Icing of Wind Turbines

Vindforsk projects, a survey of the development and research needs.

Elforsk report 12:13

René Cattin

January 2012

Vindforsk Energimyndigheten ELFORSK

Icing of Wind Turbines

Vindforsk projects, a survey of the development and research needs

Elforsk report 12:13

René Cattin

January 2012

Preface

Vindforsk III is Swedish research programme that is running in the period 2009-2012.

The programme is divided into five activity areas:

1. The wind resource and external conditions.
2. Cost-effective plants
3. Operation and maintenance
4. Wind power in the power system
5. Standardization

In the preparation of a synthesis report at the end of the program work with survey reports for different research areas is being carried out.

One such research area is “Icing of windturbines”

Work with a survey report for this area is carried out by René Cattin from Meteotest in the Switzerland.

As part of the work for this survey report and specially the discussion on research needs, a special workshop will be held at the 8 February the Winterwind conference in Skellefteå Sweden.

On this workshop the state of art and thought on future research needs based on this draft version of the report “Icing of Wind Turbines, Vindforsk projects, a survey of the development and research needs. Elforsk report 12:13” will be presented. A final version of the report will be ready during the spring 2012.

Vindforsk-III is funded by ABB, Arise windpower, AQ System, E.ON Elnät, E.ON Vind Sverige, EnergiNorge, Falkenberg Energi, Fortum, Fred. Olsen Renewables, Gothia Vind, Göteborg Energi, HS Kraft, Jämtkraft, Karlstads Energi, Luleå Energi, Mälarenergi, o2 Vindkompaniet, Rabbalshede Kraft, Skellefteå Kraft, Statkraft, Sena Renewable, Svenska kraftnät, Tekniska Verken i Linköping, Triventus, Wallenstam, Varberg Energi, Vattenfall Vindkraft, Vestas Northern Europe, Öresundskraft and the Swedish Energy Agency.

Stockholm january 2011

Anders Björck

Programme manager Vindforsk-III

Electricity and heat production, Elforsk AB

Summary

To be written

Innehåll

1 Projects within Vindforsk III 2
1.1 About the Vindforsk programme 2009-2012 2
1.2 Vindforsk projects within the research area of icing of wind turbines 2

2 Trends and developments 6
2.1 Introduction to icing on wind turbines 6
2.2 Icing simulation 10
2.2.1 Icing Climatologies 10
2.2.2 Icing Forecasts 14
2.2.3 Activities in the world 16
2.2.4 Activities in Sweden 17
2.3 Effects of icing on wind energy production 17
2.3.1 Activities in the world 18
2.3.2 Activities in Sweden 18
2.4 Icing measurements 19
2.4.1 Activities in the world 21
2.4.2 Activities in Sweden 21
2.5 De-Icing and Anti-Icing 22
2.6 Safety issues 24
2.6.1 Ice throw 24
2.6.2 Noise 26

3 Future research needs 28
3.1 General thoughts 28
3.2 Icing simulations 30
3.2.1 Icing climatologies 30
3.2.2 Icing Forecasts 31
3.3 Effects of icing on wind energy production 31
3.4 Icing measurements 31
3.5 De-icing and Anti-icing 32
3.6 Safety issues 32
3.6.1 Ice throw 32
3.6.2 Noise 32

1 Projects within Vindforsk III

1.1 About the Vindforsk programme 2009-2012

Vindforsk III is a co-financed research programme that provides funding for basic and applied wind energy research. The Swedish Energy Agency is financing 50 percent of the costs within the programme, and the other half is financed by energy companies and other companies with connection to wind power. The programme total budget is 80 million SEK over a four-year period.

The overall objective of Vindforsk is to strengthen the conditions for building and operating wind power by:

- producing generalizable results concerning wind energy characteristics and opportunities
- conducting research at the international forefront within a number of technology areas to preserve and strengthen the skills of existing research groups at universities and engineering consultants.
- strengthening the recruitment base for Swedish wind power industry
- making wind energy research visible and disseminate its results

The programme is divided into five activity areas:

6. The wind resource and external conditions.
7. Cost-effective plants
8. Operation and maintenance
9. Wind power in the power system
10. Standardization

1.2 Vindforsk projects within the research area of icing of wind turbines

Specific conditions in Sweden such that wind power will be built in forested areas and in areas with icing of turbines and equipment has motivated the activity area “The wind resource and external conditions”. The objective of the research is to develop tools and models to enable more reliable estimates of production and design loads.

One sub-research area within the activity area is wind power in cold climate. For this research area, the programme description states:

The overall goal is to increase the ability to estimate the electricity production from the turbines in areas at risk of icing of blades and anemometers and low temperatures. The goal is increase this ability both during the planning phase of projects as well as for production forecasts during operation.

The goal for the programme period 2009-2012 is to have sufficient knowledge to produce an icing mapping over Sweden with estimates of site-specific effects of icing and cold climate on the energy production.

From project applications to the programme, four projects with a total budget of around 13 Million SEK is has been given funding within the cold climate area.

Project number	Project title	Project leader	Financing
V-313	Wind Energy in Cold climate	Hans Bergström, Uppsala University	SEK 8 000 000 cash funding and SEK 3 000 000 in kind
V-338	IEA RD&D Wind, Task 19	Göran Ronsten, WindRen AB	SEK 450 000 cash funding and SEK 450 000 in kind
V-359	Prestudy, Verification data for project V-313	Peter Schelander, Swedpower Poyry	SEK 225 000 cash funding and SEK 84 000 in kind
V-363	Complementary ice measurements to V-313	Hans Bergström, Uppsala University	SEK 753 000 cash funding and SEK 220 000 in kind

Table 1 Vindforsk projects within the area icing of wind turbines.

Project number	Project title	Important international cooperation	Planned Concrete use of results of the project
V-313	Wind power in cold climate	Within the Top-level Research Initiative project ICEWIND where Weathertech Scandinavia takes part in cooperation with several partners from the Nordic countries.	Will make it possible to determine an icing climatology over Sweden on a 1x1 km^2 resolution, and using this to predict production loss due to icing.
V-338	IEA RD&D Wind, Task 19		
V-359	Prestudy, Verification data for project V-313		A measurement plan for verification of input/output data in the transitional step between two numerical models. The concrete use of this plan will facilitate the improvement of methods used in coupling a NWP-

			model with an ice accretion model, and potentially reduce the uncertainties involved in icing prediction.
V-363	Icing–complementary measurements to V-313		Increase the possibility to reach the goals in V-313 by new icing measurements.

Table 1 Expected results from the Vindforsk projects.

Short summaries of Vindforsk projects here

2 Trends and developments

Note from the author: This is a draft version of the report; the final report will be ready by mid-march. In that sense, the level of detail and language varies strongly through the document. Especially the section on the future research needs is still in a very raw state and will be completed also based on the feedback of the Winterwind workshop. As it is a draft version, references are not yet included and some important projects or findings might still be missing. The author apologies for that.

2.1 Introduction to icing on wind turbines

Cold Climate (CC) areas are regions where icing events or periods with temperatures below the operational limits of standard wind turbines occur, which may impact project implementation, economics and safety. Areas where periods with temperatures below the operational limits of standard wind turbines occur are defined as Low Temperature Climate (LTC) whereas areas with icing events are defined as Icing Climate (IC). Although theoretically possible, active icing rarely occurs at temperatures below minus 25°C. In some areas wind turbines (WT) are only exposed to either icing or low temperature events. In some regions both low temperatures and icing events may take place. Therefore, a site can be in a Low Temperature Climate or in an Icing Climate or both while they are still all denoted Cold Climate sites. These definitions are further illustrated in Figure 2-1.

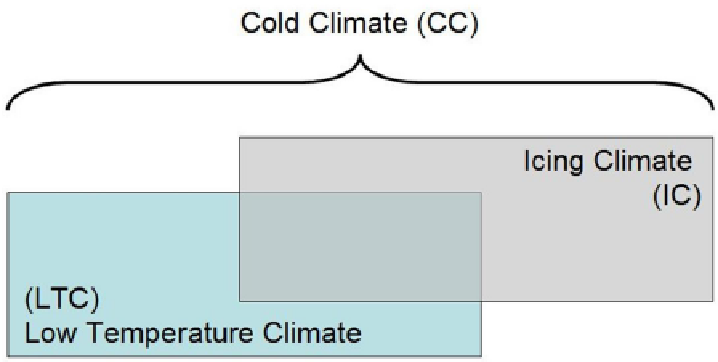


Figure XX Definition of Cold Climate, Low Temperature Climate and Icing Climate.

