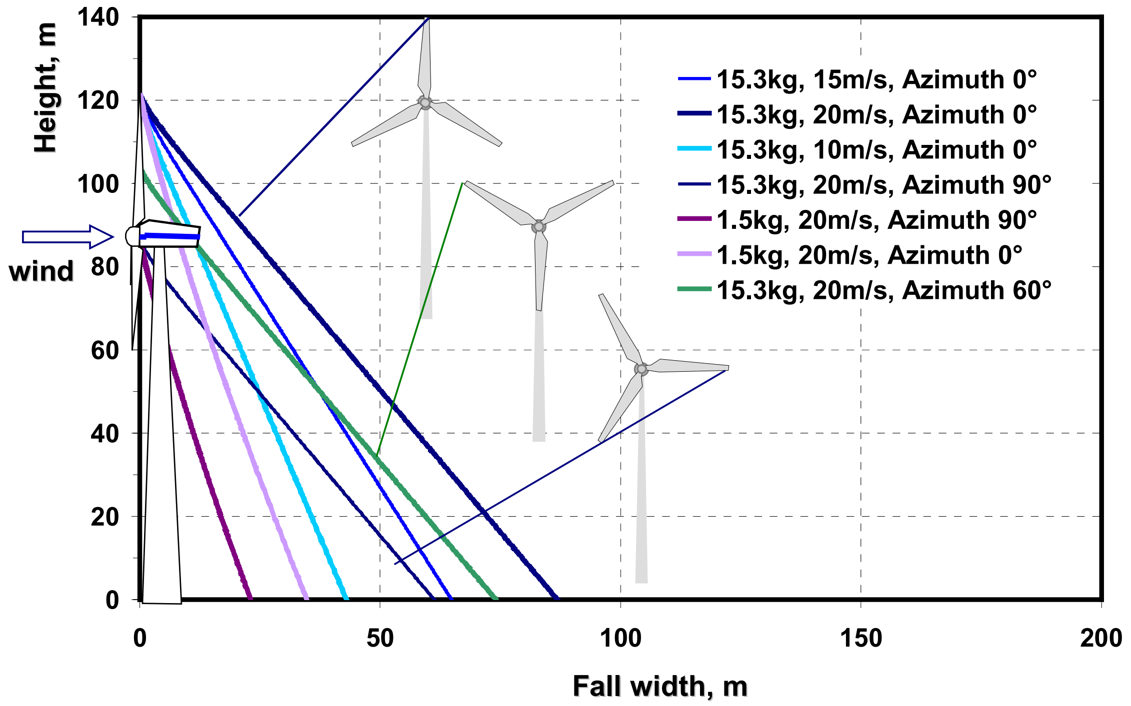


Figure 5 Typical result of an ice fall width calculation for a turbine at standstill. Parameters: Wind speed, rotor position and size of ice fragments.

As mentioned before, icing is defined as an extreme external condition and - according to the design standard's philosophy - must not be combined with a faulty control system. In the example shown in Figure 5 the turbine always heads towards the wind without yaw error.

A parameter calculation has been performed and as a result a simplified empirical equation developed for a stillstanding turbine:

$$d = v\frac{D/2 + H}{15}$$ with

$v$ = wind speed at hub height in m/s

$d$ = maximum falling distance in m

$D$ = rotor diameter in m

$H$ = hub height in m.

However, it is recommended to calculate more in detail. For a quick shot and rough estimation it may be sufficient to use the simple equation for a turbine iced at standstill.

## 4. Risk analysis

The two situations described above show the worst case scenario during icing conditions for an operating and an idling turbine, respectively. In fact, reality shows a few days of icing per year only. During these icing days only situations with a proper wind speed and wind direction in combination with detachment of ice fragments at the right time and right location will cause a hit at a certain spot at the ground. Provided that a person stays exactly at that time on that location an incident or accident occurs. The risk analysis aims at this probability and figures the quantity.

