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.

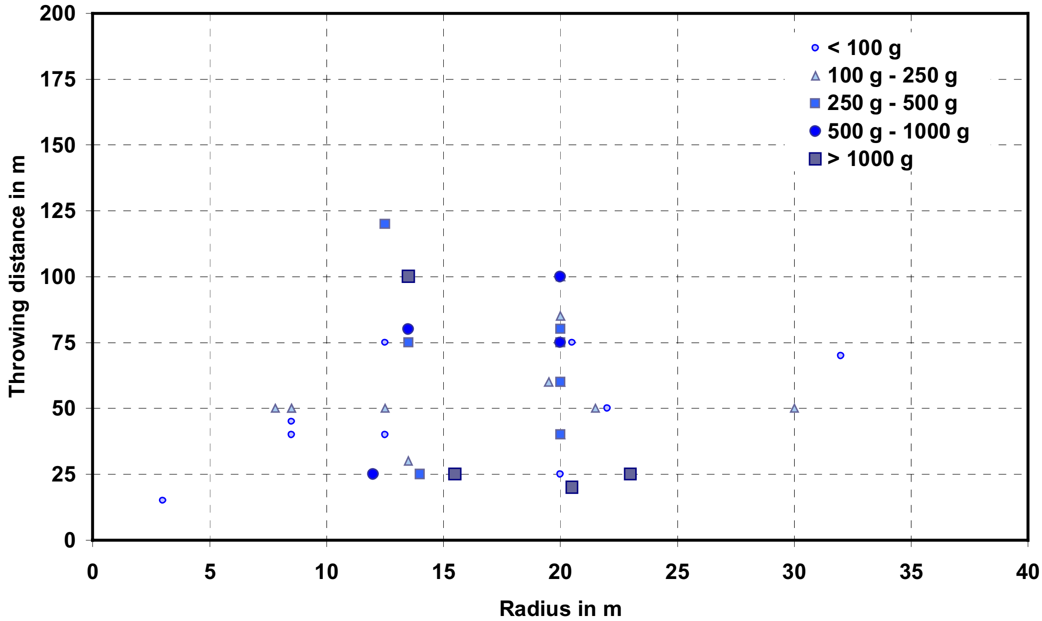

Figure 2 Observed ice fragments from the WECO data base [1] and own additional data.

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.

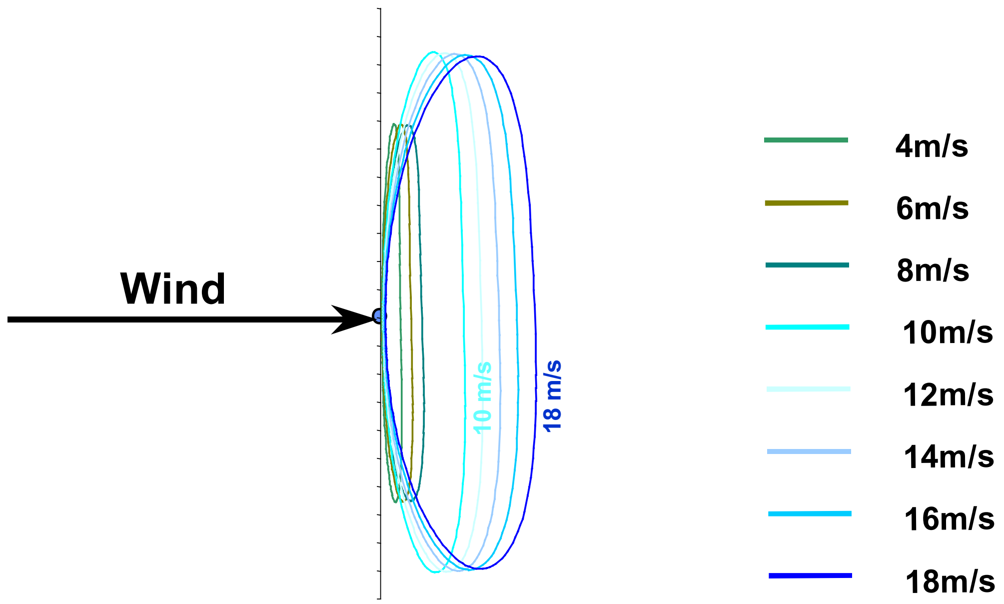

Figure 3 Result of the ice throw calculation. The curves represent the worst case width per wind speed.

