State-of-the-art of wind energy in cold climates

WIND ENERGY IN COLD CLIMATES

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ABSTRACT

Wind turbines in cold climates refer to sites that have either icing events or low temperatures outside the operational limits of standard wind turbines. International Energy Agency, IEA R&D Wind has started a new annex, Wind Energy in Cold Climates. This is an international collaboration on gathering and providing information about wind turbine icing and low temperature operation. The goal is to monitor reliability of standard and adapted technology and establish guidelines for applying wind power in cold climates. In this report, the state-of-the-art of arctic wind energy is presented: knowledge on climatic conditions and resources, technical solutions in use and operational experience of wind turbines in cold climates.

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1 INTRODUCTION

In 2001, the International Energy Agency (IEA) R&D Wind Programme started a new annex, number XIX, called Wind Energy in Cold Climates. This international collaboration between the participating countries has as objectives to gather operational experience of wind turbines and measurement campaigns in icing or cold climates to enable a better understanding of turbine operation under there conditions. The goal is to formulate site categories based on climatological conditions and site infrastructure and then link the wind turbine technologies and operational strategies to these categories. This will give guidelines to operators and manufacturers operating wind turbines in cold climates.

Information is gathered and disseminated on the project website http://arcticwind.vtt.fi/.

The operating agent of the annex is Technical Research Centre of Finland VTT and participating institutes are FOI/FFA from Sweden, Kjeller Vindteknikk from Norway, Risø National Laboratories from Denmark, the National Renewable Energy Laboratory (NREL) from the USA, ENCO from Switzerland and Natural Resources Canada [1].

At the moment there are a relatively small number of wind power projects in the cold climate, however this global market segment is estimated to be substantial, although no real market assessment has yet to be performed. There does seem to be lack of information regarding the operational experience and exact climatic conditions relevant to sites in cold climates, especially when risk of icing is concerned.

In addition, when siting wind turbines in cold climates, the assessment of the climatic conditions, their impact on turbine production and economy (reliability, O&M costs) have to be made (Fig. 1). Generally information about the average and minimum temperatures on perspective sites is usually available however icing frequency is more difficult to obtain. Current IEA and other international standards simply state that standard methodologies do not hold for sites outside of normal operating conditions and thus projects in these areas are often carried out with inadequate knowledge on icing and other extreme weather conditions.

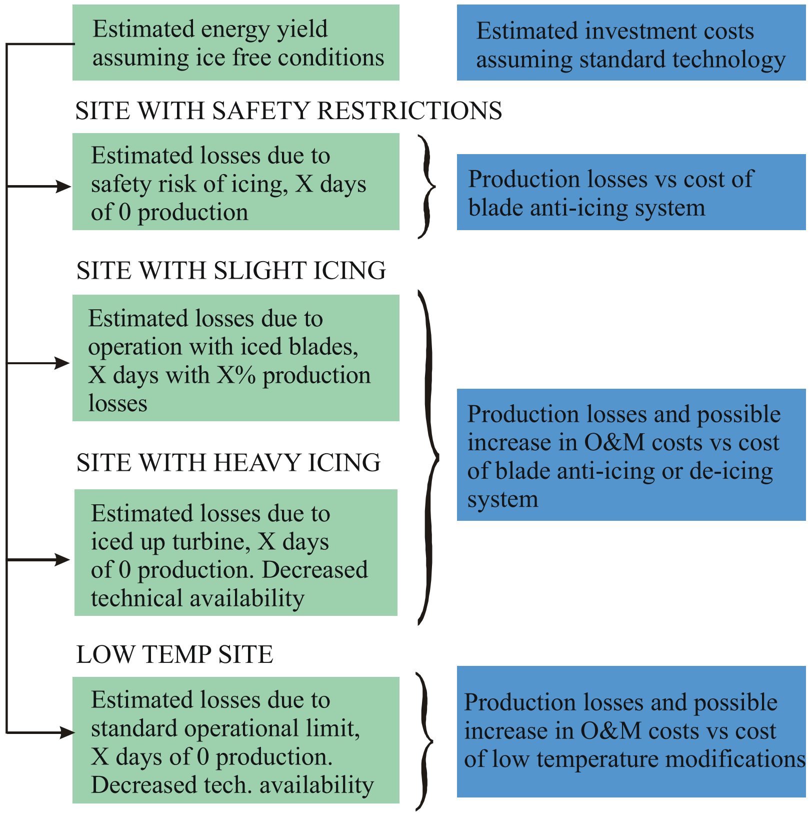

Figure 1. Assessment of sites in cold climates: there are sites in very low temperatures but dry climate with no icing events. Icing is most frequent just below 0°C. Some sites have to consider all the cases above.

2 WIND TURBINES IN COLD CLIMATES

There are already several sites with either existing or projected wind parks in cold climates: Northern and Central Europe, Northern America and Asia (China and Russia). All together approximately 500 MW (Fig.2).

The following describes operational experience reported by the permanent members of the IEA Annex on wind turbine operation in cold climates.

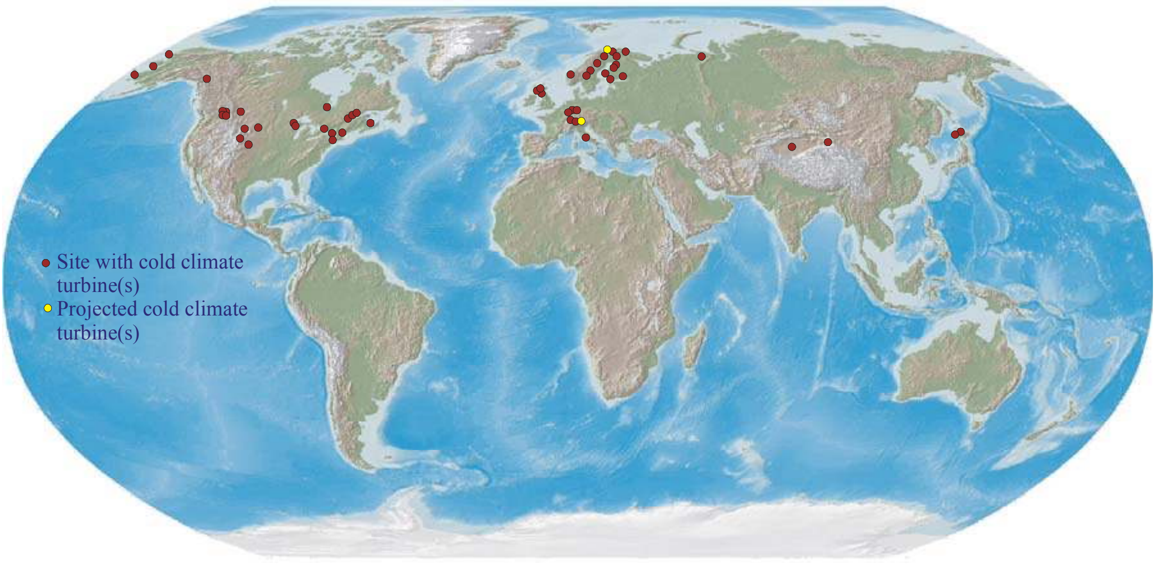

Figure 2. Locations of operating wind turbines in cold climate sites [2,3,4,5,6,7].

2.1 NORTHERN EUROPE

In Scandinavia there are existing sites in Finland and the mountains of Sweden and Norway. In Scandinavia icing is occasional on the coastline, and severe icing conditions occur in high altitudes regularly. Temperatures may fall below –20 °C often in higher altitudes and few times during the winter on coastal areas. Due to the combination of very good wind conditions, severe icing and low temperatures on arctic fell tops, arctic modifications for turbines have been developed [12]. Though designed for arctic conditions blade heating systems have been installed also to milder icing conditions [9].

In the Lapland region of Finland icing is severe, with rime icing conditions up to 200 hours a month making wind turbine usage without adapted technology impossible. Icing is most harsh between November and February and occurs most often in a temperature range of 0°C--7°C. [8] There is two find farms in Finnish Lapland Olostunturi-fjell and Lammasoaivi, both in Northwest Lapland. Olostunturi-fjell wind farm consists of five Bonus Mk IV 600kW wind turbines and Lammasoaivi contains one Bonus Mk IV 600 kW and two Bonus Mk III 450 kW turbines. All turbines are equipped with an ice prevention system called the JE-System. Manufacturer of the JE-Blade heating systems is Kemijoki Arctic Technology OY. Apart from Lapland, wind turbines in Finland locate in coastal areas and in the southern archipelago where they also experience occasional and moderate icing. Cold climate versions of the standard turbines are used in these projects but blade heating systems have not been utilised extensively. An exception is the wind farm at Pori, located along the western coast of Finland (N 61.3°, E 21.2°) where the four turbines that are located next to a busy road were equipped with blade heating systems to improve road safety. The entire Pori wind farm consists of 9 wind turbines of which eight have nominal power of 1 MW and one 2 MW. The wind turbine supplier was Bonus Energy A/S and the turbines use the JE-System blade heating technology. Icing occurs occasionally at Pori, most often at temperatures just below freezing (0°C--3°C). [9]

According to the Finnish wind turbine statistics nearly every site in Finland reports down time due to icing or low temperatures during the winter. [21]

Norway has a long shoreline facing the warm waters of the eastern part of the north Atlantic ocean currents. Low pressure systems forming in the polar jet stream areas over the warm Atlantic waters move eastward and ensure high wind speeds and a mild climate along the Norwegian coast. Well exposed Islands and ridges along the coast are well suited for wind energy. Compared to other areas in the world at the same latitude, the temperatures in wintertime are relatively high. At North Cape (71º), -4ºC is the lowest monthly average temperature at sea level.

In cloud icing occur frequently above a certain altitude all along the coastline. From experience with wind monitoring programs, it seems as the frequency of icing is more dependent of altitude then latitude. The wind turbines located at Havøygavlen (Latitude 71º and 275 m above sea level) do not have heated blades.

In Sweden the prevailing winds are from the South West. Consequently the northern part of Sweden generally takes shelter from severe icing conditions behind the mountains of Norway. Icing of wind turbines still experienced, particularly in the area of Jämtland where the Norwegian mountains provide less shelter. Occasionally Sweden experience cold easterly winds flowing off of the unfrozen Baltic Sea creating severe icing over large areas. Such an event in December of 2002 caused turbines without blade heating systems to be put out of operation for several weeks.

The combination of low temperatures, below -50 in the northern Sweden, and low solar radiation during the winter months limit the ability to de-ice structures that are iced during extreme weather. Structures that have been iced up may stay iced for long periods.

Occurrences of super-cooled rain are common in Sweden and a severe case was recorded at temperatures below -10 as far south as Stockholm on Feb 6, 2003. Frequent in cloud icing will also impact all operators of large offshore wind turbines in the Baltic. In addition, the annual return of the sea ice along the coastline, lakes and northern seas will create a significant challenge for the designer of offshore wind turbine foundations.

As part of a voluntary national program the incidents of problems related to operating wind turbines in cold climate have been reported and entered into a database. 92 impact reports were received for 2000, 2001, and 2002 reporting approximately 8000 hours of missed production.

2.2 CENTRAL EUROPE

In a recent paper by Tammelin et. al., ref. 19, an analyses showed that icing conditions exists in much larger regions of Europe than earlier has been expected by the wind power community. The analysis also found that in central Europe icing and low temperatures deteriorate wind energy production at elevated sites, which unfortunately also provide good wind conditions. Areas where low operating temperatures and icing has been recorded centre on the Alps, Apennines and other mountainous areas. [19]

Heavy icing and a high number of icing days is observed at sites like the Apennines in Italy. As an example the Acqua Sruzza test site in Italy, at same latitudes as Napoli, experiences heavy icing occasionally. The amount of icing experienced at that site would lead to a significant production loses with standard wind turbines. [19]

Icing and low temperatures are also experienced frequently in mountainous regions of Southern France, in the Alps, and in the Albs in southern Germany.