The following input data are needed in order to assess the risk for a person or an object in the neighbourhood of a wind turbine under icing conditions:

§ The number of icing events per year. This information cannot be found in the standard meteorological weather reports or the sit evaluation reports. If wind measurements are available and the anemometers are not cup and shaft heated, the number of occurrences in the bin around 0 m/s in the wind speed frequency distribution is unexpectedly high in winter time and shows a normal "Weibull-like" shape in summer time, this is an indication for icing. If two anemometers, one heated and one non-heated are used, the number of icing days can roughly be estimated as shown in Figure 6. The effect of snow and low temperatures on the anemometers as shown in the Figure is discussed in [3].

§ The wind direction and wind speed frequency distribution in combination with either information of icing events (see above) or in combination with the air temperature. This can also be an icing excluding parameter.

§ The location, number and mass of the individual ice fragments thrown off or falling from the wind turbine.

§ The number of persons passing the risk area per year

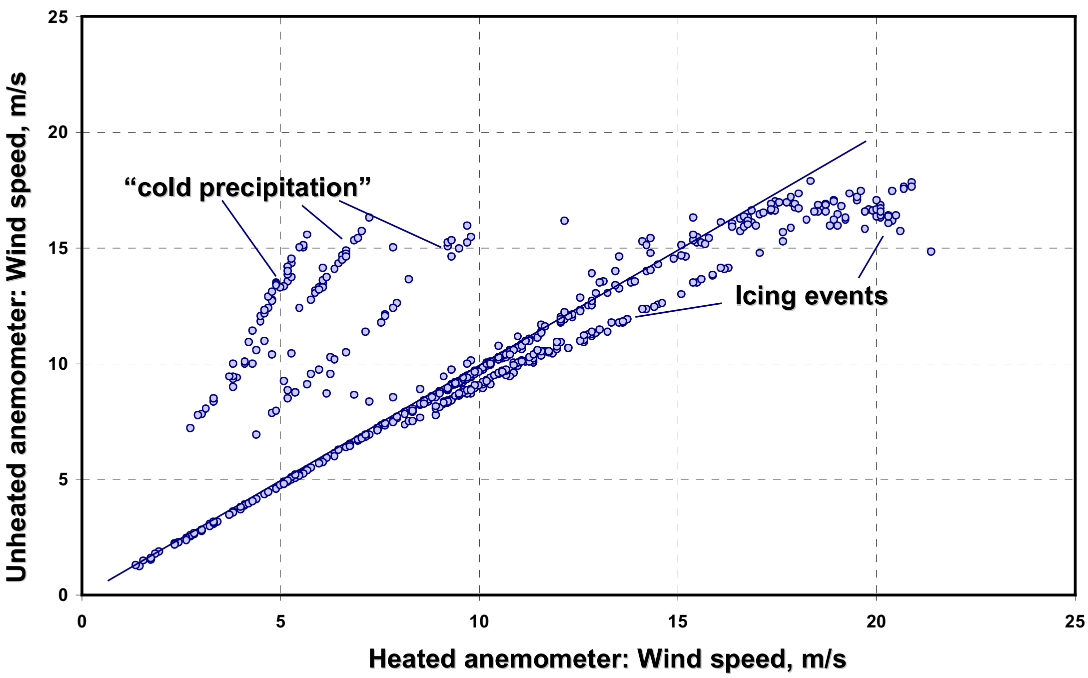


Figure 6 Measurement during icing conditions at a meteorological mast. Unheated versus heated anemometer.