This report will deal only with wind energy in an Icing Climate (IC).

Atmospheric icing is defined as the accretion of ice or snow on structures which are exposed to the atmosphere. In general, two different types of atmospheric icing that impact wind turbine development can be distinguished: in-cloud icing (rime ice or glaze) and precipitation icing (freezing rain or drizzle, wet snow).

The different forms of atmospheric icing can be described as follows:

- **Rime Ice:** Super cooled liquid water droplets from clouds or fog are transported by the wind. When they hit a surface, they freeze immediately. If the droplets are rather small, soft rime is formed, if the droplets are bigger, hard rime is formed. Its formation is asymmetrical (often needles), usually on the windward side of a structure. Its crystalline structure is rather irregular, surface uneven, and its form resembles glazed frost. Rime ice typically forms at temperatures from 0°C down to -20°C. The most severe rime icing occurs at exposed ridges where moist air is lifted and wind speed is increased. Hard rime is opaque, usually white, ice formation which adheres firmly on surfaces making it very difficult to remove it. The density of hard rime ice ranges typically between 600 and 900 kg/m3 (ISO 12494). Soft rime is a fragile, snow-like formation consisting mainly of thin ice needles or flakes of ice. The growth of soft rime starts usually at a small point and grows triangularly into the windward direction. The density of soft rime is usually between 200 and 600 kg/m3 (ISO 12494), and it can be more easily removed.
- **Glaze**: Glaze is caused by freezing rain, freezing drizzle or wet in-cloud icing and forms a smooth, transparent and homogenous ice layer with a strong adhesion on the structure. It usually occurs at temperatures between 0 and -6°C. Glaze is the type of ice having the highest density of around 900 kg/m3. Freezing rain or freezing drizzle occurs when warm air aloft melts snow crystals and forms rain droplets, which afterwards fall through a freezing air layer near the ground. Such temperature inversions may occur in connection with warm fronts or in valleys, where cold air may be trapped below warmer air aloft. Wet in-cloud icing occurs when the surface temperature is near 0°C. The water droplets which hit the surface do not freeze completely. A layer of liquid water forms which, due to wind and gravity, may flow around the object and freeze also on the leeward side.
- **Wet snow:** Partly melted snow crystals with high liquid water content become sticky and are able to adhere on the surface of an object. Wet snow accretion therefore occurs when the air temperature is between 0 and +3°C. The typical density is 300 to 600 kg/m3. The wet snow will freeze when the wet snow accretion is followed by a temperature decrease. There exists another phenomenon called sublimation, which means direct phase transition from water vapor into ice, producing hoarfrost. Although it is known to cause transmission losses through corona effects, hoarfrost is of low density, adhesion and strength, and therefore does not cause significant loads on structures. Therefore it will not be considered in this report. It has to be noted that in many cases the frequency of icing and the ice loads increase with increasing height above ground. This is due to a higher probability of a structure being inside clouds (icing frequency) and surrounded by high water content (ice load).

An icing event can be described with the following expressions (Heimo;Cattin;& Calpini, 2009), applicable to all structures and instruments exposed to atmospheric icing:

- **Meteorological icing:** Period during which the meteorological conditions for ice accretion are favorable (active ice formation)

- **Instrumental icing:** Period during which the ice remains at a structure and/or an instrument or a wind turbine is disturbed by ice.
- **Incubation time:** Delay between the start of meteorological and the start of instrumental icing (dependent on the surface and the temperature of the structure)
- **Recovery time:** Delay between the end of meteorological and the end of instrumental icing (period during which the ice remains but is not actively formed)

Figure XX illustrates how a wind measurement is affected by icing according to the definitions described above. When meteorological conditions for ice accretion are given (start of the meteorological icing), there is a certain delay – the incubation time - until ice accretion at the anemometer begins. By using anti-icing measures (coatings, warm surfaces etc.), the incubation time can be extended, in an ideal case until the end of meteorological icing avoiding icing of the instrument. As soon as there is ice on the sensor (start of the instrumental icing), the measurement is disturbed. Ice is accreted continuously on the sensor until the meteorological conditions for icing are not present anymore (end of the meteorological icing). But the ice will remain at the instrument for a certain time – the recovery time - until it melts or falls off (end of the instrumental icing). This delay can be much longer than the period of meteorological icing. Although the meteorological conditions for ice accretion are not present anymore, the readings of the instrument have to be discarded until the instrumental icing has ended. By using de-icing measures (heating, manual interference etc.), the recovery time can be shortened.

In order to describe the icing characteristics of a site, the following simplifications apply:

- Incubation time = 0, i.e. meteorological and instrumental icing start at the same time
- The duration of meteorological and instrumental icing refers to an unheated structure, typically an fully unheated anemometer, an unheated wind turbine blade or a mounting boom

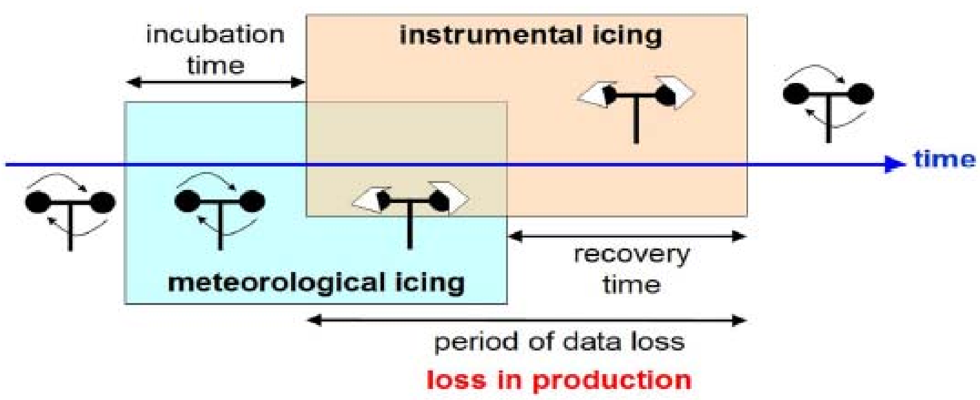


Figure XX: Definition of Meteorological Icing and Instrumental Icing.

Additional parameters to further describe the icing conditions at a site are:

- **Icing rate:** Ice accumulation per time [g/hour]
- **Maximum ice load:** Maximum ice mass accreted at a structure [kg/m]
- **Type of ice** [rime, glace, wet snow]

At sites where there is adequate solar radiation during the winter months, the ice can melt away within a rather short time after the end of the meteorological icing. At northern sites, the ice can remain on a structure for a very long time after the meteorological icing. Such site specific characteristics can be described with the **Performance Index.** It is defined as the ratio between instrumental icing and meteorological icing:

Performance Index = Instrumental Icing / Meteorological Icing

2.2 Icing simulation

2.2.1 Icing Climatologies

The ideal world

In an ideal world, there exist models which are able to deliver high resolution (25x25m), long term (> 10 years) icing climatologies for any planned wind park site. The models are able to deliver information on average icing frequency and its variability, average and maximum ice loads as well as information on the typical duration of meteorological and instrumental icing in order the derive the typical performance index at the site. Furthermore, the models should be able to deliver time series of ice loads for each wind turbine location of a planned wind park at least in hourly resolution. Finally, information on the uncertainty of the calculation should be available too for each time step. The effort to create this information should not be larger than it is nowadays to perform an energy yield analysis for a wind park site.

This information can then be used to determine the icing losses at the given site (see chapter 2.3, effects of icing), to exclude "suspicious" measurement data from the local measurements (chapter 2.4, icing measurements) and allow for an accurate cost/benefit analysis for different market available de-icing or anti-icing systems (chapter 2.5).

There exist long term icing maps for all countries which are affected by icing.