Icing has also been recorded to deteriorate wind energy production of several wind farms at the high altitudes in Scotland mountains.

In Switzerland several projects have been carried out in icing and in low temperature climates. Wind turbines that experience icing and low temperatures are located at high altitudes, generally from 1300 to 3000 metre above the sea level. Typically sites below 2000 metre above sea level experience only light icing and sites with higher altitude are prone to heavy icing and low temperatures. Important experience on the use of wind energy under climatically extreme conditions will be gained from the 800 kW plant on the Guetsch near Andermatt (2300 m above sea-level) which was commissioned in spring 2002. This is the first wind turbine in Switzerland that uses adapted technology to protect it against icing and low temperatures. Further projects such as St.Moritz (2200 m above sea-level) as well as Crêt Meuron (1300 m above sea-level), will increase the knowledge about wind energy production in alpine region and harsh climatic conditions.

In Europe there is a growing and identified interest to erect more wind turbines at sites in which the wind turbines will be prone to icing. [19]

2.3 NORTHERN AMERICA

Wind farms are being installed in three general climatic regimes effected by cold weather. In the north central region, such as the 200 MW wind plants in the Lake Benton, Minnesota area, snowfall and cold temperatures are common but turbine icing is uncommon due to the low humidity. Additionally along the eastern coast of the US and Canada, and specifically the north east such as the 6 MW plant in Searsburg, Vermont, turbines are located on low altitude mountain ridges or in coastal regimes where icing is frequent. Depending on the location and altitude, cloud or rime icing is common. The last clarification of sites are along the arctic coast, such as the 0.8 MW plant located in Kotzebue Alaska and specific units in northern Canada. These sites experience icing, cold temperatures and high density air flows.

In Canada, one can say with confidence that all turbines installed, except maybe the ones immediately located on the East and West coasts that benefit from the ocean effect, will be exposed to temperatures below –20°C at one time or another during the year.

Atmospheric in-cloud icing is encountered on the elevations of British Columbia, Yukon and, to a lesser extent, in the Appalachian domain of the East coast. Freezing precipitation on the other hand is more likely to occur in Central and Eastern Canada.

2.4 ASIA

In China turbines are generally located on sites where winter humidity is typically low, but temperature may drop below –20 °C, and diurnal temperature changes may be as high as 40 °C.

3 KNOWLEDGE ON CLIMATIC CONDITIONS

Generally information about the average and minimum temperatures at a site is usually available however icing frequency is more difficult to obtain, and projects are often carried out with inadequate knowledge on icing conditions.

To assess the consequences of icing and the required modifications to standard wind turbines, information on the frequency of icing events and the duration of ice on different parts of the wind turbines, such as the blades, anemometers, nacelle, and tower are needed. Icing can also effect wind resource estimation due to the occasional icing of anemometers during a measuring campaign, which can be difficult to detect.

According to statistics on Finnish coast, icing can be 5 times as frequent at 100 meters above ground level as at 50 m. Direct measurements of icing are very rare and improvement of ice sensors is still needed. Also, development of models to be used in estimating the amount of icing days on a specific site are still needed. This is especially true for mountainous areas where the local terrain effects can be difficult to assess in modelling. Measurements of the conditions further than 1 km away may also not give enough information about a specific site in question.

Icing occurs at temperatures below 0 °C when there is humidity in the air. The type, amount and density of ice depend on both meteorological conditions and on the dimensions and type of structure (moving/static). There are also different icing climates, such as cloud icing, when small water droplets in the cloud impact and freeze on the surface of structures, or cold and extreme low temperature icing. This is demonstrated in Fig.3, which shows examples of two different sites in Finland: Pori is a coastal site in Southern Finland and Olostunturi is a site with heavy icing in the arctic fells of Northern Finland [8,9].

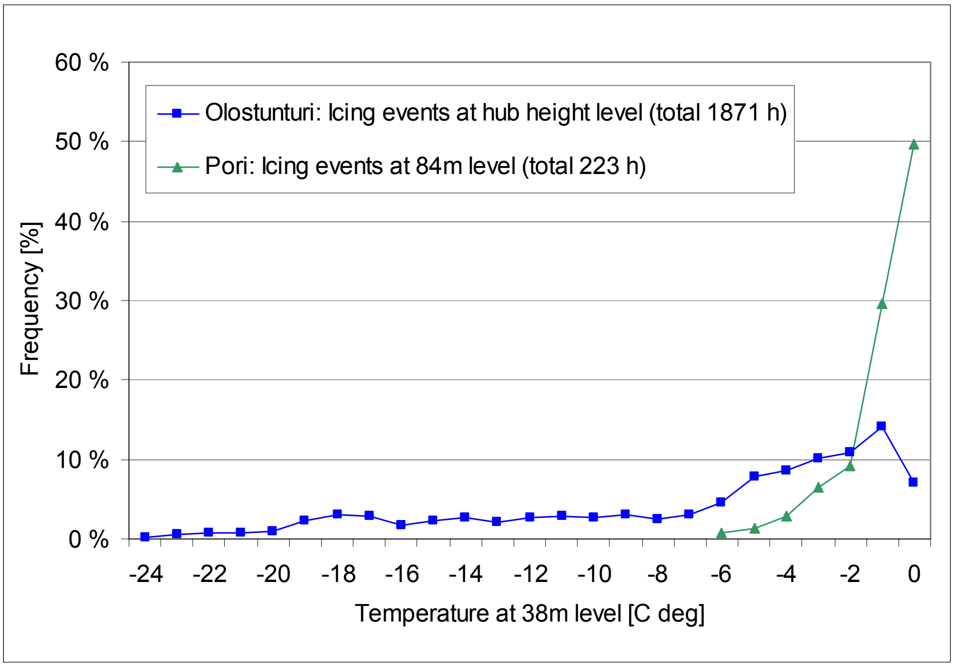

Figure 3. Temperatures during icing events. Two different sites in Finland with annual mean temperatures of 0.3 °C (Olos) and 7.1 °C (Pori).

3.1 MEASUREMENTS

Proper measurement of climatic and icing conditions in extreme climates is not as simple as purchasing the right sensor. Before any sensor can be connected to a data acquisition system one has to find a suitable set of cables, connectors and cable ties. In extreme cases simply using weather and UV-resistant equipment is not sufficient, everything must also be specified for low temperature usage. Currently, modern sensors, such as ultra-sonic anemometers and data acquisition networks can be connected via fibre optical cables. However, fibre cables for cold climate operation need to be adopted for such use by, for example, using non-freezing gel that is pumped into conduits surrounding the interior cables to prevent water ingress and subsequent ice formation. One such example is described in ref [17]. The gel will also protect a cable against breaking if exposed to unforeseen external loads by a maintenance crews, or reindeers; and the movement when cable attachments are deteriorating. Cable attachments will occasionally break and standard weather resistant cable ties are not sufficient in cold climates. Generally weather resistant Nylon 12 cable ties should be used in cold climate and/or high moisture conditions. . A similar reasoning can be applied to connectors.

Instruments for cold climate measurements, including humidity, temperature, wind speed, wind direction, precipitation and radiation, have to be properly heated under icing conditions to maintain their accuracy (Fig. 3). Instruments, more or less suitable for cold climate measurements, are continuously being developed and evaluated by manufacturers and users [11]. Depending on the required accuracy and in standard conditions, the exact location of an instrument might be required to adhere to IEA recommended practices or standards, which ensure proper mounting including sufficient distances to surrounding objects. IEA recommended practices are not available for icing conditions, one is typically recommended to stay away from such events, like ice storms, which is one reason for the creation of this IEA Annex.

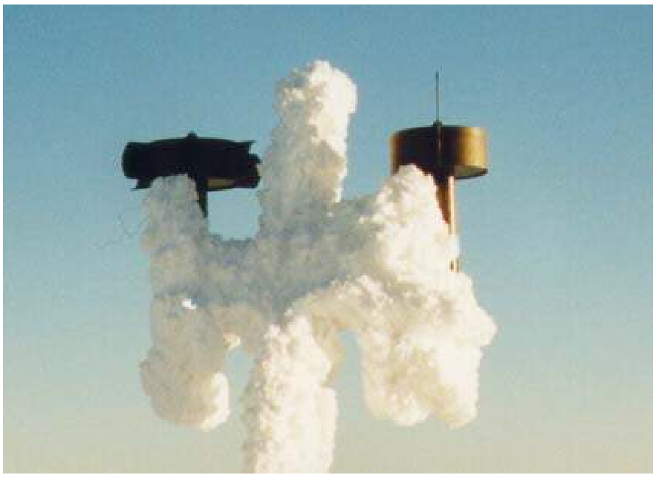

Figure 4. Ice free anemometer in severe icing conditions.(Photo, VTT)

3.1.1 Wind conditions

In the field of wind energy a properly acquired wind speed is of outmost importance. There are three basic categories of needed accuracy when measuring wind speed in flat terrain. In resource estimation accuracy requirements are around ± 5%, the accuracy level of European Wind Atlas [42]. Standard IEC 61400-1 gives an accuracy requirement for anemometer used in power performance testing of ±2% [34]. For wind turbine control a lower anemometer accuracy is needed, commonly±3% however an even lower accuracy level may be acceptable. [51-53]. Many different types of anemometers are available with wide degrees of accuracy, down to below 2% for calibrated anemometers. Specific requirements are defined for different conditions by several national and international standard.

In addition, accurate wind speed measurements in complex terrain have other difficult and do not need the uncertainty introduced by improperly heated or mounted wind velocity sensors.

Up until this point not much attention has been paid to icing of the wind gauges in the wind energy sector even though anemometers and vanes are very sensitive to icing. This is surprising given the importance of wind speed measurement in siting and system control. Tests have repeatedly shown that a small amount of ice reduces measured wind speed significantly and large ice accretions may stop the anemometer entirely. For example, a small amount of rime ice on the cups and shaft of an anemometer may lead to underestimation in wind speed of about 30 % at wind speed of 10 m/s. The level of underestimation depends on severity of icing conditions. [Refs. 23-26]. This decrease is more insidious as, without other monitoring equipment, there is no way to determine if a given anemometer is reading an accurate wind measurement. This may lead to an underestimation of the wind speed or the failure of a turbine to shut down in a high wind event.

Although many different ice mitigation methods have been investigated, the most common solution for accurate measurement in icing climate is the use of a heated anemometers and wind vanes. Instruments suitable for cold and icing climate are available and new devices are actively being developed and evaluated by manufacturers and users [11].

Access to an electricity grid is generally required in order to heat the sensors, which need to be properly heated to maintain their accuracy; solar panels will not suffice as power requirements up to 1500 W are needed. Where no electricity grid is available, alternative measurement setups should be considered. One such alternative is the use of propeller type anemometers. The Swiss Federal Institute for Snow and Avalanche Research has been employing propeller type anemometers in the Jura mountains with good experience. In severe icing conditions and temperatures below 0°C with high humidity their propeller type anemometers have provided reasonable data more than 98% of the time.

Icing and high winds also cause higher loads on masts and measurement booms. In these regions wind measurements are often performed at lower levels, 30 m instead of 50 m for example. As a result, it may be difficult to extrapolate measurement results to the hub height of a future wind turbine. If electricity grid access is available SODARs suitable for harsh climates may become an option. Experience with SODAR units in Switzerland have demonstrated that the technology may be used in harsh climates, but careful oversight of the equipment is necessary and it should it is likely not applicable for long term measurement programs.

If cup or propeller type anemometers are used, the anemometer's cup shaft and post should be heated in order to prevent ice from accumulating and impacting measurement quality.