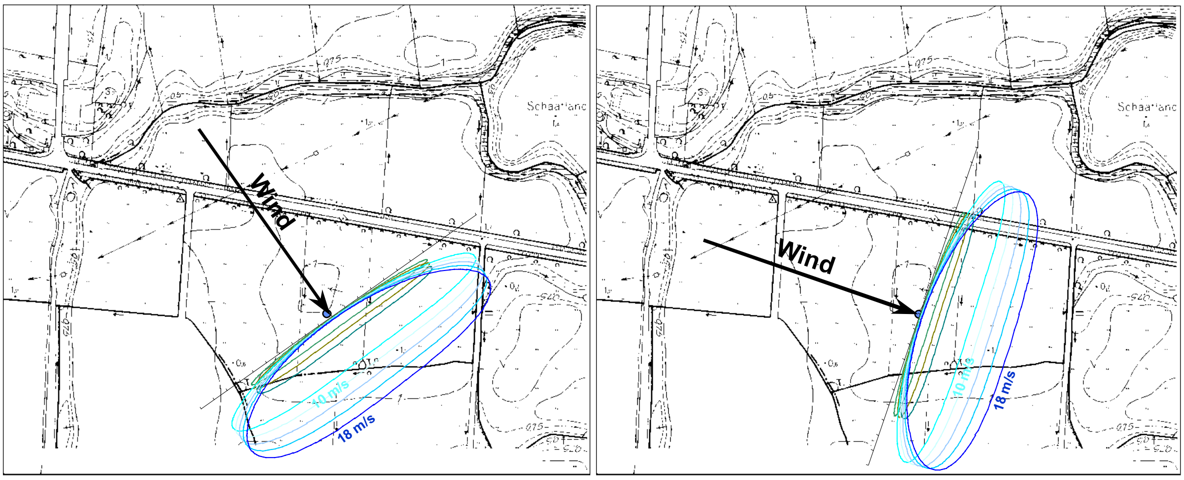

Figure 4 Combination of the ice throw calculation and the topographical map. In the right side the wind direction causes risky operation during icing conditions for the road, whereas the situation in the left side is not critical.

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.

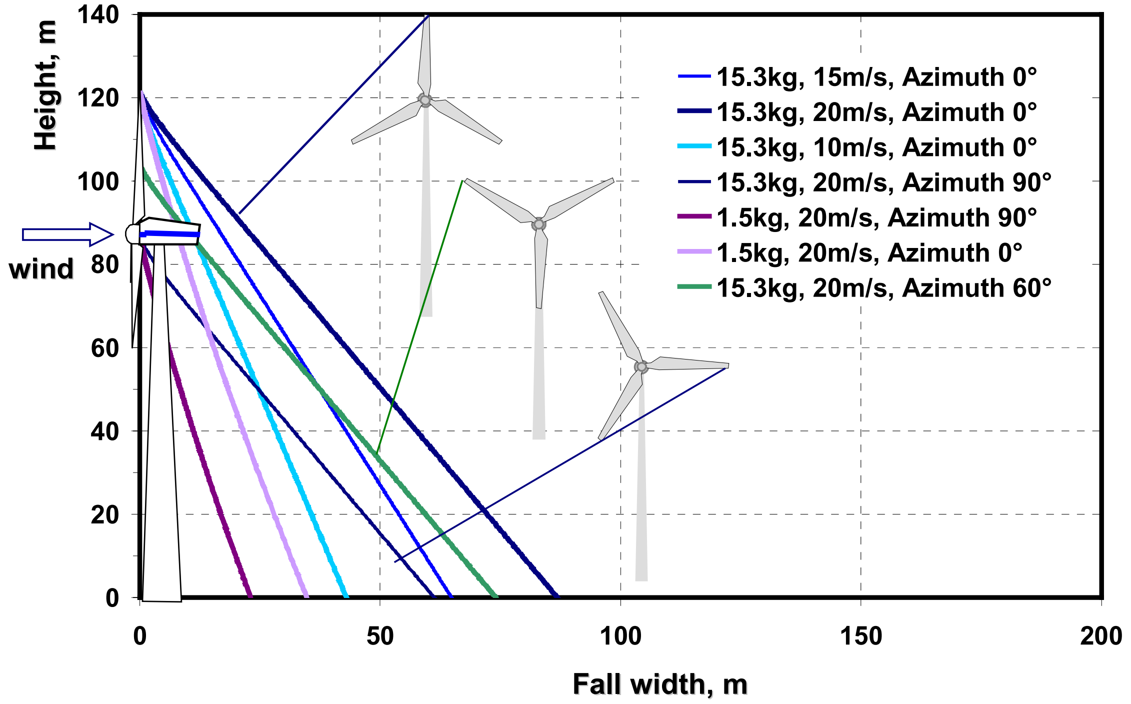

Figure 5 Typical result of an ice fall width calculation for a turbine at standstill. Parameters: Wind speed, rotor position and size of ice fragments.