State of the art

The most common approach for icing simulations is to couple meteorological information with an ice accretion model. Today, there exist two different types of ice accretion models:

- Model for simulation of ice accretion on a vertical, freely rotating cylinder (Makkonen)
- Models for simulation of ice accretion to two-dimensional (Turbice, Lewice) and three-dimensional (fensap-ice) airfoils

There are two main sources for getting the meteorological information for an icing simulation:

- Numerical weather models
- Analysis of measurement data of weather stations

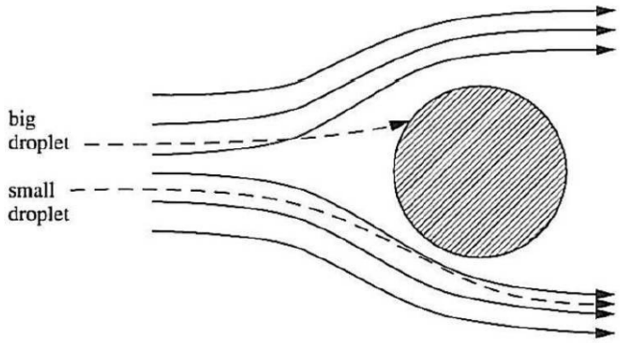
Ice accretion models

One commonly used approach today is to model the ice accretion with the ice accretion model as formulated by Makkonen. The formula has its origin in the research of icing on overhead power lines where the conductors behave like rotating cylinders collecting ice. It references to ISO 12494.

The accretion model developed by Makkonen (2000) describes describes the ice accretion of in-cloud icing on a vertical, freely rotating cylinder with an initial diameter of 3 cm. Beside cloud droplets also freezing drizzle is taken into consideration. Freezing drizzle is not very frequent, but if it occurs it gives a strong contribution to the ice load. The ice load accumulating on a cylindrical structure is simulated by using information about temperature, liquid water content (LWC) and wind speed, taken from the numerical weather model, as well as the volume number concentration of droplets. The latter is used to calculate the median volume droplet size (MVD). During ice accretion, the diameter of the cylinder is constantly increased.

The accretion model calculates the liquid water mass flux that hits the cylindrical structure and the part of liquid water that contributes to icing. The latter is described by several coefficients:

- Collision efficiency: ratio of droplets that actually hits the object, reduced because small particles are transported around the obstacle (Fig. 1).
- Sticking efficiency: ratio of droplets that hit the object that is collected, reduced because some particles bounce from the surface.
- Accretion efficiency: part of collected droplets that contributes to the rate of icing, reduced if the heat flux is too small to cause sufficient freezing.



One major shortcoming for wind energy applications is that fact that this model simulates icing for a vertical, freely rotating cylinder. This approach is dedicated to overhead power line icing and far from the characteristics of a moving wind turbine blade which has a different shape, different dimensions and is moving perpendicularly to the prevailing wind speed at different speeds between the tip to the root of the blade. Furthermore, a wind turbine blade crosses a vertical section of the atmosphere between 80 and 120 m length. There is currently no algorithm which is able to convert the ice load modeled on a cylinder into an ice load on a wind turbine blade.

There exist similar models for freezing rain and wet snow on overhead power lines but these have not been applied for wind energy purposes.

There exist dedicated numerical models for simulation of ice accretion to two-dimensional airfoils such as TURBICE and LEWICE. In these models, constant external conditions have to be set for simulating an icing event. Rotational speed of the blade is taken into account. There exists at least one model which allows simulating ice accretion on a three-dimensional airfoil (fensap-ice). Also in this model, constant external conditions have to be set for simulating an icing event. This model has been thoroughly validated for aircraft applications. It has only rarely been used in wind energy applications (Homola 2009).

To the knowledge of the author, none of these models has been coupled with the results of numerical weather models, i.e. with time series of meteorological data during an icing event. Furthermore, only ice accretion is simulated, melting and sublimation effects are not simulated so far.

Nowadays, there is no mechanical model which can parameterize the mechanical effects on ice accreted to a structure based on meteorological conditions such as wind speed or mechanical influences such as vibrations in general or bending effects on wind turbine blades. However, such a model is needed to be able to accurately simulate a whole icing event on a wind turbine blade. It is the reason that in general, only short periods of ice accretion are simulated with the 2D and 3D models. Longer model runs would lead to unrealistic results as these mechanical effects are not considered.

Numerical weather models

Numerical weather models are able to calculate the needed input parameters for the ice accretion models such as temperature, wind speed and LWC. An important aspect is which cloud microphysics is applied in the numerical weather model. Nowadays, several options exist which are capable of predicting the LWC such as the Thompson or the Morrison scheme. A good and accurate simulation of MVD by numerical weather models is not yet available to the public. This parameter has to be estimated using literature.

Another important parameter is the horizontal resolution of the numerical weather models. The icing rate is strongly dependent on small scale effects such as lifting of air or speed up effects. Therefore it is highly important to have a as good as possible representation of the terrain in order to achieve accurate icing forecasts. Today's computer resources allow running the numerical weather models at horizontal resolutions of typically 1-3 km, single test cases with even lower resolution have been run too. The horizontal resolution needed for the representation of complex terrain or for the micro siting of wind parks (< 100 m) could not be reached so far.

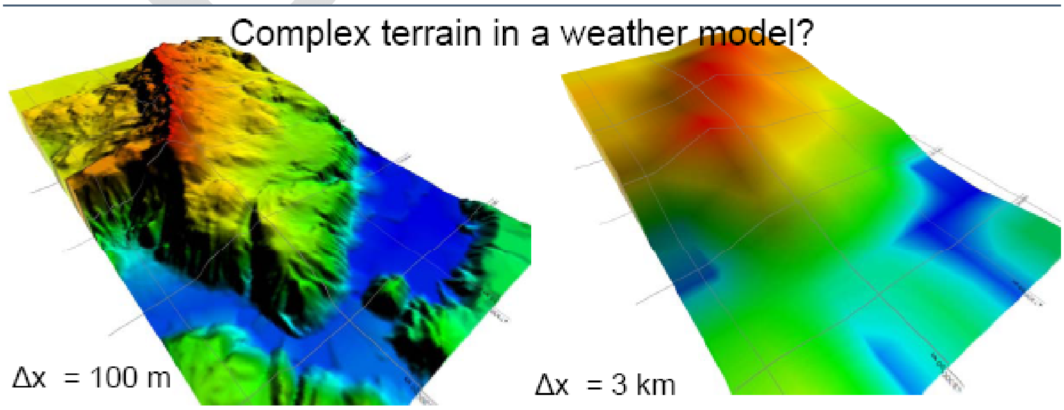


Figure XX: Effect of horizontal grid resolution on terrain representation.

Numerical weather models with high horizontal resolution and sophisticated cloud microphysics today still require extensive computer resources. This does not allow for calculation of long term (>10 years) model runs in an economic way. One widely used approach is to correlate a short term (1 year) high resolution model run (e.g. 1 km) with a long term (10 years) model run at a coarser resolution (e.g. 5 km). This allows for temporal extrapolation of the high resolution icing data. However, reliable measurement data for validation of this extrapolation is rare and therefore the accuracy of this approach unknown.

Climate change scenarios have not been used for producing icing climatologies so far.

Icing simulations usually focus on one specific point (instrument position or position of the hub of the wind turbine). When using numerical weather models as input, mostly the ice accretion on a cylinder is chose as an ice accretion model. Ice accretion models for wind turbines are usually not used. There is currently no algorithm which can translate icing on a cylinder into icing on a wind turbine blade.

There is only rare information of the vertical profile of the LWC, the icing rate or ice loads. This is mainly due to a lack of suitable verification data. However, the blades of a wind turbine will cover a vertical profile of up to 120 m vertical distance. Fig XX shows the dependence of the ice load on the height above ground. In relation to the levels, a wind turbine is indicated in the graph.