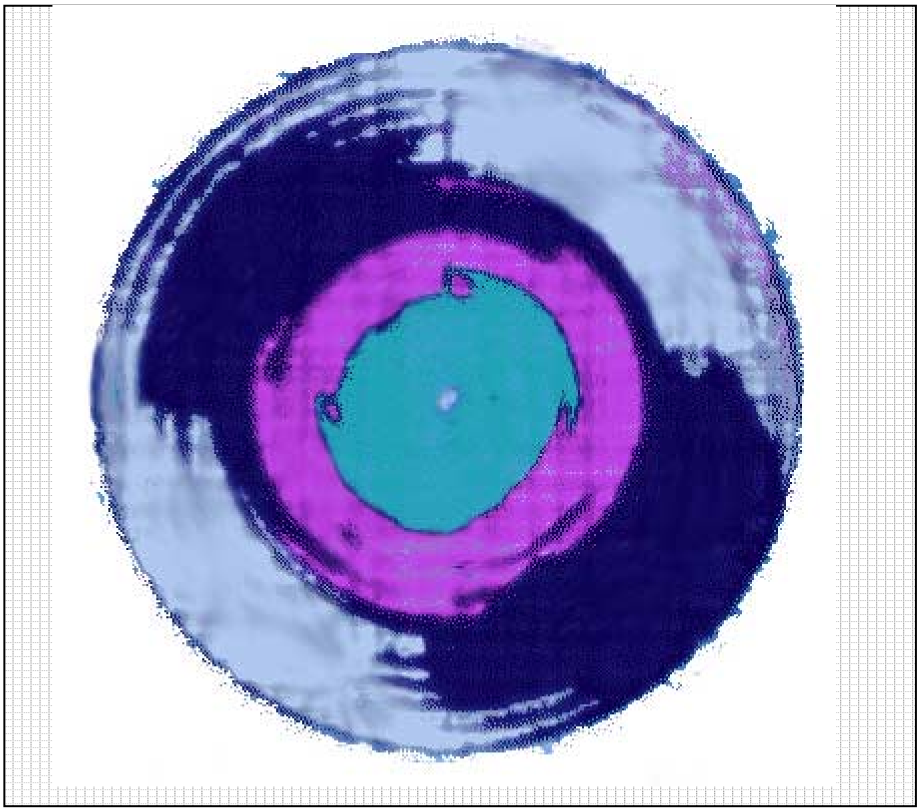

Figure 7 Principle sketch of the probability of hits per m² and year. The colours indicate the numbers of hits. The influence of the wind direction evident.

Additionally, some principal assumptions related to the site have to be taken into account before summarising the overall risk which is shown in Figure 7 which shows the principle sketch of the probability of hits per m² and year. The colours indicate the numbers of hits. The influence of the wind direction evident. This type of result can be interpreted for example for a road as follows: If 15,000 persons pass the road close to the wind turbine per year there might be one accident in 300 years. This result is normally compared against the general risk for life in a country. The requirement is that the introduction of a new technology such as a wind turbine at ice endangered sites must not increase this general risk in a given range.

## 5. Conclusion

The experience and the results of many calculations show that during operation small fragments are hitting the ground in a larger distance than those with a big area whereas from stopped turbines the larger pieces can be transported wider than small ones. However, provided that the turbine is operating the area of risk is larger than at standstill. In both cases the wind direction is an important parameter for the assessment of possible risk and an important parameter for the control systems concerning its behaviour during icing events. Ice sensors and also ice detection by using power curve plausibilisation or two anemometers - one heated, one unheated - is not reliable enough at the moment and needs to be improved.

There is still a lot of information required from operators after icing events in their wind farms. Observation of the turbines and especially the blades by web cameras proved to be a suited, but time consuming method in the Tauernwind project. The calculation methods as well as the assumptions made for the ice fragments have to be improved and validated against observation, if available. Bench mark tests or round robin actions, respectively, have to be carried out for various computer codes, calculating the ice throw trajectories. Furthermore, after the validation of the models, parameter studies have to be performed in order to improve simplified assumptions for international Standards and recommendations.

In Germany and Austria ice throw/fall prediction reports are required by the building authorities of some districts, especially in the inland and mountainous regions. Together with the increasing number of wind turbines at these sites the number of ice throw reports for building permission increases. It is to be expected that in connection with this, the number of experts and competing companies will increase as well and will improve the knowledge.

As a general recommendation it can be stated that wind farm developers should be very careful at ice endangered sites in the planning phase and take ice throw into account as a safety issue. Each incident or accident caused by ice throw is an unnecessary event and will decrease the public acceptance of wind energy.

## 6. References

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# ASSESSMENT OF SAFETY RISKS ARISING FROM WIND TURBINE ICING

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## ABSTRACT

Developers and owners of wind turbines have a duty to ensure the safety of the general public and their own staff. However, there are currently no guidelines for dealing with potential dangers arising from ice thrown off wind turbines. This puts developers, owners, planning authorities and insurers in a difficult position. To rectify this situation, the work presented here has commenced in order to produce an authoritative set of guidelines. Initial work has resulted in the development of a risk assessment methodology which has been used to demonstrate that the risk of being struck by ice thrown from a turbine is diminishingly small at distances greater than approximately 250 m from the turbine in a climate where moderate icing occurs.