Attention must be paid also to the positioning of the anemometer and wind vane in icing conditions. In severe icing conditions the accuracy gained through heating is quickly lost if neighbouring objects such as booms and masts are allowed to collect ice. Therefore surrounding objects need to be heated as well. When used for wind turbine control, considerations may also be needed to the change in wake and turbulence on top of nacelle under different icing conditions even if a heated anemometer is used.

References 19 and 31 provide reviews of anemometers suitable for the use in icing climates. As part of the “Wind Energy Production in Cold Climate” (WECO) project, funded in part by the European Union, several research institutions are currently conducting operational tests on a number of anemometers and wind measurement options for icing climates. As presented by Tammelin et. al. at the BOREAS IV conference [22] the annual market for ice-free sensors only in Europe is estimated to be some 11 million Euro.

3.1.2 Icing conditions

Detection of ice is similarly complex. Traditional ice-detectors used to be extremely unreliable however this technology has improved considerably, as has knowledge about the occurrence and conditions of ice. In addition to improved technology research, commercial organisations are also conducting and sharing extensive research on ice accretion due to temperature, humidity, radiation, wind direction, wind speed and precipitation.

Currently there are several types of ice detectors on the market and are mainly manufactured for aviation and meteorological purposes. [19] Principles of operation of ice detectors, some specific icing sensors and other ad hock approaches that have been used in research projects are presented in this text.

Finnish company Labko Oy has two versions of ice detectors to offer, LID (Labko Ice Detector) 3200 and LID 3500. The working principle of the both models is that a longitudinal wire waves is transmitted into an non magnetic wire with piezoelectric transducers. Solid ice attenuates the signal more than water or other non solid substances. This attenuation can be monitored and used in icing indication [27].

The Instrumar Limited ice sensor IM101 function through measurement of the surface electrical impedance and temperature of a proprietary ceramic probe. This data is combined to sense the surface conditions of the probe. A default icing window is programmed into each device and when the parameters fall within this window, an "icing" signal is triggered. The IM101 has an internal solid state switch that is closed when icing is detected and remains closed for a set period of time. This closure may be used to turn on/off low power devices directly, or as input to a controller. It can be used for controlling devices such as alarms, event recorders, or heaters. [28]

Goodrich Deicing Systems offer the Model 0871LH1 ice detector. The sensor works on the principle of magnetostriction. A detection probe vibrates ultrasonically at a resonant frequency of 40 kHz. The mass of the ice collecting on the probe causes the resonant frequency to decrease. A frequency decrease equivalent to 0.508 mm (0.020 inch) of ice thickness triggers an ice signal for a 60-second duration. At the same time, the detector undergoes a self-deicing cycle that removes the ice from the probe. Another icing event detected within that 60 seconds resets the timer to zero and the ice signal remains activated for an additional 60 seconds [39].

One interesting possibility is the use of dew point detector, which is designed to operate in below zero temperatures, as an ice detector i.e. one has to decide a limit for the relative humidity e.g. 97% and assume that when temperature is lower than zero icing occurs. The use such a dew point measurement as an ice detector was studied at the Pori site in Finland [9] and is discussed in greater detail in the paper by Makkonen et al. [29]. One of the main issues identified in the report is more general, there is no absolute reference for calibrating ice detectors because even the most up-to-date ice detectors are not 100% accurate.

For wind turbine applications it is possible to identify icing using one heated and one standard anemometers looking at the difference in wind speed, however a few questions arise. How much slower should the unheated anemometer read compared to the heated one to be interpreted as an icing signal? Is it possible to avoid false alarms caused by wakes on top of wind turbine nacelle by careful placing of the anemometer? When a standard unheated anemometer freezes it may take a long time before the anemometer is ice-free again, ref. [30], which can make determining the actual icing time difficult. This method however enables the estimation of energy losses that a wind turbine would experience at that specific site in icing conditions, especially if unheated anemometers are to be used for turbine control.

In an experiment on measuring icing in Northern Canada two heated and one unheated anemometers were used to measure the actual wind speed, icing time and sublimation time of ice. ref. [33] One of the heated anemometers was kept ice-free and the other was heated after every occasion when the wind speed of that anemometer showed a 15% lower value than the anemometer that was kept ice free. The unheated anemometer was allowed to ice naturally. Results showed that it is possible to estimate the icing time that a wind turbine would experience in an icing climate. It was also demonstrated that one could estimate of actual icing time with this method.

Production power of the wind turbine compared to the presumed production power according to the nacelle anemometer may also provide a guide of icing since a turbine with ice on the blades will produce less compared to the power curve. However it is still unclear what conclusions can be made due to ongoing issues such as how small should the power degradations be and how quickly after the beginning of the icing can such a method be used. In Finland if the turbine is located in a remote site and no visual observations are possible, reduced power production is often interpreted as an “anemometer error” when the cause of such error is icing.

Automatic visibility sensors may also be used as an ice detector however the entire instrument especially the lenses, must be heated in low temperatures and icing climate to ensure appropriate operation of the device.

3.1.3 Measurement of other meteorological parameters

It is known that temperature measurements are impacted by their surroundings, vegetation and design of the radiation shield. The performance of thermometers in icing conditions has also been studied extensively. Results of those studies have shown that errors of several degrees are possible when thermometers not designed for icing conditions are used in icing climates. An ice layer on a thermometer or on a radiation shield insulates the probe from the surrounding air and causes delays and dampening errors to the temperature measurements. In worst case the closed measurement conditions of the air inside the radiation shield may continue until the ice has melted. [31]

In icing climates the radiation shields for thermocouples should be heated or the instrument protected from being covered in ice. Thermometer itself should be designed for icing and low temperature operation. [31]

Measuring humidity reliably in icing and low temperatures climate is also a nontrivial task. Humidity sensors and dew point detectors should be placed with the same carefulness as temperature sensors. As described above the improper use of the radiation shield could impact the temperature measurement, in which the calculation of dew point is based. Standard hygrometers designed for temperatures over 0°C will give unreliable results at low temperatures. [31]

Instruments for cold climate measurements, including humidity, temperature, wind speed, wind direction, precipitation and radiation, have to be properly designed and heated under icing conditions to maintain their accuracy (Fig. 4). Instruments that are suitable for cold climate measurements are continuously being developed and evaluated by manufacturers and users [11].

3.2 MODELLING

Models for predicting local weather events including wind and icing estimates are being developed and improved continuously. The major factor limiting the progress of modelling is the calculation capacity of computers, which is too low to enable accurate weather predictions in a reasonable time. Commercial computer programs and models for calculating ice induced loads are available. Models for calculating shapes and masses of ice build up and blade heating demand in certain icing conditions have also been developed for wind turbines. Before wind turbine icing research took hold the aerospace industry had developed computer programs that model leading edge icing of aircraft wings. In the late 1970's power companies also developed models to calculate ice loads on electricity grids in severe icing conditions. Two models, TURBICE and LEWICE, that are used in calculating ice masses and blade heating demands in different icing conditions are described in this section. In addition, the basis of methods that are used to calculate different types of icing from standard meteorological observations is presented.

Of the various models that have been developed, two basic categories, physical and empirical, have been distinguished based on the different standpoints, backgrounds and the different physical properties of different icing phenomenon.

3.2.1 Physical Models

Physical icing and meteorological models are quite detailed and require specific definition of meteorological parameters including the water content of the air, droplet size, wind speeds, and temperature. When modelling the ice accretion on wind turbine blade or power line, one has to also know accurately the shape and size of the object under consideration. Detailed models are computationally demanding and have therefore been improved together with the technological improvements of computers.

As a separate category, full physical meteorological models can also be used to predict icing events. For instance meso-scale models (MM5, MC2 and others) have the physical basis to be extended to determine icing events. These models, generally used in regional weather prediction, can be used to predict upcoming icing events or to provide a general prediction of the likelihood of such events for specific projects under consideration.

3.2.2 Empirical/Statistical Models

Empirical and statistical models are based on historical data. Icing rate caused by in-cloud icing at a certain site may be quantified first by data from the nearest meteorological station. With cloud height, cloud cover and temperature data together with site elevation it is possible to estimate the frequency of icing that site is likely to experience.

Knowledge of icing events has increased and more meteorological and topographical parameters have been added to the empirical models. Parameters such as temperature (air, object, wet-bulb and dew point), wind direction, wind speed, cloud height, cloud cover, the humidity profile, precipitation, regional topography, local topography, object size, shape and material composite and solar radiation have been added to more sophisticated models. The outcome has been that these models can now also provide information about the amount and rate of icing instead of just the frequency of icing events.

3.2.3 Icing Types and Description of Calculation Methods

In-cloud icing is considered to occur if the height of cloud base is less than the site elevation and the temperature at the site is below zero.

Empirical and statistical models have been modified because accurate cloud base observations are made at mainly airports. Modelling results can be improved, by using statistical relation between weather situations and cloud position (cloud base height and horizontal location/extent). By using statistical values of droplet size, wind speed, direction, and object size and shape, the amount of icing can be calculated. The mass of a accumulated ice accretion may also be estimated with this method.

Calculations using full physical models with meteorological and topographical parameters, particle size, concentration, momentum, heat balance and object shape change may provide more accurate results depending on the accuracy of the initial parameters. Full scale physical models require large calculation capacities.

Freezing precipitation occurs when it is raining and wet-bulb temperature lies below zero.

Empirical and statistical models calculate icing frequency and amount from precipitation intensity, duration, wind speed, mean air temperature, object size, shape and an empirical correction factor.

As with in-could icing calculations using full physical models it is possible to model freezing precipitation with the same input data described above. This method also has the same drawbacks, they are computationally intensive.

Frost occurs when the surface temperature of an object drops below the frost or dew point temperature due to radiation heat transfer. The amount and type of frost are given as an equation of temperature ratios, empiric correction factor and humidity.

Wet snow and sleet is formed from dry snow when at lower elevations there is a strong enough positive heat flux from the environment to melt the surface of dry snowflakes. [43]

3.2.4 Icing rate

The rate of icing is dependent on the flux of particles (concentration times velocity) in the projection area of an object with respect to the wind direction. Due to the different size and therefore different inertia of particles, some of them will collide with an object while other smaller ones, which have less inertia, follow the air stream and pass the object. Some particles also bounce when colliding with an object and thus will not increase the total ice mass. Also depending on the heat flux form the surface to the surroundings, colliding particles freeze at their impact spot, rime ice, or form a thin water film on the surface of an object, glaze ice. Different icing process also leads to different density of ice formation. In general, due to its complexity and the many process parameters a physical icing model that would apply to all icing processes still needs to be developed. Physical descriptions, including heat transfer, of different icing processes are presented in detail in ref. [44-49].

3.2.5 TURBICE and LEWICE

Small amounts of ice on wind turbine blades deteriorate their aerodynamic performance and thus dramatically reduce the power generated by the turbine. Furthermore, large ice accretions may cause turbine vibrations and structural failure. Ice pieces are also hazardous when they shed off the turbine blades with high velocity.

As introduced previously, two software models have been developed that can be used to analyse ice formation, TURBICE and LEWICE.

TURBICE

This numerical model simulates ice accretion, amount and ice shapes on wind turbine blades. It has been under development at the Technical Research Centre of Finland (VTT) since 1991.

The model accretes ice on a two-dimensional airfoil section in a potential flow field directed perpendicular to the airfoil axis. The numerical solution for the potential flow follows the commonly used "panel" method. Droplet trajectories are integrated from the steady-state equation of motion, using droplet drag coefficients of Langmuir and

Blodgett (1946) and Beard and Pruppacher (1969). The integration begins ten chord lengths upstream of the airfoil section, and is carried out using a fifth-order Runge-Kutta scheme with an adaptive step-size control. The impact point is determined by linear interpolation between the 600 coordinate points, which define the airfoil section.

The model simulates both rime and glaze icing. All angles of attack experienced by a wind turbine blade may also be calculated. The model can also simulate icing when the blade is heated.