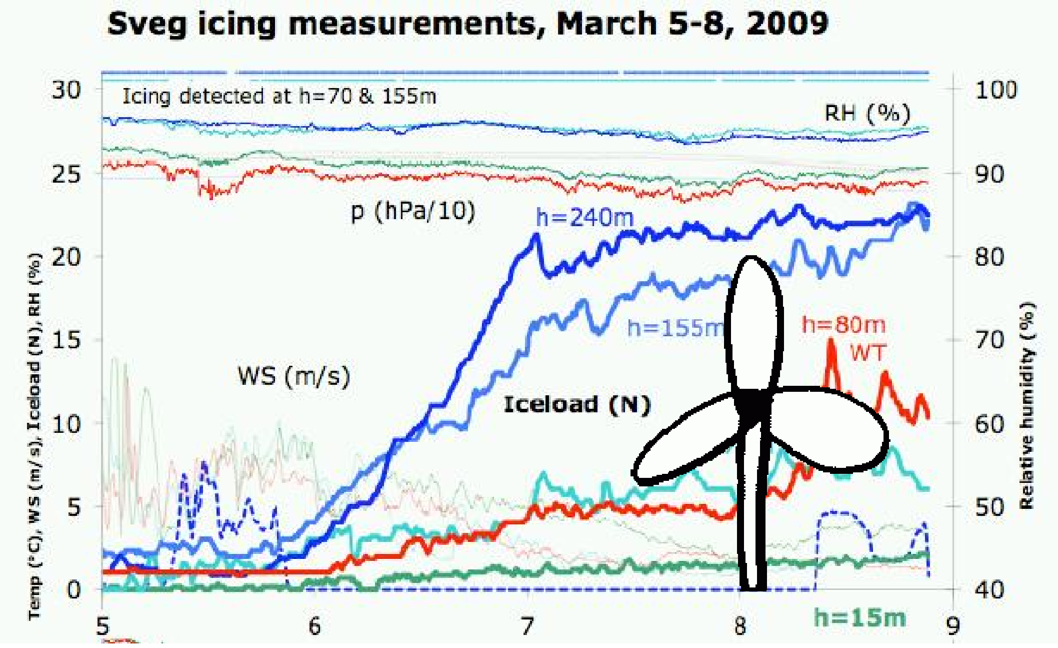


Fig XX: Different Ice loads at different heights above ground, analysis from Sveg tower Sweden. The indicated wind turbine shows the different ice loads that occur at different positions of the rotor.

The timing of icing episodes (especially the start and end of meteorological icing) can be predicted pretty well today. Problems occur for the end of instrumental icing (melting and sublimation, mechanically induced fall off of ice) as well as for simulation of the ice loads. Most of the validation work is done in a rather qualitative way, comparing ice loads visually on a graph. Detailed analysis on the quality of the simulation with regard to the differentiation between meteorological and instrumental icing, icing intensity, ice loads or the melting process have not been carried out.

Wind speed and temperature forecasts can easily be compared with measurements. A validation of icing forecast and especially the ice load is difficult as there is a lack of reliable instruments. Finally, LWC and MVD are very hard to measure. However, it is suspected that these deviations in simulations of ice loads are often related to inaccurate prediction of the wind speed, the LWC and the estimated MVD. LWC and MVD are rarely measured at a site (chapter 2.4) In that sense there is important information missing for a proper validation of the forecasted values. There exist some case studies at selected sites but the availability of data and especially the relations with wind energy projects is too small. This leaves a high uncertainty on both, the measurements and the simulations of icing. It is not clear where we are with the quality of the simulations, especially with respect to wind turbines.

Analysis of meteorological data

There exist numerous statistical methods to derive icing climatologies from observation data directly (e.g. cloud height, air temperature, satellite images). At some locations, these methods yield good results. However, this approach is strongly dependent on the density and the quality of the measurements as well as on the complexity of the terrain which rules the transferability of the results away from the measurement point. Relative humidity has been found to be a unreliable parameter to be used for the characterization of icing conditions.

Today, Norway, Finland and Switzerland have produced its own national icing atlas based on a coupling of a numerical weather model with the Makkonen ice accretion formula.

2.2.2 Icing Forecasts

<u>The ideal world</u>

In an ideal world, weather forecast systems are capable of providing accurate wind energy production forecasts for the next 72 hours which include potential production losses due to icing on the wind turbines. The calculation of the production includes and the adaptation to the available de-icing or anti-icing systems in the wind park as well as to the operation strategy (immediate stop if iced blades, operation with iced blades allowed etc.). If a ramp in energy production is likely to occur due to icing, a dedicated warning message will be displayed. Probabilistic forecasts are delivered i.e. the uncertainty can be determined from ensemble forecasts.

The information is the used either for trading the energy on the spot market or for grid management (overhead power lines are also affected by icing!)

On the very short term level (0-6h), icing forecasts are available and used for turbine control, i.e. for preventive operation of de-icing systems. These forecasts strongly base on measurements on the wind turbines itself as well as on weather forecast information submitted to the SCADA system.

State-of-the-Art

With a large penetration of wind energy in the grid, wind energy production forecasts become important in order to keep the grid stable and to sell the energy at the spot market. According to the state-of-the-art workshop of COST Action ES1002 (www.wire1002.ch) held in March 2011, the following main subjects need further research efforts in the field of wind energy production forecasts

- Ramp forecasts (sudden drops or rises in production)
- Complex terrain
- Special external conditions such as icing

During light to moderate icing events, icing results in a reduced power production compared to the forecasted wind speeds. During strong icing events, the influence of icing on wind energy production can be seen as a special sort of a ramp. During the icing event, the production quickly drops or even comes to a full stop within short time. If this phenomenon occurs in a large wind park, there is suddenly much less energy available than expected which can result in problems to keep the grid stable.

The basic background for the implementation of icing forecasts in wind energy production forecasts is the same as it is for icing climatologies (chapter 2.2.1), a numerical weather model is coupled with an ice accretion model (typically Makkonen) in order to simulate ice loads. This information is coupled with the forecasted wind speeds and transformed into energy production using a power curve with respect to icing. Therefore the same limitations are present as they are described in chapter 2.2.1.

Today, there a hardly any operational production forecasts available which include icing. One main reason is that icing forecasts are critical in terms of availability at given times of the day and require extensive computer resources. With today's computers, it is not yet possible to achieve the needed performance for operational forecasts or at least, its additional investment does not cover the benefit. Icing forecasts are mainly available for aviation purposes where a much coarser spatial resolution and less requirements on the accuracy are required.

With the horizontal resolutions available today for operational numerical weather models, the details of local topography cannot be described sufficiently. Therefore, it is a common approach to perform statistical or dynamical post-processing in order to allow the elimination of systematic errors (e.g. bias) in the forecasts for parameters such as temperature or wind speed (e.g. Model Output Statistics MOS or Kalman Filter). Today, there is no post-processing of the output of the numerical weather models when performing icing simulations. Wind, speed temperature and LWC are usually taken from the direct model output DMO. As wind speed and LWC are sensitive input parameters to the ice accretion model (ice accretion but also sublimation effects), a statistical post-processing of wind speed forecasts might improve the results.

In weather forecasting it is a common approach to apply ensemble forecasts, i.e. the same model is run with slightly different starting conditions. This results in a large number of model runs which can be compared and give information on the uncertainty of the forecast. Icing simulations are today carried out in a deterministic way, i.e. no ensemble runs are being carried out so far. In that sense, information on the uncertainty is not available.

Very short term forecasts (0-6h) for icing seem not to be existent at all at the moment.

2.2.3 Activities in the world

The former COST Action 727 performed a lot of activities in the field of icing simulation. First steps were carried out by the Norwegian Meteorological Institute which is also today very active in this field although they more focus on icing on overhead power lines. During COST Action 727, Meteotest from Switzerland formed a strong collaboration with Norwegian Meteorological Institute for further case studies. Finally, a broad study was carried out by the Norwegian Meteorological Institute carrying out icing simulations for six test sites in Europe. At these sites, the simulations could be validated with measurement data.