## 1 INTRODUCTION

The work presented here is being undertaken as part of a project entitled "Wind Energy in Cold Climates (WECO)" part-funded under contract JOR3-CT95-0014 of the Non-Nuclear Energy Programme managed by the European Commission, DGXII, and by the UK Department of Trade and Industry. This project is being co-ordinated by the Finnish Meteorological Institute with DEWI (D), Garrad Hassan (UK), Risø (DK) and VTT (FI) as contractors. The project also involves associate contractors and subcontractors from many other European countries. The WECO project has three central objectives:

- To refine current assessments of the European wind energy resource through development of ice maps for the constituent countries.

- To identify methods for the improvement of the performance of wind turbines and anemometry technology in ice-prone climates and to quantify the cost implications of these methods.
- To produce safety guidelines for wind developments in ice-prone areas.

The work presented here addresses the last of these and has been motivated by an absence of authoritative reference material on the subject when it is raised as a concern by planning authorities and neighbours to proposed wind turbine developments. The findings of this research have been previously published [1,2] and this paper aims to summarise and update those previous publications. The lack of previous work by others on the subject may reflect the fact that there has been no reported injury from ice thrown from wind turbines, despite the installation of more than 6000 MW of wind energy world-wide. In addition, relatively few turbines have been installed in climates where icing is a serious problem. That situation is rapidly changing as extensive development of the wind resource in many Northern European countries has now commenced. Indeed, the potential risk has recently attracted significant publicity in Germany, where a number of significant incidents have been reported in the past year, indicating an urgent need for suitable safety guidelines.

## 2. THE PHENOMENON OF ROTOR BLADE ICING

Under icing conditions, all exposed parts of the wind turbine are liable to ice build-up. However, it has been observed that a moving turbine rotor is liable to accrete significantly heavier quantities of ice than stationary components for reasons which are explained below. Furthermore, the rotor blade ice has the potential to be cast some distance from the turbine if it breaks off a rotating blade. It is these aspects which set rotor blade icing apart from icing of stationary turbine components or indeed any stationary structure, and make it worthy of research.

There are several mechanisms of ice accretion on structures. The most important of these, for wind turbines, is rime icing which occurs when the structure is at a sub-zero temperature and is subject to incident flow with significant velocity and liquid water content. The precise deposition mechanism is the subject of ongoing experimental and theoretical research. However, the authors have a substantial body of field observations which has played an important role in the work reported here.