TURBICE simulations have been compared and verified with data from icing wind tunnel experiments for aircraft wind sections and from a field study of natural wind turbine icing. Simulations have shown good agreement with actual data. [54]

In the development of the blade heating technology TURBICE simulations have been utilised in the determination of the impingement area of water droplets on blade surface and in determination of blade heating power needed in different icing conditions. Results have enabled the optimisation of the necessary heating power and has been utilised in the positioning of a blade-heating element.

LEWICE

Another software that can be used for ice accretion and heating demand is Lewice 2.0. Lewice [40] was developed by the icing branch at the NASA Glenn Research Center in Cleveland, Ohio. It is an ice accretion prediction code that applies a time stepping procedure to calculate the shape of an ice accretion. Lewice does not predict the degradation in aerodynamic performances due to icing rather it evaluates the thermodynamics of the freezing process that occurs when supercooled droplets impinge on a body. Its primary use is for evaluating icing on aircraft but has been adapted to work on other applications.

The particle trajectories and impingement points on the body are calculated from a potential flow solution that is produced by the Douglas Hess-Smith 2-D panel code included in Lewice. Alternately and if specified, the flow solution can be obtained from a grid generator and grid-based flow solver or read in as a solution file from this flow solver. Notwithstanding the method used, the flow solution determines the distribution of liquid water impinging on the body, which then serves as input to the icing thermodynamic code. The ice growth rate on the surface body is calculated from the icing model that was first developed by Messinger [40, 41]. This is an iterative process by which an ice thickness is added to a body through the ice growth rate. This procedure is repeated for a specific time duration.

Lewice can model both dry and wet (glaze) ice growth. In addition to simulating the ice accretion, Lewice 2.0 incorporates a thermal anti-icing function. It works in conjunction with the ice accretion routine and calculates the power density required to prevent the formation of ice on the body. Two anti-icing modes are possible: running wet and evaporative. They will be further defined later in the text. The heat source for the anti-icing capability can be specified as being electrothermal or hot air.

In the current application, Lewice is used primarily to obtain anti-icing values. It can also generate data about droplet trajectories, collection efficiencies, impingement limits, energy and mass balances, ice accretion shape and thickness. Since potential flow cannot model stall or post-stall behaviour, the calculations are valid for unstalled rotor regions only.

3.3 MAPS

An icing map of Europe has been developed in order to estimate the areas in which icing may endanger wind energy production. First versions of the European Icing Map and Frost map were produced in WECO EU project [19,20,50], presented in Figure 5.

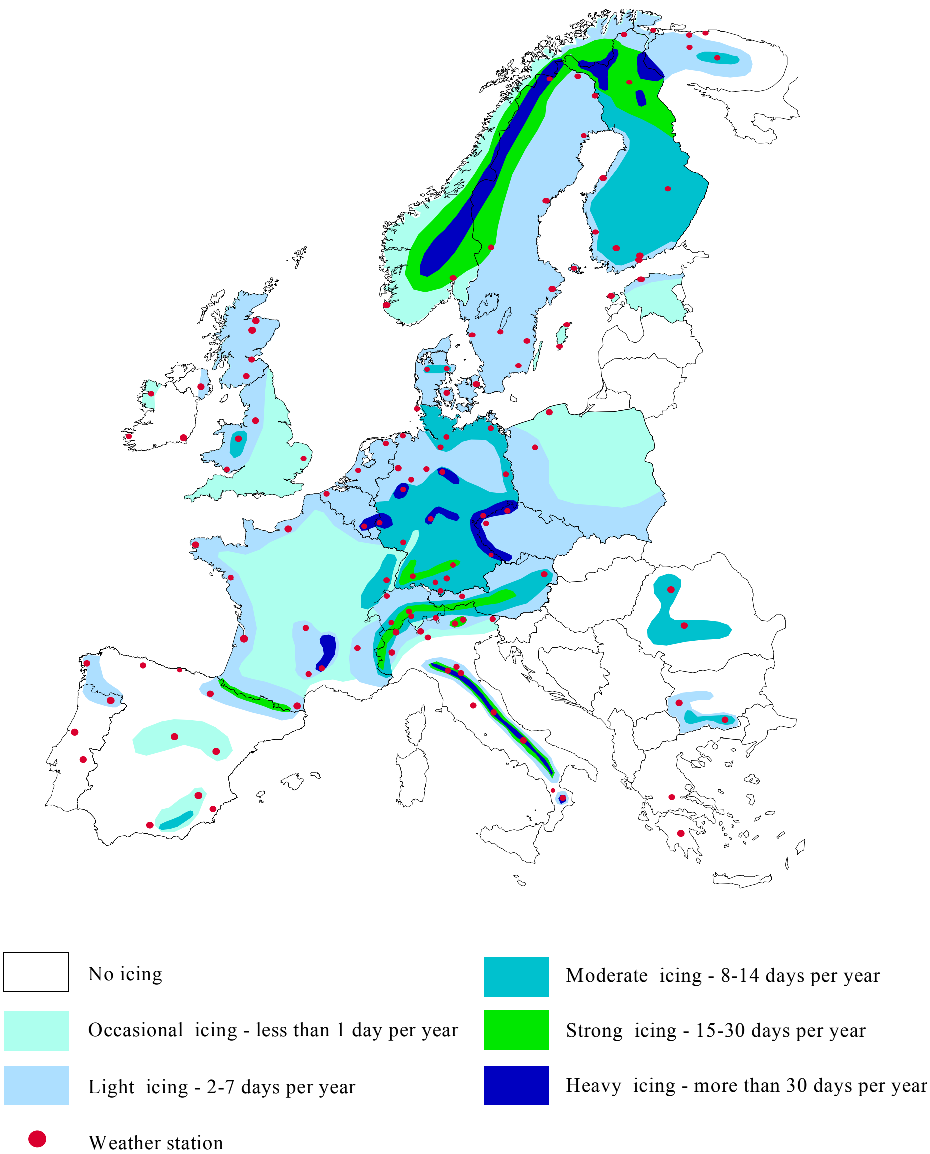

Figure 5. Icing map of Europe. [19]

An updated versions of the European Icing Map are currently under development in the framework of the EU project ICETOOLS project. However, a tool for estimating the number of icing days and icing intensity at a given site is still missing.

Due to the local topography, variations in icing severity and intensity may vary greatly within short distances and therefore icing maps, such as in Figure 5, cannot be interpreted as exact and must be used in connection with local topographical information and, if possible, with measurement statistics.

A more exact icing map for the British Isles where the effect of terrain has been taken into account is presented in Figure 6. . The icing map was produced by first examining the number of icing days at 0 m, 250 m and 500 m elevations above sea level at nine meteorological measurements stations shown in the figure. Those three levels were interpolated to cover the entire land mass. Local and detailed estimation of the number of icing days was then interpolated and extrapolated by using the previous three levels and digital terrain models. The result is a clear picture of areas were icing could be faced. [50] Due to the local climatic conditions and low number of weather stations used in the production of the map, the actual number of icing days experienced at some site may differ from the amount presented in the map.

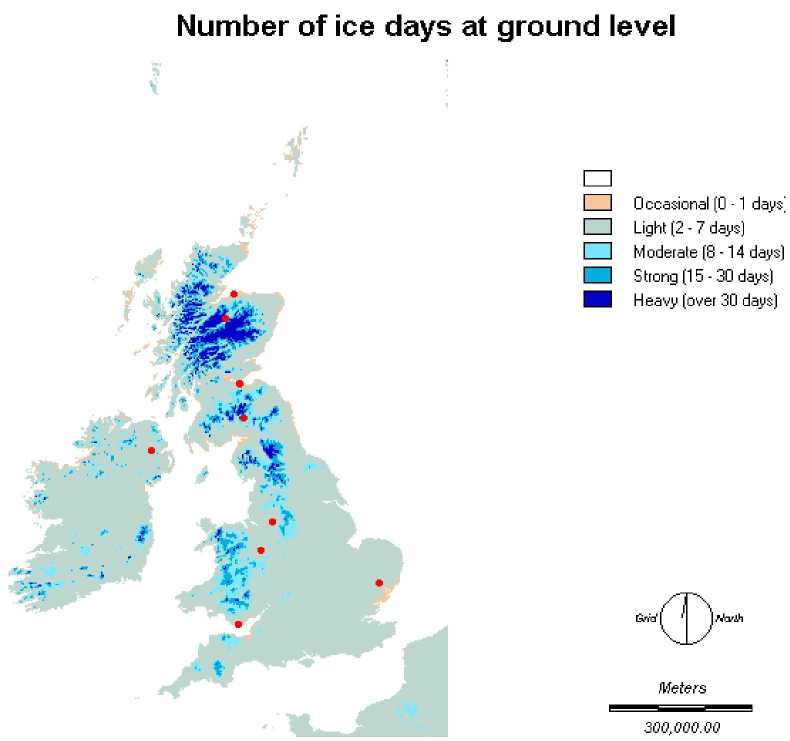

Figure 6. Annual number of in-cloud icing days in the UK and Ireland at ground level and the weather stations used in calculation [50].

Icing map of Switzerland is presented in figure 7. As with all such maps the severity and intensity of icing may vary greatly with short distance and the map in Figure 7 should be interpreted as indicative only.

Map for the average number days with freezing precipitation during a year in Canada is presented in Figure 8.

Similar general maps of this nature are generally available from the weather service agencies of most countries in northern and southern countries.