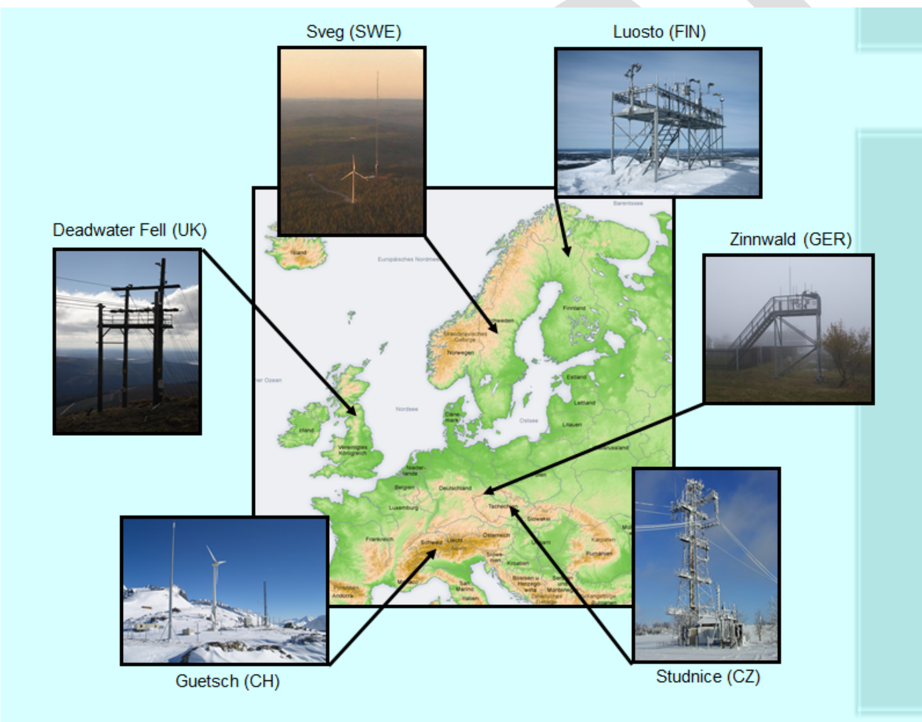


Fig. XX: Test stations of COST Action 727.

Most intensive work on cloud microphysics of the WRF model has been carried out at the NCAR in the USA (Greg Thompson). Currently, the work is focused on a new version of the cloud microphysics scheme which is to include predictions of the cloud droplet number concentration.

Meanwhile, Norway (by Kjeller Vindtekknik), Switzerland (by Meteotest) and Finland (by FMI) have created their own icing atlas based on coupling of a numerical weather model with the ice accretion model. Different weather models were used as input: WRF down to 1 km in Norway, COSMO 2.2 km in Sweden and AROME 2.7 km in Finland.

In the field of wind power forecasting considering icing, First studies were carried out in Switzerland (Meteotest). At the NCAR, USA, there is also a model development in progress.

2.2.4 Activities in Sweden

Missing in this version

2.3 Effects of icing on wind energy production

The ideal world

In an ideal world, the effect of icing on wind energy production is exactly known. This means that the process of an icing event and its influence on wind turbine blades is fully understood and there exist specific power curves for different ice loads and icing intensities. Wind power production of a wind turbine can be exactly predicted as a function of temperature, wind speed, ice loads on the blade (or LWC and MVD) and icing intensity. Furthermore, the effect of different anti-icing or de-icing systems is also known and can be included in the calculation depending on the icing frequency and the ratio between the meteorological and instrumental icing.

There exists a site classification which allows putting a given site into an icing class depending on the icing characteristics of the site. This classification is validated and used as a standard. Wind turbines are certified with respect to this site classification i.e. the planner knows exactly how a given turbine will perform in each icing class.

During planning process, it is possible to include icing effects in the energy yield calculation accurately (similar e.g. to the calculation of the park effect).

State of the Art

Today it is obvious that icing affects the wind energy production. A lot of simulations (icing wind tunnels and numerical models) have been carried out in order to quantify the production loss depending on the ice load on the blade. Already small amounts of ice can cause reduced power production. It also seems that the inner parts of the blade are less sensitive to production loss caused by icing). Usually, only small ice loads have been simulated.

Based on these experiments, modified power curves for iced wind turbines were developed. There also exist specific 3D power curves which include the power production as a function of wind speed and ice load. These power curves are able to predict the modification of the power curve due to icing in the right order of magnitude. There also exist comparisons of the predicted icing losses to the real power production. However, these comparisons show that there still remains a rather large uncertainty on the effective loss in power production.

One main problem in this field is the clear lack of trustable validation data, especially on the real ice loads on the blades and its development during an icing event. In many cases, the ice load measurements are taken from a point measurement on the nacelle of the wind turbine which is not representative for the blades neither during the meteorological icing (ice build-up) nor during the recovery time (ice melting, sublimation). There is no clear information of the effective degradation of the blade due to the ice. Icing intensity as well as the difference between meteorological and instrumental icing is hardly separated in the calculations. Another problem lies in the difficulty to access production data.

There exists a site classification by IEA which indicates production losses depending on the icing frequency. But these numbers have a rather high uncertainty range and have not been validated very thoroughly due to a lack of available production data

Due to the lack of commercially available de-icing and anti-icing systems, it is nowadays hard to quantify the effect of such systems on the wind power production. Some studies from Switzerland indicate that the hot air heating system of EMERSON is mainly active during periods with meteorological icing. In most cases, undisturbed operation can then be resumed after the end of the meteorological icing whereas a turbine without such system would remain disturbed until the end of instrumental icing. Heating during operation of the wind turbine represents a fully new situation again which has not been examined yet. There is little experience with the effect of such systems on the incubation and the recovery time of the blade during icing events.

2.3.1 Activities in the world

Finland: VTT power line, wind tunnel, Turbice

Norway: Kjeller Vindtekknik, modified power curves, Homola: tests in Narvik

Switzerland: Monitoring at Guetsch and St. Brais

Canada: Test site in Riviere-au-Renard, Québec, Canada

2.3.2 Activities in Sweden

2.4 Icing measurements

The ideal world

In an ideal world, there exist instruments which are able to measure icing reliably and automatically and which are on the same level maintenance free as today's anemometers. These instruments can deliver information on duration of meteorological and instrumental icing, the icing intensity as well as on the total ice load. Furthermore there are instruments which can measure LWC and MVD automatically and for an affordable cost. The price of such a system is similar to the cost of a high class anemometer. This information can be used in order to determine the influence of icing on the production of a planned wind park. The readings are also used to validate the results of icing simulations.

There exist systems which are able to exactly measure the presence of ice, the ice load and the level of coverage of ice on a wind turbine blade (tip to root). This measurement is possible during operation and stand still of the wind turbine. This information is used to control the turbine and its anti-icing or de-icing systems.

State of the Art

Today there exist a variety of instruments which intend to measure icing in some way. Some focus on meteorological icing (vibrating rods, IR beam reflection, attenuation of ultrasonic signal), others directly measure the ice load (load cells) giving also information on the instrumental icing. All approaches follow feasible principles of measurement of icing.

The ISO issued in 2001 a standard ISO 12494 for ice accretion on all kinds of structures, except for electric overhead line conductors. In this recommendation, a standard ice-measuring device is described as:

- A smooth cylinder with a diameter of 30 mm placed with the axis vertical and rotating around the axis. The cylinder length should be a minimum length of 0.5 m, but, if heavy ice accretion is expected, the length should be 1 m.
- The cylinder is placed 10 m above terrain.

There is one instrument which refers to this recommendation, the Icemonitor. This instrument is often used as a reference when comparing icing simulations with measurement data.

These recommendations can be applied for meteorological purposes where icing information is needed from a standstill structure at a given height above ground.

Many of the available ice detection instruments are in prototype state and suffer from technical limitations. Firstly, some of the instruments need a lot of maintenance and are sensible for failures, especially when operated during harsh conditions. Other systems deliver readings which are suffering from noise or drifts and therefore hard to be interpreted. Finally, all instruments experience specific conditions under which they are not able to detect icing conditions or they produce false alarms. In summary, it is nowadays not possible to fully rely on the readings of the existing instruments; one has to interpret other measurements or camera images. There is a clear need for better instruments.

A large intercomparison of ice detectors was carried our during COST Action 727. At Guetsch mountain, 5 different ice detectors were examined none of them was found to operate properly.

There are various indirect approaches to measure icing such as the use of temperature, relative humidity, visibility or cloud height. However, these approaches are strongly dependent on the characteristics of the site and the quality of data. Especially the relative humidity has been found to be a not very good indicator. A further approach is to compare a heated and an unheated anemometer in order to identify the icing conditions. This has been proven to be a robust approach; however, it can deliver only information on instrumental icing. An ongoing study is adding a third anemometer which is heated only during intervals during periods of meteorological icing. If successful, this approach might be able to deliver the needed information on meteorological icing too.