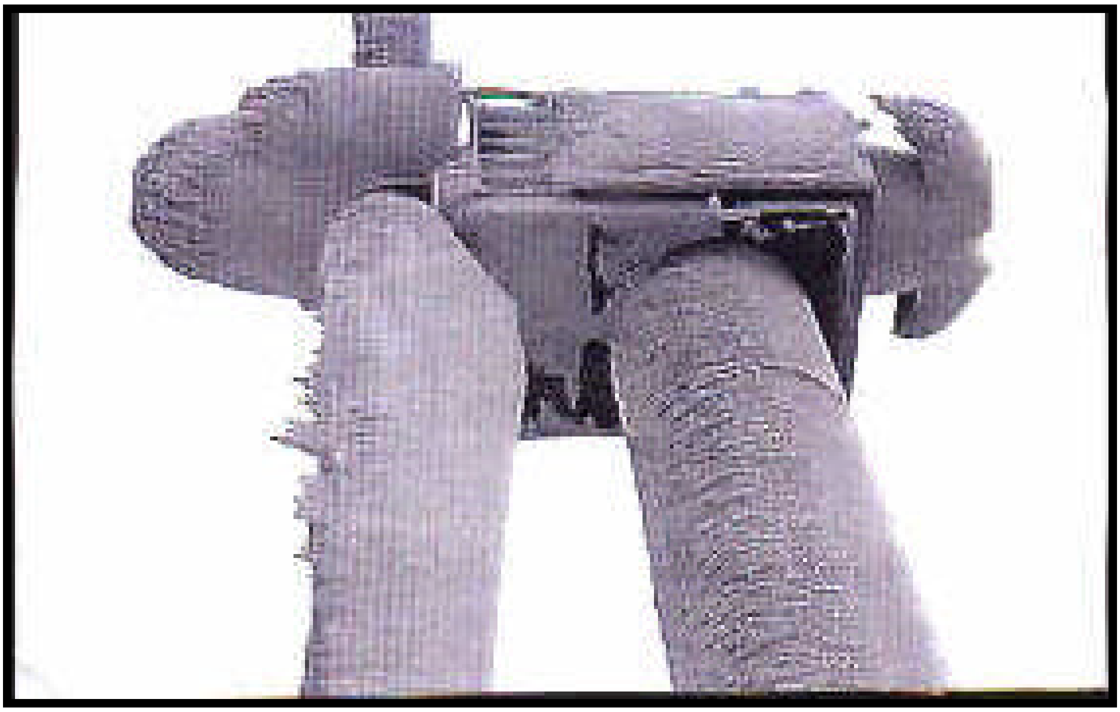

*Figure 1 Heavy ice accretion on a 300 kW wind turbine rotor*

A typical example of heavy rime icing on a wind turbine rotor is shown in Figure 1. It can clearly be seen that the heaviest ice build-up is at the tip of the blade but what is surprising is the amount of accretion with a chordwise thickness of up to about 0.5m. The build-up at the root of the blade is much less severe compared to nearby stationary structures.

The rime build-up is quite hard but it is also less brittle than might expected and remains attached to the rotor under significant flexure of the blades. Field observations indicate that most ice shedding occurs as temperatures rise and the ice thaws from the rotor. A typical scenario is that ice builds up on the rotor and on the wind speed and direction sensors which are mounted on the nacelle. Sensor malfunction causes automatic turbine shutdown. In this situation, most turbines will restart only when the ice has thawed and fallen from the stationary turbine which the operator then resets. However it is common practice for the operator to accelerate the process by thawing the sensors and restarting the turbine with ice still on the rotor. This circumstance has been observed to lead to heavy shedding of ice.

As regards the size of ice fragments shed from rotor blades, their mass and the distance which they are cast, there is very limited objective and subjective information. The only objective source of information is that collected in the recently completed EU Joule project "Icing of wind turbines", also funded by DGXII. As part of this work, carried out by DEWI and FMI, a questionnaire was circulated to a large number of turbine operators as described by Seifert [3]. The questionnaire asked for information on the occurrence of icing including mass and location of any observed ice debris flung off the rotor. The distribution of this questionnaire has continued as part of the WECO project.