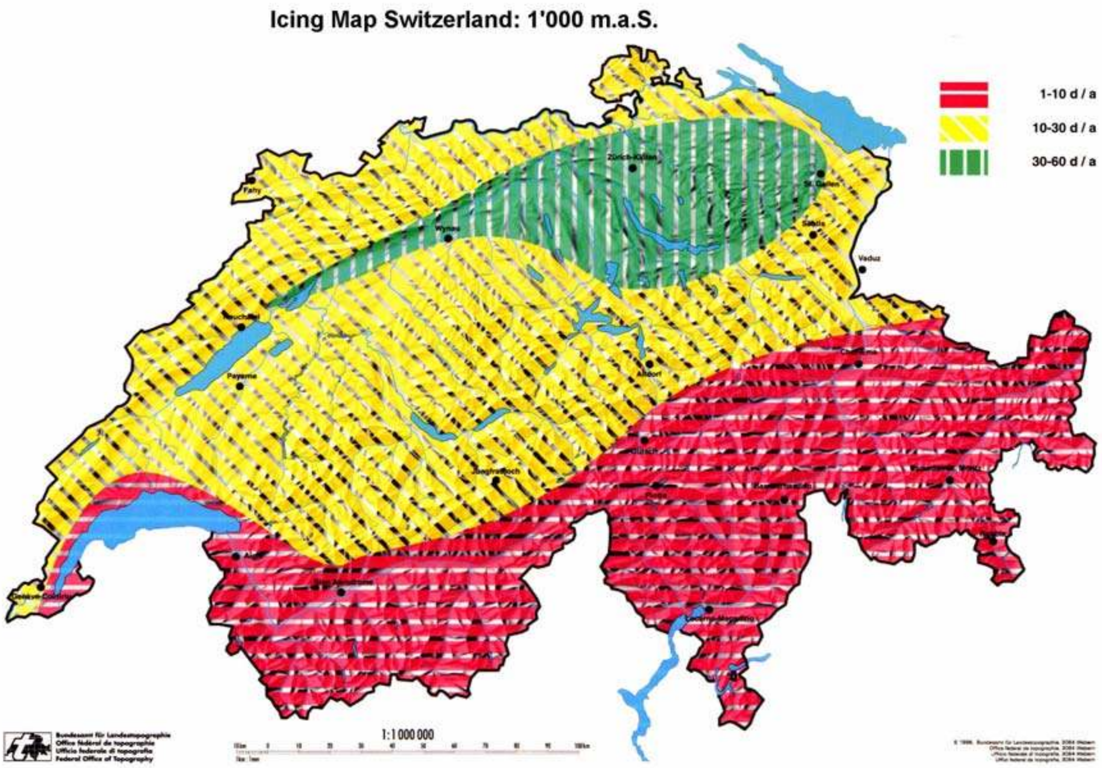

Figure 7. Icing map of Switzerland for 1000 m.a.s.l

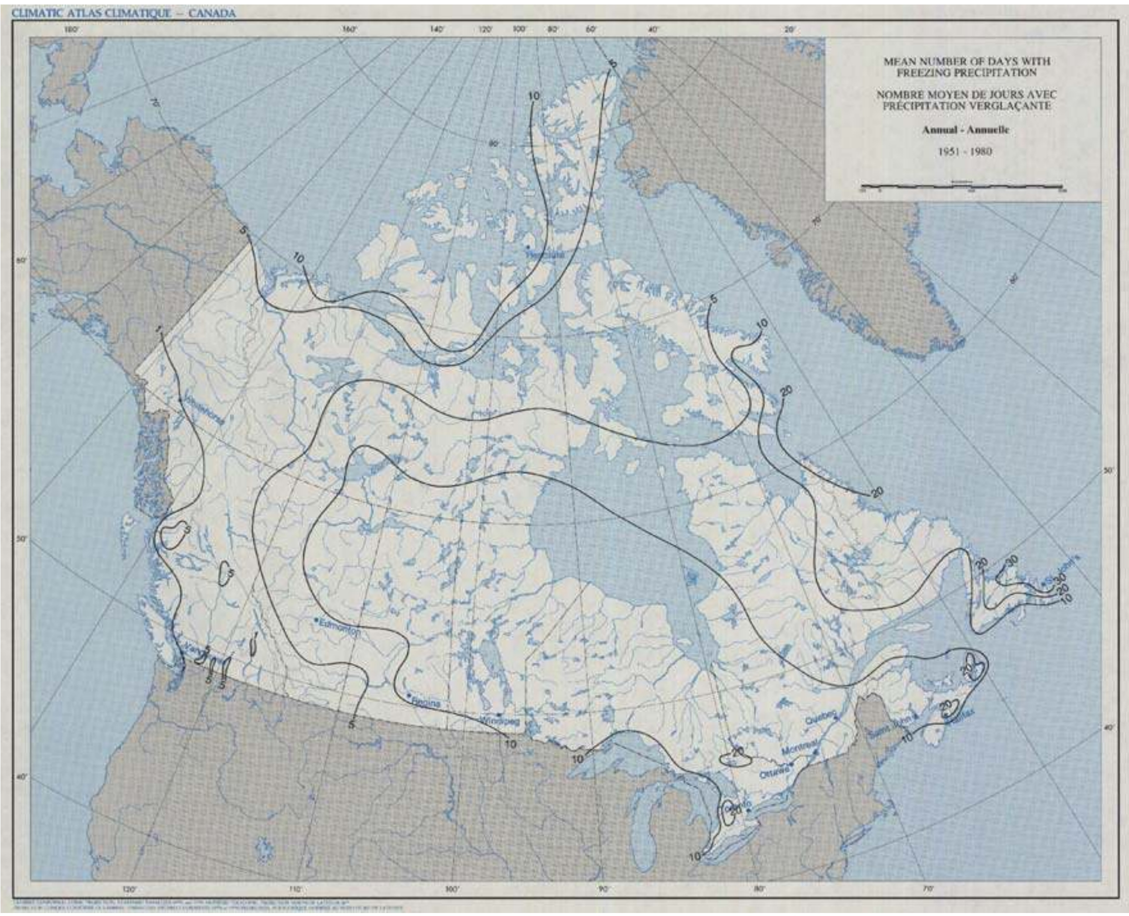

Figure 8. Mean number of days with freezing rain during one year in Canada between 1951-1980. Map from National Archives & Data Management Branch of the Meteorological Service of Canada.

4 TECHNICAL SOLUTIONS IN USE

There are a wide array of solutions that have been used to reduce the impact of cold weather and ice events on wind turbine design and operation. The following section of this document reviews current experience.

4.1 TECHNICAL SOLUTIONS FOR ICING

4.1.1 Sensors/Instruments

A variety of heated wind sensors, as discussed in greater depth earlier in this paper, are available, tested and used at sites where icing is frequent [11].

Currently some manufacturers also use anemometers to indicate weather turbines are functioning correctly. Using the anticipated production power, calculated from the wind speed, compared to actual production power. If the difference is large enough an alarm is given. Also ice-induced vibrations may cause vibration sensor alarms. In both cases turbine are shut down.

4.1.2 Blades

Blade heating may be necessary or profitable at sites that experience frequent icing or have high safety requirements such as proximity to roads. The break-even cost of such a heating system depends on lost energy production due to icing and the price of electricity. Therefore when the financial benefits of a blade heating system are evaluated, icing time, severity of icing and wind resources need to be known. Blade heating system may also be required as a safety precaution in connection to the planning or permission granting process. One of the limitations of blade heating systems is their energy consumption, which can be quite high. A simple approach to estimate the break-even conditions has been developed by Peltola et. al. [12].

A number of different approaches for the blade heating have been presented, developed and tested but current practice indicates that in heavy icing conditions the outer surfaces of the blades need to be heated in order to achieve satisfactory results.

At present there are some commercially available blade heating options available. The Finnish blade heating system, where carbon fibre elements are mounted to the blades near the surface, has the widest operating experience, from 18 turbines at various sites, with a total of nearly 100 operating winters [12].

One low power consumption method for heavy icing environments is the use of pneumatic deicing system that works with the rapid expansion of inflatable membranes within the blades. A similar system has been in use on some small and regional aircrafts for several years. Experience from wind turbines however is lacking.

In sites where icing is slight, infrequent and the icing periods are followed by temperature rising above 0 °C or areas of high winter solar intensity, blades coated with black paint may be sufficient. Stopping the turbine and circulating heated air inside the blades may be adequate in slight icing conditions. A method that uses blower and heater to circulate hot air inside the turbine blade is under the development in Switzerland. First experiences from this method will be available at the spring 2003. This however is likely a valid option in light icing environments. Stopping the wind turbine when icing starts may also be a sufficient solution in such environments. However, this method does require ice detectors.

There have been a number of other proposed solutions, like blade-heating systems based on microwave technology but to date they have not been successfully implemented.

Turbine Safety

Turbines, with or without blade heating systems, pose a risk in the form of thrown ice. Irrespective of whether the turbines are equipped with blade heating systems, warning signs should be used. Signs should be located at least 150m from turbine in all directions. Reference 19 provides a method to estimate the risk that results from ice fragments that are thrown off a wind turbine. An example of a warning sign is shown in Figure 9.

Figure 9. Warning against shedding ice fragments at Tauernwindpark in Austria. Photo from http://www.tauernwind.com.

4.1.3 Other components

Turbines that are modified for severe icing climate must also cope with snow and the freezing of moisture in the gearbox, yaw system or other components. Without properly sealing the nacelle, it may fill with drifting snow as has been experienced in Lapland and the Alps. Gearboxes and yaw systems need to be heated and kept free of ice, as do any disk breaks or separators.

4.2 TECHNICAL SOLUTIONS FOR COLD CLIMATES

Little specific information is available about material properties and lubricants for cold climates in specific relation to their application in wind energy systems. Most available information comes in the form of reports citing field experiences from projects in cold climates. There are however some common areas of concern that are expressed repeatedly in the area of turbine materials and lubricants.

Most turbine manufactures offer products or upgrades to products for cold environments. All information indicates that the use of these upgrades is required for successful unit operation in these climates.

4.2.1 Materials and lubricants

The use of cold resistant steel in all structural members with welds does not increase the costs significantly. Standard hot-dip galvanized bolts have proven adequate in low temperatures [15].

Recent testing at the National Wind Technology Centre, USA, has looked at the cyclic loading of wind turbine blade root studs at ambient and extreme cold temperatures, -45° to -51° C (-50° to -60° F). Testing considered 4140 steel root studs, a Vinyl Ester / E-glass laminate with an epoxy annulus to pot the root stud inserts into the fibreglass. In the limited tests "all of the cold temperature samples tested exceeded the life of the room temperature control group, though none of the cold temperature samples exhibited any evidence of superior construction over the room temperature samples" [16]. These tests, one of the few being conducted specifically to look at issues related to wind turbine construction, show that operation in cold temperatures do not always result in damage, but may actually improve the performance of the system.

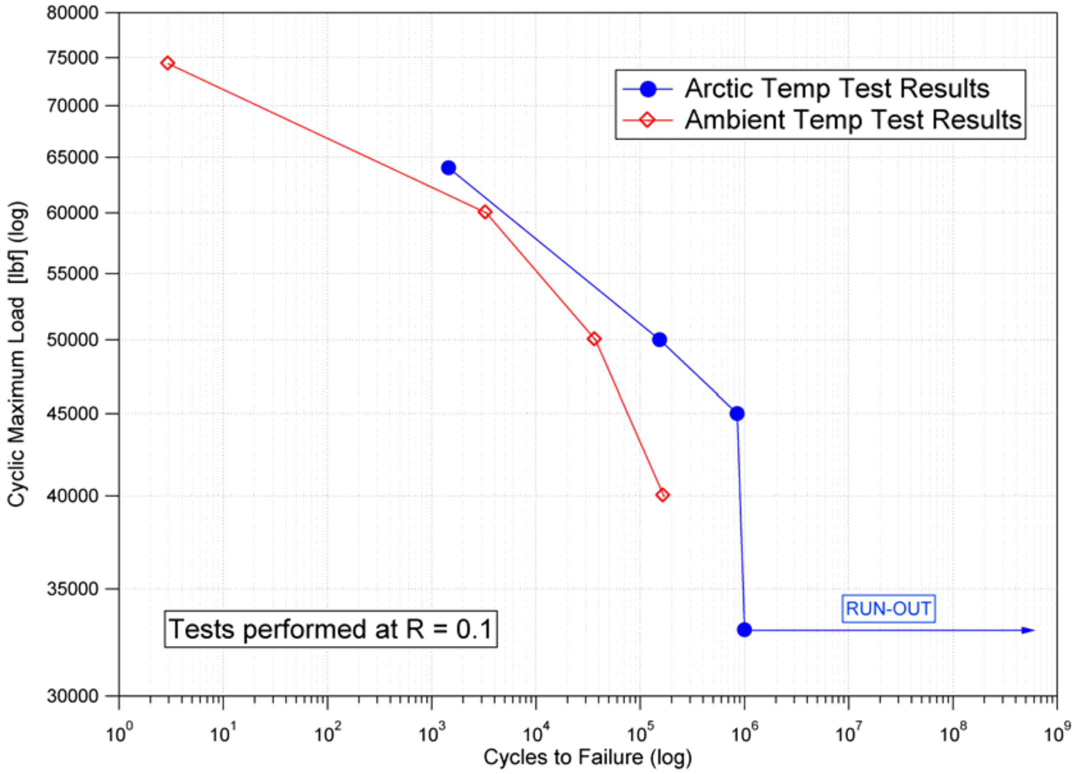

Figure 10. Cyclic fatigue pull tests on blade studs conducted at NREL comparing studs at standard(20°C) and arctic(-48°C) temperatures.

Lubrication: In the area of lubrication and hydraulic oils, similar practical work has been conducted though few scientifically based reports are available. In all cases synthetic lubricants that are rated for cold temperatures should be used. All manufactures recommend specific lubricants based on their particular turbine design. In most cases these lubricants have been tested but the operator is encouraged to obtain specific certifications prior to their use.