One of the most reliable ways to identify icing today is still by visual inspection. The use of automatic cameras has proven to be a good tool to identify icing on standstill structures. However, the image analysis has to be done manually today, there don't exist automatic algorithms to determine the presence of ice in camera images. IR lens in combination with IR light has been proven to be able to also deliver good images also during night conditions.

The measurement of LWC and MVD in order to measure icing indirectly is nowadays a difficult and expensive task. There exist instruments which are able to to this on a thermal (heated wires), optical (laser scanning) or mechanical basis (Rotating Multi Cylinder). The main drawbacks are, that these instruments are either very expensive or not able to measure the LWC and MVD automatically. Furthermore, the uncertainties can be very large depending on the approach.

A good but old (1996) data set exists from the TV tower at Kivenlahti in Finland. Here a rotating multicylinder was used for manual measurements.

There exist systems which intend to measure icing directly on the blades of a wind turbine. The most common and straightforward approach is to detect icing through a deviation from the current production compared to the production according to the power curve. This approach has been proven to be very robust and efficient to detect iced blades during operation. However, it is not applicable when the turbine is not operating or when the wind speeds are very low. Furthermore, it doesn’t give any direct information on the ice loads.

There exist specific measurement systems for the detection of ice on wind turbine blades. These systems identify the ice on the blades through changes of the "Eigen frequency" of the blades or changes in mass. The sensors are either accelerators or strain gauges which are installed directly inside the blades. The manufacturers claim that these systems are working, however there exist hardly any independent test cases from R&D projects. Some of these systems are dependent on access to the current pitch data of the wind turbine which might not be accessible depending on the manufacturer. Some of these systems are also able to measure the ice load. Here again, an independent study from an R&D project is not available.

Another approach to identify icing on the blades of a wind turbine is again the use of automatic cameras. First approaches mounted the camera on the spinner of the rotor so that the camera was rotating and always pointing to the same blade (Tauernwindpark, study Göran). The disadvantage of this approach was that the camera is strongly exposed to the weather (icing) and the the view angle towards the blade is very flat. This results in the effect that especially with long rotor blades, it is hard if not impossible to see the tip of the blades.

A different approach is to mount the camera on the nacelle pointing side wards and catching the blade by motion detection when it moves through the image. This approach has the advantage that it is not necessary to put a hole in to the spinner, the camera is less exposed (view angle approximately perpendicular to the wind direction) and the view angle towards the blade is more steep, i.e. it is possible to see the whole blade. The disadvantages are that the video detection cannot capture 100% of the situations, the front of the blade cannot be seen properly and the system randomly catches a blade so it is not always the same blade which is captured. Again, there doesn't exist an automatic algorithm to detect ice from the camera images, the analysis has to be done manually.

One problem which is related to all camera approaches to detect icing on the blades is the illumination during the night. Strong headlights disturb the neighborhood. Stroboscopic light is hard to trigger and again disturbs the neighborhood. Best results were achieved so far by using very strong IR headlights and a camera with a lens sensitive for IR light. However, the headlight must be over dimensioned strongly in order to achieve useful images.

Today there is no clear standardization of icing measurements available.

2.4.1 Activities in the world

COST 727:
- Measurements at 6 stations with two instruments
- Instrument intercomparison at Guetsch
- Wind tunnel Tests in Kanagawa, Japan

Wind tunnel at VTT, Finland

Test site in Canada

2.4.2 Activities in Sweden

Many icing measurements in Sweden, mainly with IceMonitor and Holooptics instruments. Lot of data collection.

2.5 De-Icing and Anti-Icing

The ideal world

In an ideal world, the planer of a wind park can chose between an anti-icing system which completely prevents ice to be built up on entire wind turbine or a de-icing system which is capable of fast and efficiently remove the ice from the wind turbine during icing events. The performance and the costs of these systems are well known so that the choice of the system depending on the site specific icing characteristics can be easily made. The additional cost of such a system can be compensated by additional production within 2-3 years of operation. The system has the same level of maintenance as the other parts of the wind turbine.

State of the Art

De-icing refers to removal of ice from the blades. It corresponds to a shortening of the recovery time during an icing event. Anti-icing refers to the prevention or at least delay of ice buildup on the blades. It corresponds to an increase of the incubation time during an icing event.

One thing which is common for this research field is that most of this work is done internally by manufacturers and therefore, only very little information about the technical specifications and the performance of these systems is available to the public.

Up to know, there exists only one system which is sold on a large basis and has been tested in independent R&D projects, the hot air heating de-icing system of ENERCON. The other manufacturers all claim to work on a system.

The main research trends are towards Hot Air Heatings, Electro-Thermal Systems and Anti-Freeze Coatings.

De-icing

Description of Enercon hot air system.

Electro-Thermal systems consist usually of heating surfaces which are installed typically on the leading edge of the wind turbine. Today, many prototypes exist and are been tested on wind turbines.

The electrical heating uses an electrical resistance embedded inside the membrane or laminated on the surface. Electrically heated foils can be heating wires or carbon fibers. Heating elements cover the leading edge area of the blade. The ice detector and blade surface temperature are used to control the operation of the heating system. Additional temperature sensors are installed to protect the blade from permanent damage induced by over-heating.

Apart from the technical challenges related to Electro-Thermal systems for removal of ice, the control of such a system is another important field. The right timing for switching on and off the heating systems has to be identified during operation of the wind turbine on the most economical way to optimize the cost/benefit in terms of the used energy for heating versus additional production.

Currently, it is not possible to predict icing turbine-specifically in order to start up de-icing systems before there is ice on the blades. Only after the detection of ice, the process of removing the ice can be started. A preventive de-icing, which would then be anti-icing is not possible.

No information of long term effects of heating systems on the blade structure.

As de-icing systems mostly focus on the leading edge of a rotor blade, there is a probability for secondary icing, i.e. the ice is melted but re-freezes on the unheated parts of the rotor blades.

Anti-icing

Over recent years, much emphasis has been placed on the development of coatings that act as passive anti-ice surfaces. Most products that are available are hydrophobic coatings that prevent the water from settling on the surface and subsequently reduce the ice formation. On first thought, (super-) hydrophobic coatings should improve the anti-icing behavior due to the reduced wetting. Nevertheless, it has been shown in comprehensive studies performed by the Fraunhofer IFAM that the hydrophobicity is only one of the determining factors for predicting anti-ice properties – and furthermore, a hydrophobic coating is not necessarily an anti-ice coating. A systematic study showed that with increasing the hydrophobicity of a coating with polysiloxane additives, an increase of ice formation occurs at angles of more than 140°. Up to now no general coating type could be observed with outstanding results.

A further coating concept is chemical freezing point depression which is based on the leaching of depressors out of the paint matrix. Due to the leaching aspect, this effect is only temporary and is only suitable for technical applications that require ice free surfaces for a short time. Tests of such coatings have shown promising results.

Another concept is the use of biochemical technologies for the prevention of ice formation on technical surfaces, this biochemical method is used by organisms in polar and sub-polar regions and is the reason for the survival of, for example, fish, amphibians, plants and insects. It involves coupling anti-freeze proteins to coatings. It is based on substances with constitutive properties that cause freezing point depression due to the configuration and conformation of the molecules. Such molecules selectively depress the freezing point, but have no effect on the melting point of ice. This leads to a temperature difference between melting point and freezing point and is called "thermal hysteresis". These molecules are described as thermal hysteresis proteins or (more commonly) anti-freeze proteins (AFPs).

Another approach is the development of coatings that contain hydrophilic centres in a hydrophobic environment. This allows water molecules to adhere to certain sites, yet the hydrophobic surroundings of these sites promote the removal of ice crystals.

Most of these approaches are tested in labs, there are only few field tests. Field tests are mainly available for hydrophobic coatings. Biochemical technologies are still in the labs.

One big advantage is, that the whole surface of the blade can be kept icefree with this method (no secondary icing). Furthermore, no control system is needed. As a side effect, such coatings could also be used for meteorological instruments, e.g. ice free anemometers.