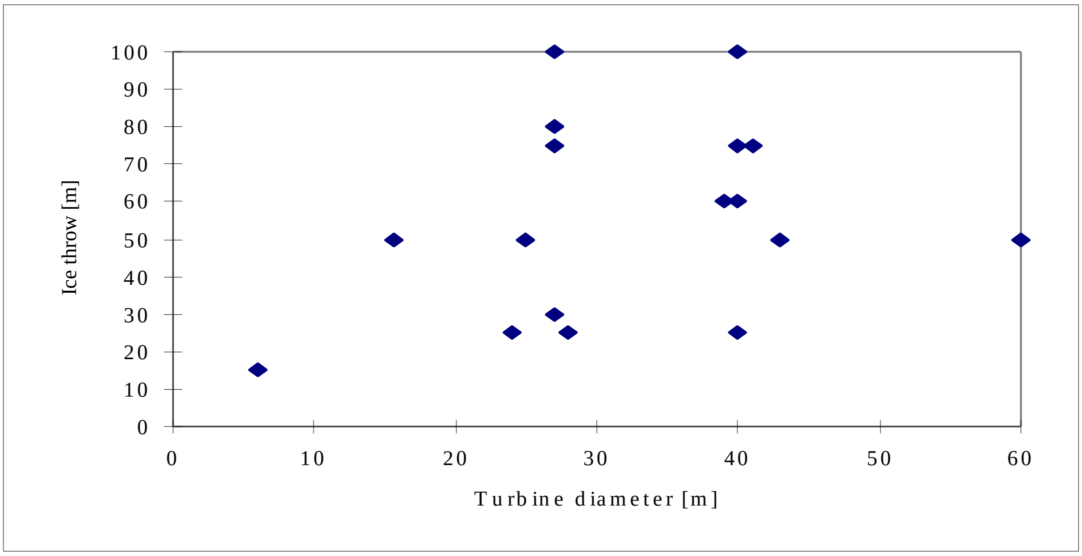


*Figure 2 Ice throw data collected by icing questionnaire*

Figure 2 summarises the data collected so far, as supplied by DEWI [4]. The data presented in Figure 2 show that most fragments which were found on the ground were estimated to be in the range 0.1 to 1 kg mass and were found 15 to 100 m from the turbines. Of course these figures must be taken as very approximate, and it is not possible to know how well the ground was searched especially at larger distances from the turbines.

In addition to this objective information, anecdotal evidence suggests that the tendency is for ice fragments to be dropped off, rather than thrown off, the rotor. Also, it tends to be shed off the tips in preference to other parts of the blade and large pieces of debris tend to fragment in flight. There is significant evidence that rime ice continues to form when the turbine is operating and is not shaken off by blade flexing, even though this may be the case for other types of ice formation. Also, rime ice formation appears to occur with remarkable symmetry on all turbine blades with the result that no imbalance occurs and the turbine continues to operate.

## 3. MODELLING OF ICE THROW

### *3.1 Aspects to be modelled*

The risk of a person being hit by a fragment of ice thrown from an operational wind turbine depends on the following factors:

- The probability of the turbine having ice build-up on the blades
- The likelihood of ice fragments becoming detached from the blade, which is undoubtedly a function of radial position on the blade and on blade azimuth. It may also depend on the speed of rotation of the blades, as well as on blade pitch, blade profile and flexibility.
- The point where the detached ice fragment lands, which also depends on the radial position and azimuth at the time of becoming detached, and on the rotor speed and wind speed. The speed of the fragment at the end of its trajectory is also of interest, and this depends on the same factors.
- The probability of the person being in an area of risk and any safety precautions taken.

### *3.2 Method for ice throw trajectory prediction*

While little is known about the probability of ice fragments becoming detached from various parts of the blade, it is relatively easy to calculate the distance travelled and the final velocity of the fragment once it has become detached, assuming that it does not break up in flight. A method for doing this has been developed as part of WECO and has been previously described by the authors [1,2]. This model has been further developed and now includes modelling of the effect on the trajectory, of:

- Blade azimuth at the instant when the fragment is released
- Radial location of the fragment on the blade at the instant of release
- Any radial sliding velocity developed by the fragment prior to release (the 'slingshot' effect)
- Turbine dimensions and rotor speed
- Gravity
- Fragment dimensions
- Aerodynamic drag
- Aerodynamic lift
- Mean downstream wind speed

### *3.3 Calculating the risk at a given distance*

In practice the ice fragments shed from a turbine will follow a whole range of trajectories depending of the mass and shape of each fragment, the wind speed and direction, the point on the rotor at which the ice is released, etc. As previously described [1,2], Monte-Carlo simulation is used to generate a large number of possible trajectories and the probability of each one, so as to arrive at an assessment of the risk of ice fragments landing in any particular square metre of ground area.

## 4. GUIDANCE IN RISK ASSESSMENT

It is possible that guidelines for use by developers and planning authorities should take the following format:

**A. Public safety and turbine icing - background information.**

i. Under certain meteorological conditions, it is possible for ice accretion to occur on wind turbine rotors. The accretion process is no different to that experienced by many exposed structures although heavier accretion has been observed on wind turbine rotors.

ii. Fragments of ice will drop or be cast from the rotor when this ice melts or is shaken off the rotor. In theory, these fragments may present a risk to the safety of the public or operational staff. This risk can be assessed and mitigated by steps given below.

iii. When more than a few metres from the turbine, the risk of ice landing at a specific location is found to reduce quite quickly with the distance of the location from the turbine. It is also found that ice falls predominantly downwind of the rotor plane.

iv. Fragments of ice have been observed to have masses in the range of less than 1 kg.

v. As operational staff work more regularly and in closer proximity to the turbines, they can be exposed to more risk than members of the public.