4.2.2 Heating of components

At the present moment surface heated gearboxes and gearboxes with immersed heaters with constant oil circulation, generator heaters and also heaters for the cabins containing control electronics are used to avoid cold related problems. [15,32]. Especially important is the protection of control electronics against moisture and condensation at sites where low temperatures during the winter is frequent.

4.3 OPERATIONAL SOLUTIONS FOR COLD CLIMATES

Wind turbine manufacturers recommend that, even the turbines that are equipped with cold weather package should be stopped at temperatures below -30°C. At some sites this would lead to significant amount of annual energy loss. Possible solution might be to allow the turbine to operate at partial load where the stresses would stay below the design limit.

An additional concern with the operation of wind turbines in cold climates is that low temperature air masses have a much higher air density. This can overpower wind turbine generators and has been known to brake gearboxes or turbine main shafts. Measuring temperature and disabling the wind turbines during extreme low temperatures have been used to reduce the chance of such failures.

4.4 O&M CONSTRAINTS

Turbines may locate at remote sites and the access to the sites may be difficult or even impossible part of the winter. It is possible that the access to site may be limited to motor sledge and light repair instruments. It is therefore outmost important that basic tools that enable light repairs such as wrenches, hammers, power drills etc. are kept at site. Also working conditions due to humidity, high wind speed, snowing or icing may prevent maintenance during wintertime. Basic operation and maintenance should also include the maintenance of cold climate modifications.

5 OPERATIONAL EXPERIENCE

5.1 OPERATIONAL EXPERIENCE IN ICING CONDITIONS

Icing of the blades causes production losses for wind turbines. This is the case even with slight icing as the aerodynamic properties of the blade are sensitive to minor changes in the blade profile and roughness. Heavy icing can result in a total stop of the turbine. The duration of ice on the blades can be considerably longer than the time of icing conditions. Downtimes of several weeks with a single icing incident have been reported in Southern Germany.

On the other hand, glaze ice accretion has been shown to cause overproduction due to delayed stall on passive pitch controlled wind turbines [57]. In most cases this will be detected by the wind turbine controller resulting in a turbine shutdown. Any operation over rated power causes additional damage to the components and will result in a shorter life of the generators, bearing and gear boxes.

The structural loads of a turbine may increase significantly due to icing of the blades, due to either aerodynamic and mass induced forces. In addition, ice usually sheds from the blades unevenly resulting in further loading on the turbine [10] due to the mass imbalance, especially if it is allowed to operate. These forces result in two basic load types; extreme loads and fatigue loads, depending on the turbines structural design and the icing event. A properly designed control system should address issues of extreme loads, irrespective of their origin and since other extreme load causes, such as a single failing blade pitch mechanism, typically result in higher loads, the extreme load cases caused by ice are unlikely to drive turbine design. Fatigue loading is similarly influenced by aerodynamic and mass induced forces. The physical influence of the latter is relatively easy to estimate but the knowledge regarding the frequency of such occurrences is scarce, especially for specific sites. Fatigue loading caused by aerodynamic forces, such as those caused by mere rime ice accretion, are likely to be underestimated by today’s international recommendations. [58]

Ice thrown off the blade may also pose a safety risk even in areas where icing is infrequent, specifically when the turbines are situated close to the public, such as road and skiing resorts.

Ice shedding off the tower or the nacelle can also pose a similar though a more limited risk than ice that sheds of blades. Risk is higher especially for the service personnel. Cases where icing of the yaw gear has resulted in the damage of yawing motor have been recorded in Finland.

Icing also affects wind sensors, both in resource estimation and controlling the turbine. A wind turbine with an iced control anemometer may not start even in strong winds, which results in production losses. Increased loads are caused if a pitch control system is based on information of an iced anemometer. Iced wind vane may lead to operation in misaligned yaw or a production stop due to the misalignment.

5.2 OPERATIONAL EXPERIENCE IN LOW TEMPERATURES

Low temperatures effect on materials and in wind turbines primarily on glass fibre structures, plastics, steel and lubricants. Wrong lubrication oils and greases have been recorded to damage bearings and gearboxes during low temperature operation. Low temperature and condensation have also damaged control electronics.

Standard hydraulic oils become highly viscous at low temperatures. Modification of standard hydraulic system may also not be limited to the specific oil, modification of the tubes, valves and equipment associated with the hydraulic system may also be required. Due to high viscosity of standard oils in low temperatures or different properties of cold temperature oils, turbine start-up may be delayed to higher wind speeds which will impact overall turbine performance.

When going to very low temperatures, the need for cold weather or weather resistant materials extends for both the steel and plastics used in the system fabrication but also wires and other turbine parts not considered in most system impact assessments. Wires for which the insulation becomes brittle may fracture, leading to shorting, has caused many problems in turbines that have been designed for cold climates. Every piece of equipment, even the most trivial, must be assessed for flexibility and usability at extreme temperatures.

Also service and monitoring under difficult conditions has to be taken into account. This may result in increased O&M costs or extended downtime of the turbine.

Another factor that has been identified is the increased system loading due to the high density of cold air masses. It is not uncommon to have (stall controlled) turbines produce over 20% rated capacity due to the air density. Several cases of generator overheating have been reported in Canada and Finland caused by overproduction due to high air density [13]. This leads to production losses and probably has lead to generator failures [14]. Impacts on the gearbox and breaking systems will likewise need to be considered as the higher loading conditions will impact unit life. However, due to the complexity of these systems, specific tests and the impact of cold temperatures on these subsystems have not generally been carried out.

5.3 COUNTRY OPERATIONAL EXPEREANCE

5.3.1 Finland

At Olostunturi, the site described in detailed in section 2.1),in northern Finland standard power performance measurements were carried out for a single turbine and the performance was found to be according to the manufacturers power curve when icing situations were edited out. During the harshest icing periods the performance did not follow the manufacturers power curve. In some extreme icing cases the blade heating power was found to be too low. In addition to that in some cases the run back water on the blade during icing and blade heating was found to freeze after it had passed the heated area of the blade. During the falls and springs the blade heating system was able to keep the performance of the turbine at normal operating levels. The winter of 2000 to 2001 the blade heating system used 43674 kWh, which corresponds to 3.6% of the turbine's annual production in 2000. The used heating energy grew due to the problems with ice detectors, which led to the blade heating equipment receiving more power then was needed. Nevertheless wind energy conversion at sites like Olosturturi without a blade heating systems would be impossible and unprofitable due to turbine down time.

Similar power performance measurements, as at Olostunturi, were carried out at Pori, also described in section 2.1 between 1999 and 2001. In-cloud icing was observed to be seven times as frequent at the 84m level as compared to 62m. This strongly suggests that icing becomes a more important issue to coastal wind parks at sites like Pori when the dimensions of the wind turbines increase. However, the winters during the measurement period were milder than average and icing was only observed occasionally. The blade heating system was used for 10 minutes every night to avoid ice build-ups on blades. Main reason to install a blade heating system to a wind turbine at sites like Pori is for safety of public.

In Pori, lighting frequency is higher than in Northern Finland and lighting strikes to the blade heating elements have been registered although damage to the ice prevention system could not be detected.

Power consumption of the Pori ice prevention system was measured to be 1% of the turbine's annual production. The maximum heating power of the turbines is 6% of the nominal power of the turbines.

Reported down times due to icing and low temperatures in Finland between 1996-2001 are presented in Table 1 and Table 2 respectively.

Table 1. Reported down times due to icing in Finland 1996-2001. [21]

FINLAND	1996		1997		1998		1999		2000		2001	
	Hours	Turbines	Hours	Turbines	Hours	Turbines	Hours	Turbines	Hours	Turbines	Hours	Turbines
Lapland	119	2							159	8	5	1
Åland	12	1	55	5	23	3	49	9	7	3	44	3
Bay of Bothnia	858	4	372	5	98	2	532	7	573	7	4143	15
Sea of Bothnia	219	5	68	4	75	2					38	1
Gulf of Finland												
Total	1208	12	495	14	196	7	581	16	739	18	4230	20
Total number of turbines		19		21		29		38		61		61
Share of the total down time of the turbines that reported icing during the year	45 %		21 %		9 %		12 %		9 %		26 %	

Table 2. Reported down time due to low temperature in Finland 1997-2001. [21]

FINLAND	1997		1998		1999		2000		2001	
	Hours	Turbines	Hours	Turbines	Hours	Turbines	Hours	Turbines	Hours	Turbines
Lapland					450	3	32	1	100	6
Åland			1	1						
Bay of Bothnia	28	1	890	4	2477	8	72	1	706	4
Sea of Bothnia	60	4	397	4	699	4	100	2	1733	7
Gulf of Finland										
Total	88	5	1288	9	3626	15	204	4	2539	17
Total number of turbines		21		29		38		61		61
Share of the operational hours of the turbines that reported low temperatures during the year	0 %		2 %		3 %		1 %		2 %	

Icing retards more wind energy production than low temperatures in Finland (Table 1 and Table 2). There are several reasons for this difference, such as that low temperatures operation was taken into account in the design process of most turbines operating in Finland. In addition, the majority of Finland's wind turbines are located in coastal areas and thus do not often experience very low temperatures. Icing however is recorded regularly throughout the entire country.

5.3.2 Sweden

As part of a national program, monthly operational statistics from most wind turbine owners having obtained investment subsidies have been collected for more than 10 years. Data from 622 wind turbines, totalling 345 MW dispersed nationally, were available by the end of 2002 [55]. More recently, the average capacity of installed units has increased from 867 kW in 2001 to 882 kW in 2002. The total energy production also increased from the 2001 amount of 609 GWA by 23%. Figure 11 shows the location and impact of reported cold climate incident reports during 2000-2002.

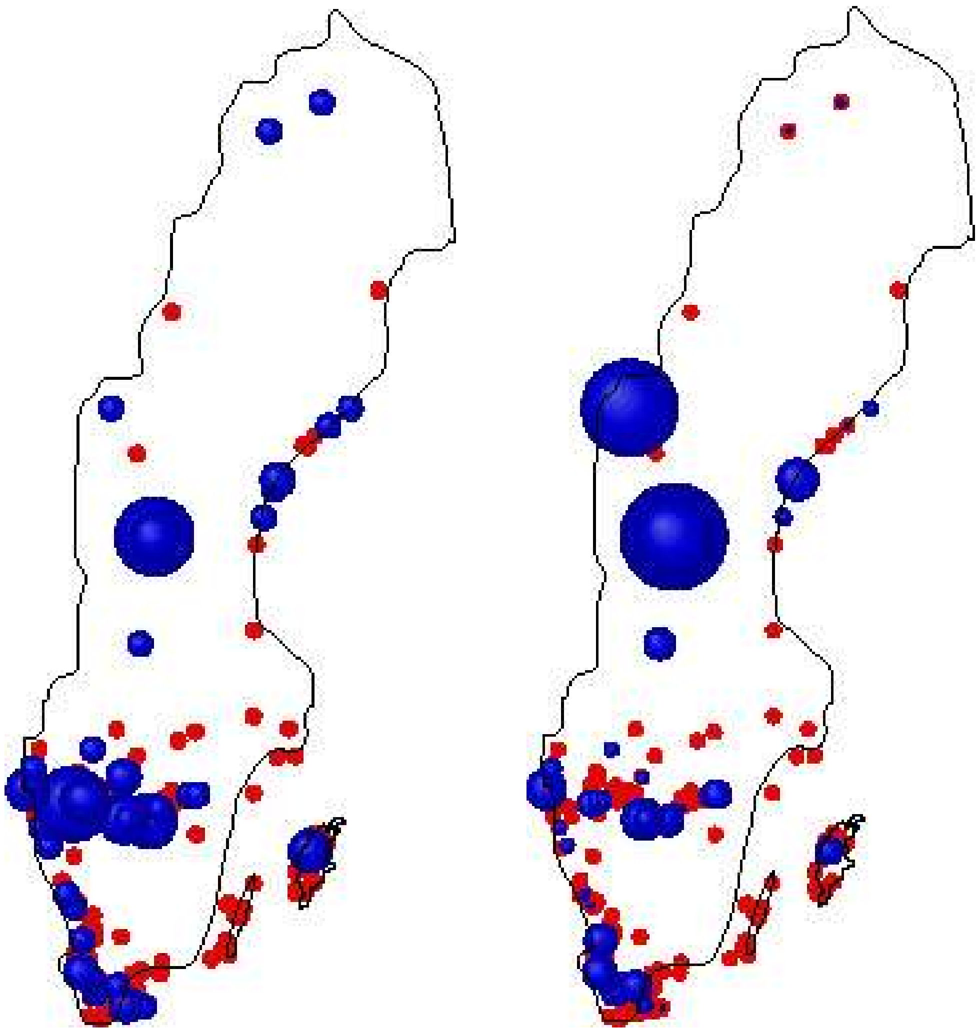

Figure 11. The location of 565 out of at least 622 wind turbines is shown (red). Cold climate reports have been submitted from 47 turbines (blue). Left: Distribution of 92 reported incidents of cold climate type during 2000-2002. Right: Distribution of 8022 reported incident hours of cold climate type during 2000-2002. Size of the circle represents the number of reports and incident hours respectively.