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

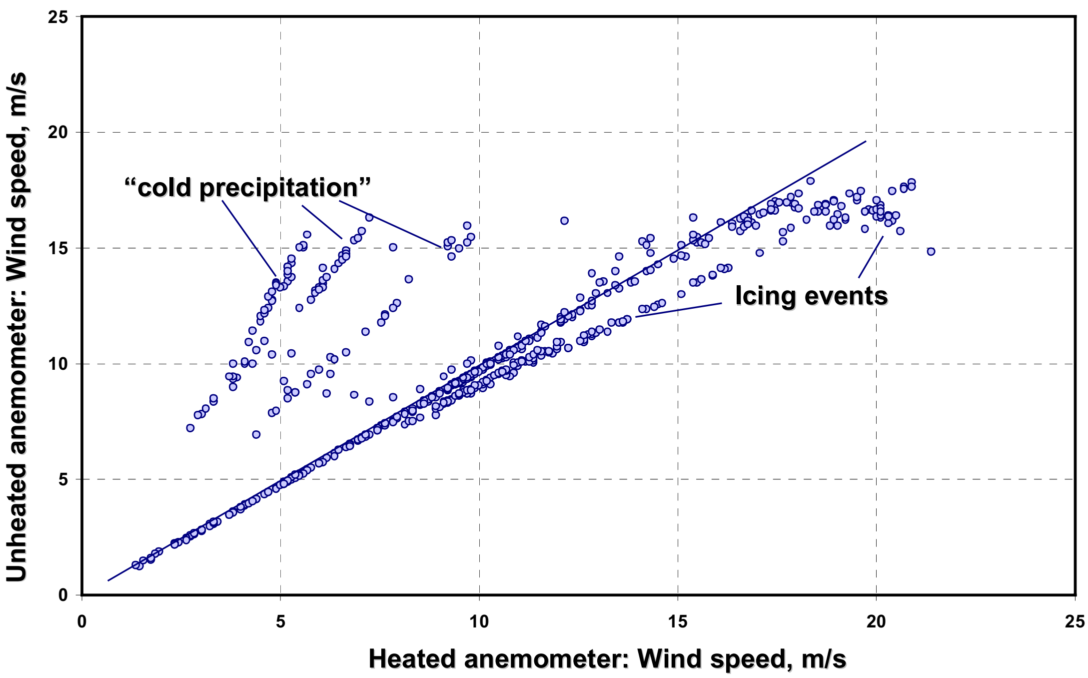

Figure 6 Measurement during icing conditions at a meteorological mast. Unheated versus heated anemometer.

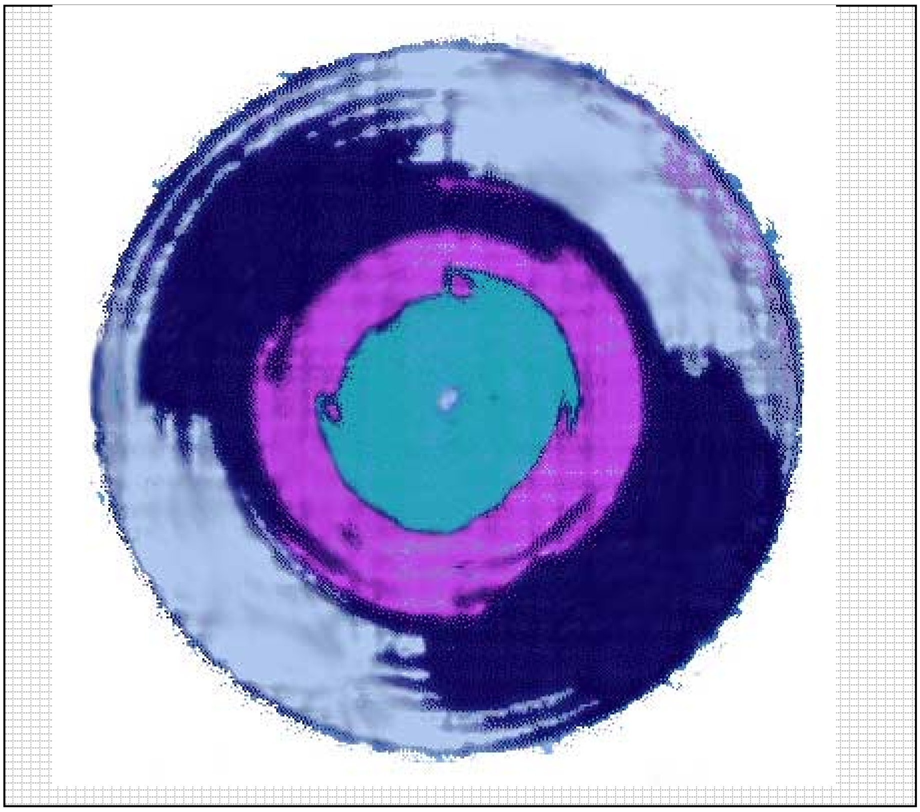

Figure 7 Principle sketch of the probability of hits per m² and year. The colours indicate the numbers of hits. The influence of the wind direction evident.

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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