**B. Assessment of risk**

It is proposed that the risk assessment should be undertaken in three stages:

**i. Occurrence of icing conditions**

An estimate should be made of the time (number of days per year) during which icing conditions occur at the turbine site:

- **"**Heavy icing" - more than 5 days, less than 25 days icing per year.
- "Moderate icing" - more than 1 day, less than 5 days icing per year.
- "Light icing" - less than 1 day icing per year.
- "No icing" - no appropriate icing conditions occur.

The method for this estimation is the subject of another aspect of the WECO project [5]. To state the obvious, if the site falls within the "No icing" category, it can be assumed that no risk exists and no further assessment is required.

**ii. Allowable risk of ice impacts on ground**.

The level of risk which is acceptable should be determined. This is subject to case-specific factors such as ease of access, however a suitable level may be $10^{-6}$ strikes/m$^2$/year which is the typical probability of lightning strike in the UK [6].

**iii. Determine safety distance.**

Use data presented in Figure 3 to determine the safety distance for the chosen level of allowable risk. Clearly the smaller the level of risk which is to be tolerated, the greater the safety distance which must be allowed.

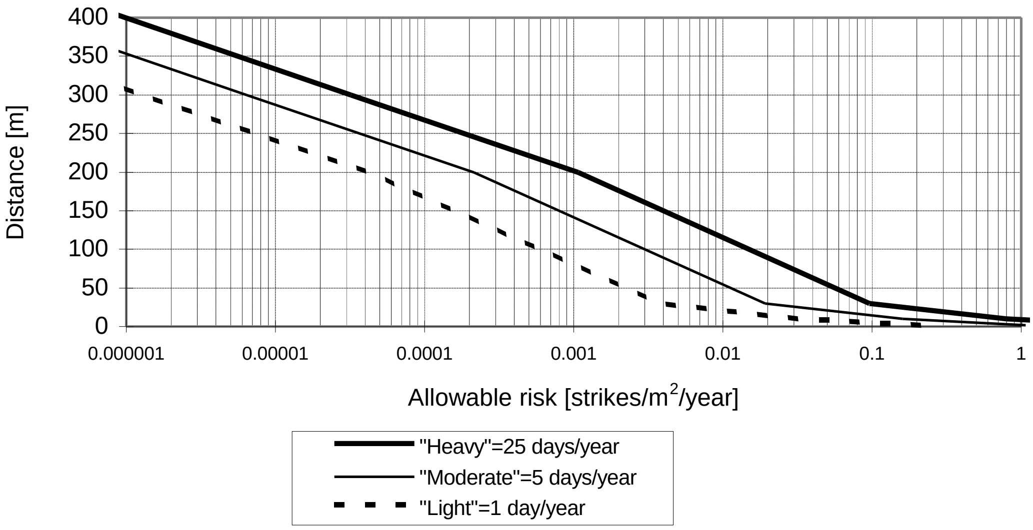


*Figure 3 Safety distance for different icing levels (50m rotor)*

Figure 3 is based on a rate of ice accretion averaging 75 kg/day during icing conditions, a figure which has been estimated for a 3-bladed turbine of 50m diameter. The allowable risk should be scaled *pro rata* under different assumptions.

## 5. MITIGATION OF RISK

In a situation where a significant risk to the public or operational staff is believed to exist, the following measures are suggested:

i. Curtailing operation of turbines during periods of ice accretion.

ii. Implementing special turbine features which prevent ice accretion or operation during periods of ice accretion.

iii. Re-siting of the turbines to remove them from areas of risk.

iv. The use of warning signs alerting anyone in the area of risk.

v. Operational staff should be aware of the conditions likely to lead to ice accretion on the turbine, of the risk of ice falling from the rotor and of the areas of risk.

## 6. ACKNOWLEDGEMENTS

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