The Swedish statistical incident database contains a total of 1337 records reported to have occurred in between 1998-01-31 to 2002-12-31 resulting in a total downtime of 161,523 hours. 92 incidents (7%) are related to cold climate resulting in 8022 (5%) lost production hours. Of the total for cold climates, the reported low temperature downtime totalled 669 hours (8%) while the equivalent for icing events was 7353 h (92%). The number of unrecorded ice cases can safely be assumed to be overwhelming due to manual reporting in combination with an inherent lack of technology and methods to reliably and automatically detect ice. Automatic energy reporting has been applied in recent years [56] and covers, by end of 2002, 65% of the installed units. It is not clear whether automatic reporting will increase or decrease the willingness of wind turbine operators to submit cold climate incident reports once manual reporting is no longer mandatory.

Data collected through the mandatory reports show that number of incidents of cold climate reporting are increasing, figure 12.

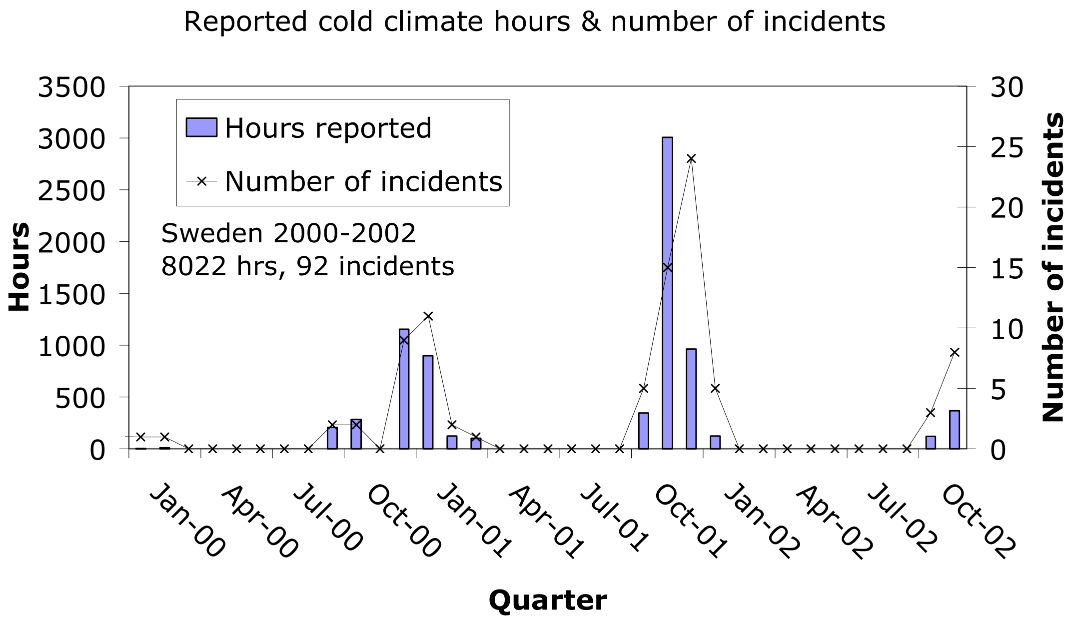

Figure 12. Monthly number of reported cold climate downtime and number of incidents.

An assumed reason for the increasing number of reported cold climate related incidents is the fact that wind turbines were built recently in areas with more extreme cold climate conditions, Figure 13.

The various causes of incidents are shown for ice and low temperature in Figure 14 and Figure 15 respectively.

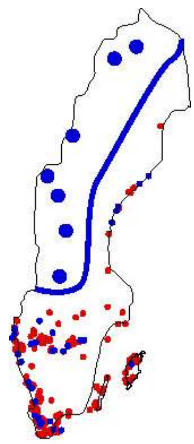

Figure 13. Main cold climate region.

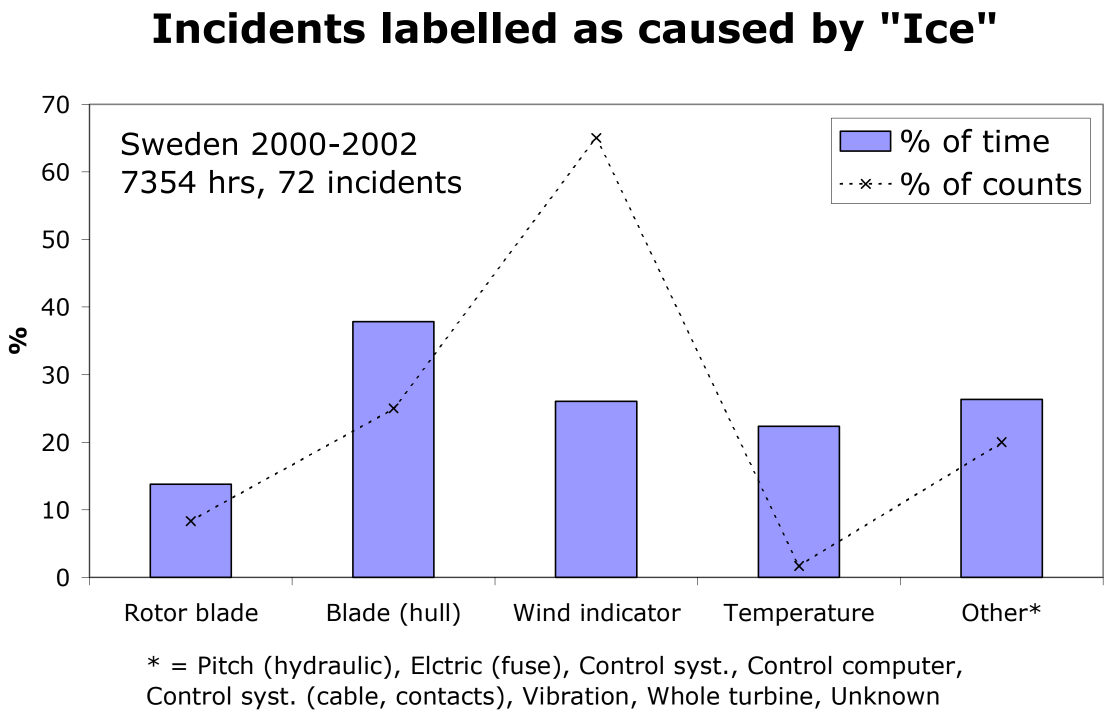

Figure 15. Cause of incidents due to ice.

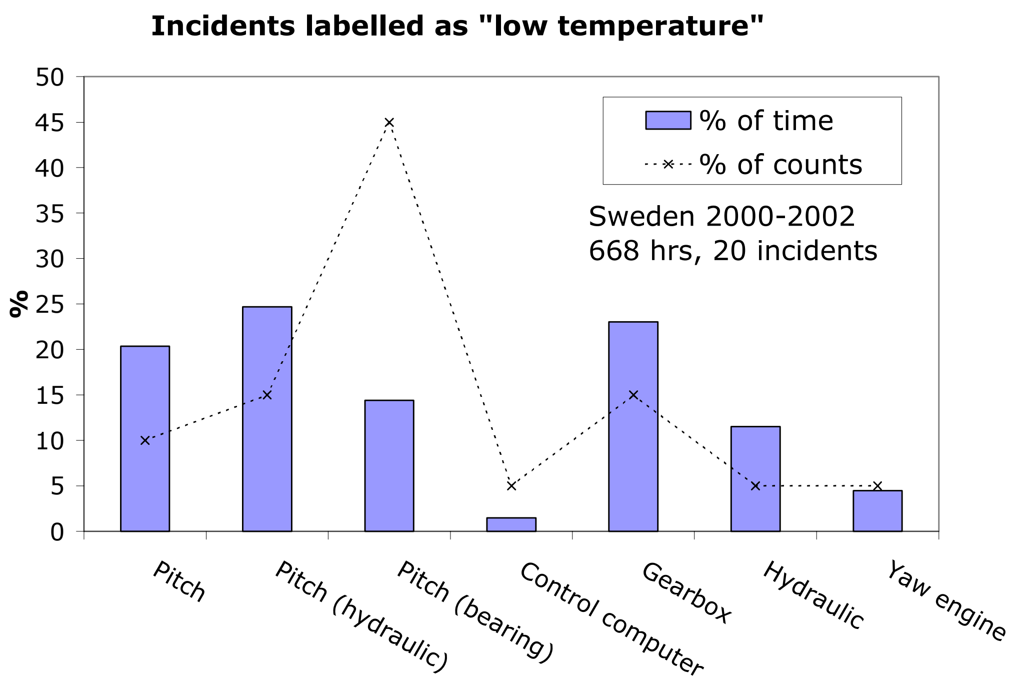

Figure 14. Cause of incidents due to low temperature.

There are 16 (3 with unknown co-ordinates) wind turbines located within the main cold climate region shown above. These are shown in table 3:

Table 3. Wind turbine types within cold climate region

#	Manufacturer	Model	Rated power [kW]	Control
10	NEG Micon	NM 900/52	900/200	stall, 2 speed
1	NEG Micon	NM 750/48	750/200	stall, 2 speed
1	NEG Micon	750kW	750/175	stall, 2 speed
1*	NEG Micon	NM72C/1500	1500/400	active stall, 2 speed
2	Bonus	Mk IV	600/120	stall, 2 speed
1 (2*)	Vestas	V52-850	850	pitch, variable speed
1	Vestas	V66-105	1750	pitch, variable speed
0 (1)	Nordex	600kW	600/125	stall, 2 speed
19 **(Total # of wind turbines)**				

* not included in national statistics

The geographical listing, from south to north, as well as 1st date of operation are shown in Table 4:

Table 4. Geographical listing, from south to north, and 1st date of operation, of present wind turbines within the main cold climate region.