2.6 Safety issues

2.6.1 Ice throw

<u>The ideal world</u>

In an ideal world, ice throw is an integral and widely accepted part of the environmental analysis of a planned wind turbine similar to noise or shadowing studies.

There exist models which can, based on measured site-specific data on frequency of icing and ice loads exactly simulate risk zones around each planned wind turbine. These models can produce such results for both, ice fall (standstill turbine) and ice throw (operating turbine) These models have been validated thoroughly by empirical studies. These models include valid assumptions on the typical rotor position when ice is thrown off as well as on the behavior of ice fragments when falling through the air. They also include different algorithms to include the changes in ice throw because of the presence of anti-icing or de-icing systems.

Furthermore, there is a dedicated risk analysis model which allows the calculation of the risk of death for each point around the planned wind turbine based on the ice throw variability but also the risk of presence of persons in this perimeter.

This information allows adjusting the siting of wind turbines according to the risk of ice throw similar to noise and shadowing.

<u>State-of-the-Art</u>

The most often approach to identify risk zone for ice throw and ice falls are the formulas presented by Henry Seifert:

$$d = 1.5(D + H)$$ for an operating turbine

$$d = v\frac{(D/2 + H)}{15},$$ for a turbine at standstill

d = maximum falling distance of ice fragments [m]

D = Rotor diameter [m]

The major drawback of the formulas is the fact, the the depenency of the ice throw risk on the wind statistics under typical icing conditions is neglected.

Ballistic model were developed which can simulate the trajectories of ice fragments which are either thrown away from a rotating blade or a dropped off a blade at standstill. Monte Carlo simulations have been carried out feeding such models with a large number of ice fragments for constant external situations (constant wind speed and direction). This method was used to determine risk zones around a wind turbine. Similar simulations which respect the orientation of the wind turbine and include real time series of wind speed and direction have also been carried out. Open questions are the preferred balde position for an ice fragment to be thrown off the blade and its flying characteristics and its typical shape. Here again mechanical models are needed to simulate the sticking of the ice to the blade during rotation influences. Additionally, the effect of breaking ice while flying through the air has not yet been examined. Finally there is a clear lack of validation data for the simulation results.

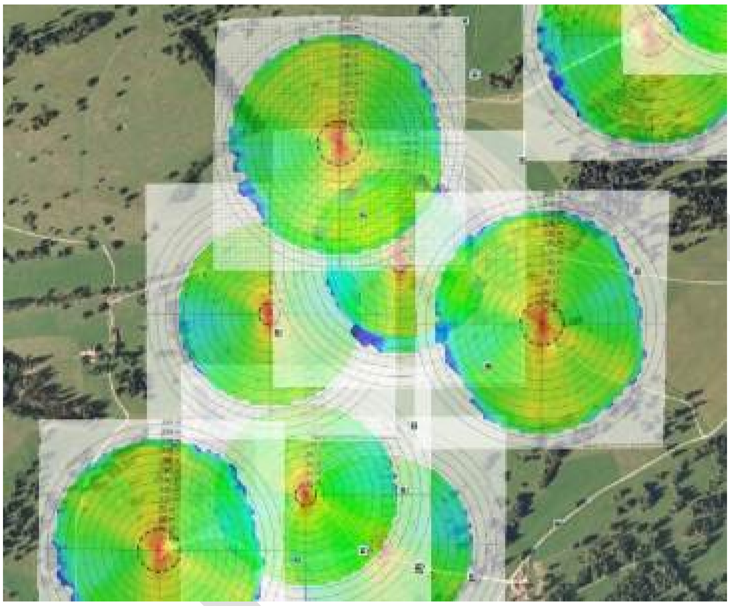


Fig XX: Example of an Ice throw simulation (Source: Meteotest)

Today there exist only rare systematic empirical studies on the distribution of ice throw of wind turbines. Maybe the best know study is the Guetsch study.

In 2004, a 600 kW Enercon E-40 wind turbine with integrated blade heating was installed on Gütsch mountain, Switzerland, at 2'300 m asl. As the wind turbine is located close to ski slopes, ice throw was considered as an important safety issue. During four winters between 2005 and 2009, the area around the wind turbine was inspected after every icing event for ice fragments that had fallen off the blades. Distance from and direction relative to the turbine as well as size and weight of the recovered fragments were mapped and, together with photos, collected in a data base. In total, more than 220 ice fragments could be recorded and analyzed giving a detailed view on the distribution of ice throw around the wind turbine.

This study is still unique in the world and therefore referenced many times. It showed a clear dependency of the ice throw on the prevailing wind conditions during icing events and gave indications on preferred rotor positions for ice throw. However, as the wind turbine at the Guetsch is rather small compared to nowadays standard wind turbines, the question was often raised, how these results can be transferred to larger wind turbines. In addition, there is no difference between ice fall and ice throw.

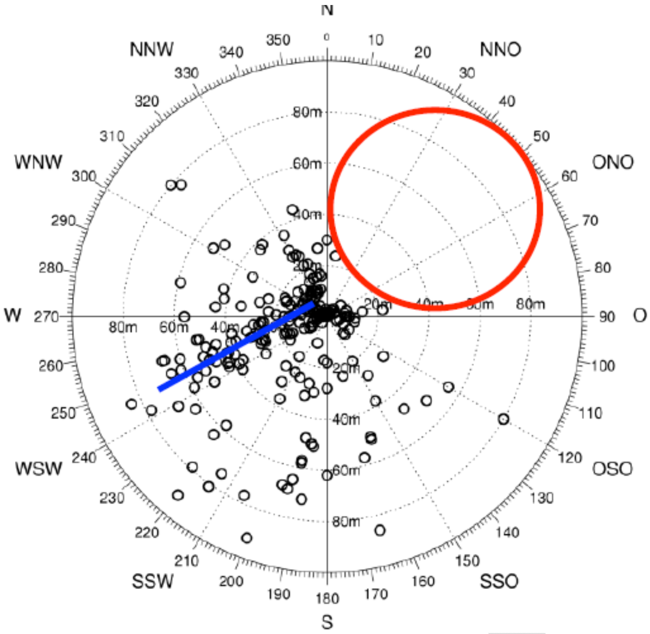


Fig. XX: Distribution of ice fragments from the Guetsch ice throw study.

An earlier experimental study carried out during the New Icetools project collected information on ice throw provided by the operators. The main problem was, that the approach was not systematic and in some cases subjective. Furthermore, the number of fragments per turbine was rather too low for a systematic analysis. This study delivered a good impression on the presence and the possible range of ice throw of wind turbines.

2.6.2 Noise

<u>The ideal world</u>

In an ideal world, the effect of iced blades on the noise emissions is clearly known depending on the ice load attached to a blade. The inclusion of icing is a standard add-on in market available tools for determining the noise impact of a planned wind park.

<u>State of the Art</u>

Today there are hardly any studies on the influence of icing on the noise emissions of a wind turbine. It is mainly unknown how this works.

An experimental noise measurement was carried out in Switzerland. There was a tendency towards higher noise emission with ice blades but it turned at them same time out, the noise measurements under icing conditions is a tricky task as the microphones get iced too (fig XX)

Fig: Iced microphone of a noise measurement (St. Brais, Switzerland)

3 Future research needs

3.1 General thoughts

The core for understanding icing on wind turbines is a funded knowledge on what effect the external meteorological conditions (wind speed, temperature, LWC and MVD) have on a wind turbine in terms of icing. The external conditions can be identified either by on-site measurements or by numerical models. Afterwards, the identified effect of icing on the wind turbine has to be translated into effect on power production of a wind turbine

Most work focuses on converting the external meteorological conditions into ice accretion at a rotating cylinder. However, when it comes to the validation of such models, there is a clear lack of trustable measurement data. While wind speed and temperature are today relatively easy to measure, the results of ice detectors are not very accurate and LWC is almost impossible to be measured. However, there is still room for improvement, especially when it comes to validation data for the existing models.

On the wind turbine side, there exist studies on ice accretion on rotor blades. However, these simulations are only run for constant conditions. Finally there is no mechanical model.

The full link between the external meteorological conditions and a wind turbine is to a large part unclear and needs to be further investigated. Figure XX illustrates the situation. Most research efforts have focused on the simulation of icing on a vertical, freely rotating cylinder with a diameter of 3 cm and a length of 50 cm (left) or on a 2D blade section. The external meteorological conditions (mainly temperature, wind speed, LWC and MVD) are in approximation the same in both cases. In the latter case they are kept constant. The cylinder itself doesn't move apart from the free rotation around the vertical axis. The reality is much different as it can be seen in Fig YY. There are different external meteorological conditions over the whole rotor (vertical profiles of temperature, wind speed and LWC). The blades of a wind turbine cover a vertical section of 80 to 120 m. MVD can be assumed to remain stable for the whole section. Furthermore, the rotor blade is not an ideal cylinder and is not rotating around the vertical axis. The dimension of the shape of the rotor blade is changing between tip and root of the blade. Finally the rotor blade is moving which results in different relative wind speeds and different exposure of the rotor blade towards the external meteorological conditions and mechanical effects also apply on the blade.

The future research should focus on the correlation between the external meteorological conditions and the rotor blade of an operating turbine. Furthermore, there is a clear need for better validation data. This implies a strong need for better instruments to detect icing on the blade of a wind turbine.

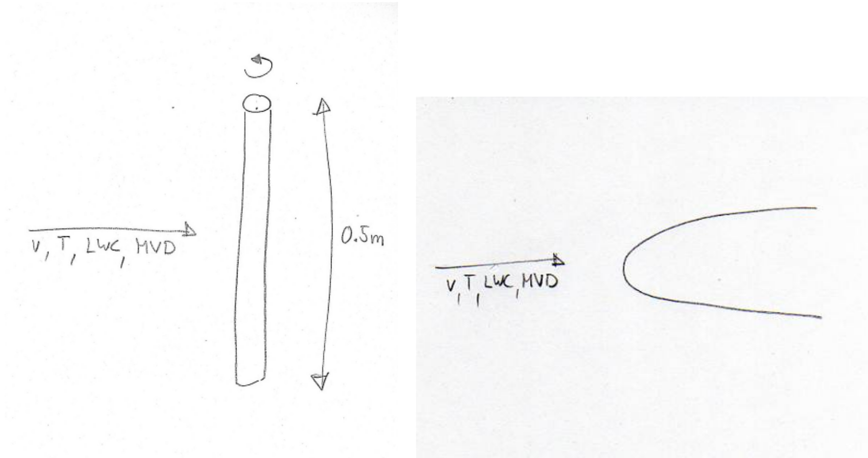


Fig. XX: Left: Icing on a vertical cylinder. Right: Icing on a 2D blade section. In both cases, the external meteorological conditions are in approximation the same.

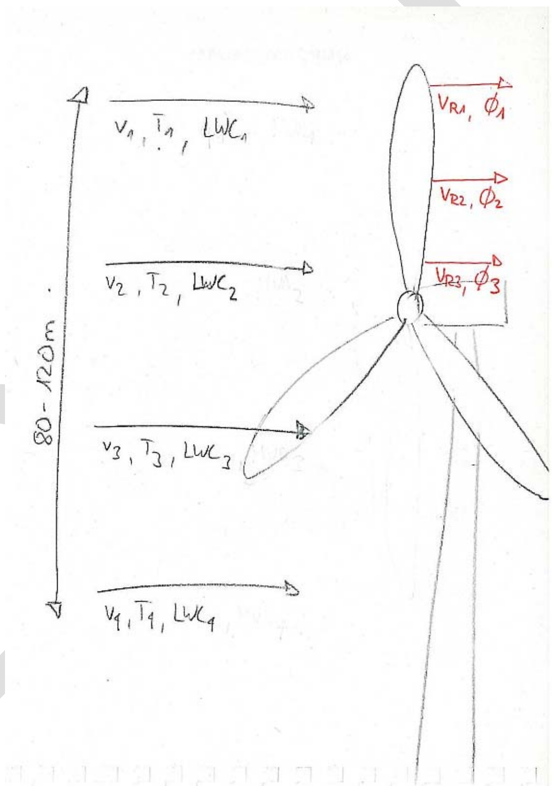


Figure XX: There are differences in the vertical profile of the external meteorological conditions for a wind turbine. Furthermore, depending on the position on the blade (tip to roof), different speeds and dimensions of the blade appear.

In order to understand the dependency of ice accretion on an unheated wind turbine based on the external conditions, these conditions have to be measured and monitored on a very detailed level. The exact ice coverage at all positions of the blade has to be known under all conditions as well as the operational parameters such as rotational speed, pitch angle and power production.

Furthermore, the external meteorological conditions also have to be available the different height levels ideally upwind of the wind turbine for the prevailing wind direction during icing conditions.

This data has to be collected and analyzed in detail for all phases and characteristics of an icing event (meteorological and instrumental icing, incubation and recovery time, icing intensity, melting, sublimation effects etc.) in order to be able to clearly understand the wind turbine under icing conditions.

Finally, the ice accretion information has to be correlated with the power output in order to derive empirical power curves for icing conditions which then can be compared with the simulated models

Many studies touch only small parts of the icing problems and furthermore the projects are often limited in time. In order to create a long term and representative research, it would be favorable to have dedicated test centers where all aspects can be examined over a long time and which have to facilities to produce complete information on the external conditions as well as on the conditions at the wind turbine blades.

With the presence of such test centers, new models or instruments can be tested at a traceable site and the results can be compared to other references. European test centers, FP7 project or similar

Needs are

3.2 Icing simulations

- Statistical post-processing
- more information of the vertical profile of icing
- melting, sublimation
- mechanical model
- more information on freezing rain events
- Couple CFD models with ice accretion models
- Improvement of Cloud Microphysics in Weather Models
- Simulation of MVD with weather models
- Transfer Makkonen formula to from cylinder to shape of wind turbine rotor blades
- Include better melting and sublimation processes (especially for moving rotor blades)

3.2.1 Icing climatologies

- better cloud microphysics, include MVD
- methods for long term correlation
- Climate change scenarios
- other downscaling methods
- validation
- improved schemes for prediction of MVD and LWC
- vertical profiles of icing
- Freezing rain models for wind energy

3.2.2 Icing Forecasts

- post-processing of wind speed and temperature (and LWC)
- Intelligent combination of measurements and forecasts for a nowcasting → preventive de-icing.
- uncertainty information
- ensemble runs

3.3 Effects of icing on wind energy production

- Field tests
- Validation of power curves
- Dependency of power curves on icing intensity
- Sublimation, melting
- Vertical profiles
- Validate Classification of wind turbines, de-icing and anti-icing systems
- ion data from operating wind turbines

3.4 Icing measurements

- Working and proven ice detection instruments
- Instrument classification, standardisation
- Measurements of LWC and MVD → Automatical RMC system
- Improved trigger for blade detection with cameras
- Automatic image analysis tools for ice detection

3.5 De-icing and Anti-icing

It is crucial to be able to understand the effects of icing on wind turbines and to develop reliable anti-icing and de-icing systems and to control them efficiently i.e. the ice accretion on a heated blade or a blade treated with an anti-icing surface

- Prototypes
- Independent validations within research projects
- Anti-Icing coatings tested in the field
- Intelligent turbine control for de-icing systems

3.6 Safety issues

3.6.1 Ice throw

There is a clear need to carry out more experimental studies in order to better understand the characteristics of ice throw. Special emphasis has to be put on

- the exact time of ice throw
- distinction between ice throw and ice fall
- difference between unheated and heated blades
- preferred blade position for ice throw
- correlation between wind direction and ice throw direction
- trajectories of ice fragments, behavior in the air, “sailing” effects
- ice throw for different ice fragments
- mechanical models for ice on blades

3.6.2 Noise

There is hardly any knowledge on the effect of iced blades on the noise emissions of a wind turbine. The following questions remain unanswered

- What’s the increase in db when operating with iced blades?
- How can it be measured
-

ELFORSK

SVENSKA ELFÖRETAGENS FORSKNINGS- OCH UTVECKLINGS - ELFORSK - AB

Elforsk AB, 101 53 Stockholm. Besöksadress: Olof Palmes Gata 31
Telefon: 08-677 25 30, Telefax: 08-677 25 35
www.elforsk.se