#	Location	Date	Manufacturer	Model
1	Äppelbo	00-12-17	NEG Micon	NM 900/52
0* (1)	Rodovålen 1	98-10-21	Nordex	600 kW
1	Rodovålen 2	98-10-07	Bonus	Mk IV, 600 kW
1	Rodovålen 3	98-10-23	NEG Micon	750 kW
1	Rodovålen	03-01-01	Vestas	V52-850
1	Bydalen	02-09-04	NEG Micon	NM 750/48
1	Gråsjön, Kall	00-11-08	Vestas	V66-105
3	Klimpfjäll	01-01-16	NEG Micon	NM 900/52
1	Suorva	98-10-13	Bonus	Mk IV
6	Viscaria, Kiruna	01-09-18	NEG Micon	NM 900/52
1**	Digerberget	02-01-01	NEG Micon	NM72C/1500
1**	Almåsa, Krokom		?	Vestas V52-850
1**	Vallrun, Krokom		?	Vestas V52-850
19 (Total # of wind turbines)				

* replaced by a V52-850 not yet included in national operational statistics
** turbines not yet included in national operational statistics

Prolonged reduced, as well as absent, wind energy production from wind turbines due to ice have been observed on several occasions. One such example can be detected in the operational statistics from the southernmost wind turbine listed above; Äppelbo. Figure 16 shows the monthly energy production from the Äppelbo turbine divided by the average ditto from two identical wind turbines located in the southern part of the country. The energy output in December 2002 can be seen to hit a record low due to ice. The turbine does not have heated blades.

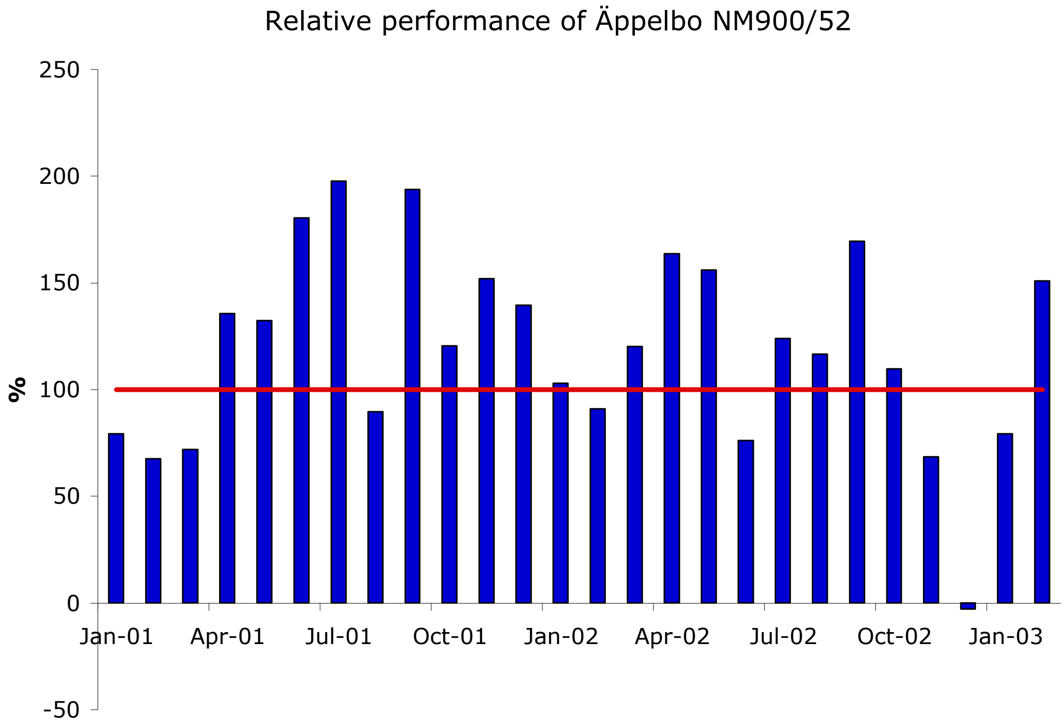

Figure 16. Monthly energy production from the Äppelbo turbine divided by the average ditto from two identical wind turbines located in the southern part of the country.

Access to offshore sites in southern Sweden has been limited during the past winter due to ice, as the cost of an ice-breaking vessel is prohibitive. Figure 17 shows such an example. The wind farm is close but yet so far away.

Figure 17. Access to offshore wind farms in southern Sweden has been limited due to ice.

The past winter, 2002/2003, ice build-ups on wind turbine blades have been reported from Gotland and the northern part of the country. An example of such an occurrence is shown in Figure 18. The wind was calm and production losses were small in this particular case. The risk of being hit by a piece of ice being shed from a starting wind turbine is small but shall not be neglected. The aerodynamic drag of a flying piece of ice need to be included in risk zone calculations, as this rightfully will reduce the size of the affected risk zone.

Figure 18. Ice build-up on a wind turbine blade during winter of 2002/2003.

5.3.3 Norway

Norway has a long shoreline facing the warm waters of the eastern part of the north Atlantic ocean currents. Low pressure systems forming in the polar jet stream areas over the warm Atlantic waters move eastward and ensure high wind speeds and a mild climate along the Norwegian coast. Well exposed Islands and ridges along the coast are well suited for wind energy. Compared to other areas in the world at the same latitude, the temperatures in wintertime are relatively high. At North Cape (71º), -4ºC is the lowest monthly average temperature at sea level.

Norway does not have a centralized system for collection of operational experience from wind farms. Numbers for downtime due to icing or low temperature are therefore not available.

So far 2003, 97 MW of wind power, have been located at low altitudes. The latest wind farm Havøygavlen is located at Latitude 71º and 275 m above sea level. Even though it is the northern most wind farm in the world, the site is not considered arctic. The average winter (January) temperature is about -6 ºC. The wind farm was installed autumn 2002, and little operational experience exists. According to the operator, very little icing has been reported so far. Only some minor problems with batteries and oil possibly due to low temperature have been reported.

Nord-Trøndelag Elektrisitetsverk has experience with operation of wind turbines since 1990. Their wind turbines are located in the middle of Norway, around latitude 65º. One Vestas V66 has been installed at 230 m above sea level, and a small wind farm is located at about 130 m above sea level. Since the installation of the wind turbines there has been no icing that would have resulted in operational interruption. After some years of usage the turbines were equipped with heating of the hydraulic oil to prevent problems related to restart in low temperatures.

Kvalheim Kraft owns a wind farm consisting of 5 Vestas 850 kW. They are located at Latitude 62º and about 410 m above sea level. The only arctic adaptation made is the use of heated sonic anemometers. Similar to the turbines at Havøygavlen, they have no arctic adjustments. No serious problems with low temperatures or icing have been experienced so far. Icing has been reported occasionally at the time of stand still of the turbines. It has been possible to start turbines with blades covered with ice by forced manual start. After the forced start ice has shed from the blades.

5.3.4 Switzerland

Switzerland has long experience of with wind energy site assessments in alpine areas. Such sites experience harsh climatic conditions such as low temperatures, high turbulence and extreme gusts.

In Switzerland several wind energy projects have been carried out in icing and in low temperature climate. Wind turbines that experience icing and low temperatures locate at high altitudes. Altitudes range from 1300 metre to 3000 metre above the sea level. Typically sites below 2000 metre above sea level experience light icing and sites with higher altitude are prone to heavy icing and low temperatures. Important experience on the use of wind energy under climatically extreme conditions will be gained, with the 800 kW plant on the Guetsch near Andermatt (2300 m above sea-level) which was commissioned in spring 2002. This is the first wind turbine in Switzerland that uses adapted technology because of icing and low temperatures. Further projects such as St.Moritz (2200 m above sea-level) as well as Crêt Meuron (1300 m above sea-level), will increase the knowledge about wind energy production in alpine region in harsh climatic conditions.

5.3.5 USA

Operational experience of wind turbines in cold and icing climates is limited and the private, unsubsidised nature of most installations make collecting data on system downtime difficult.

As stated previously wind turbines have being installed in three general climatic regimes effected by cold weather. In the north central region, such as the 200 MW wind plants in the Lake Benton, Minnesota area, snowfall and cold temperatures are common but turbine icing is uncommon due to the low humidity. Operators in these regions have not reported down time due to either cold temperatures or icing events. In the north-east and north west parts of the US, such as the 6 MW plant in Searsburg, Vermont, turbines are located on low altitude mountain ridges or in coastal regimes where icing is common, but is not usually sever at the elevations where wind turbines are installed. In most cases precipitation is in the form of snow, which does not impact turbine operation. The former company US Windpower conducted extensive tests of wind turbines on Mt. Equinox in central Vermont. This high altitude mountain ridge experienced sever rime ice and cold, humid air flows. All of the research from these sites, which were active in the mid to late 1980's was never made public. All other sites are at much lower elevations and thus do not experience the same rime ice conditions. The last clarification of sites are along the arctic coast, such as the 0.5 MW plant located in Kotzebue, Whales and St Paul Alaska. These sites do experience cold temperatures and high density air flows, but usually little icing due to the low humidity. Turbines installed in these areas are outfitted with cold weather packages, including oil heaters and special metal treatment. None of the turbines installed have included blade heating options, other then the use of black painted blades.

Of the sites outfitted with governmental supported monitoring systems, reports of downtime result more due to turbine maintenance in cold climates as compared to actual operational issues.

5.3.6 Canada

One operator in Canada has identified overproduction in cold temperatures has being its most significant cold weather issue. For a 600 kW Tacke machine located in Tiverton, Ontario, second-averaged power peaks of 950 kW were recorded in -20° C weather and the generator overheated and tripped out [13]. Also on a 65 kW Bonus machine located in Kuujjuaq (58° N), a 5-minute average power output of 89 kW was recorded [13].

Yukon Energy Corporation has a significant amount of experience in operating wind turbines in low temperatures and severe in-cloud icing environment. The company owns two turbines: one 150 kW Mark III Bonus and one 660 kW V47 Vestas in Haeckel Hill, Yukon (altitude 1430 meters). They were installed in 1993 and 2000 respectively [32]. Maissan [32] reports that low temperature steels, synthetic lubricants and heating systems for items like gearbox, generator and electrical cabinets have worked well. However, anemometers and aerial power lines proved to be adversely affected by in-cloud icing. In addition, problems were encountered with the ice detector that controls the heating strips installed on the first turbine. The ice detector was removed and the heating strips controlled manually. Another ice detector was installed but outside the control loop of the heating strips. It recorded approximately 800 hours of rime icing at the site [32].

Based on the experiences of Yukon Energy, Maissan identifies icing as probably the most significant issue. Yukon has experimented with a protective coating on their first turbine. They covered the blade surfaces with a black low adhesion type of paint. They noticed an improvement in turbine output. In addition to the more obvious solutions for cold weather climates, he recommends that turbines be fitted with full blade surface ice protection and wished that such a system had been available for the second turbine installed on Haeckel Hill. He also would like to see the operating temperature range reach down to -40°C [32].

6 EXISTING STANDARDS, REQUIREMENTS AND RECOMMENDATIONS

6.1 WIND TURBINES

Certifying wind turbines for cold and mountainous regions requires reliable procedures for the prediction of the amount of ice accretion during standstill and operation. International design standards take icing load cases into consideration in different ways. The IEC-61400-1 Wind Turbine Generator Systems - Part 1 Safety Requirements recommends to take ice loads into account but a special load case is not given and no minimum ice requirements are given for standard wind turbines [34]. Germanischer Lloyd requires that two icing cases for rotating parts and one for non-rotating parts must be considered when designing a wind turbine. For rotating parts the two cases are “all blades covered with ice” and “all but one blade iced over”. For non-rotating parts icing of 30mm for all exposed parts must be taken into account. Simple formula for calculating the design ice loads is given. [35,36] The Danish Energy Agency gives it’s recommendation for Offshore wind. Typical sea ice characteristics and formula for calculating static ice loads are given. The loads from dynamic sea ice behaviour are advised to be noticed, but no clear recommendation how to estimate those dynamic loads is given. Icing of the rotating parts follows the guidelines of Germanischer Lloyd. However at North Sea the design ice thickness is recommended to be increased from 30mm to 150mm due to the water spray for parts less than 20m from the water level. [37]

6.2 RESOURCE ESTIMATION AND POWER PERFORMANCE MEASUREMENTS

The IEC-61400-12 Wind Turbine Generator Systems - Part 12 Wind turbines power performance testing sets no requirements for equipments or data treatment used in power performance testing in low temperatures or in icing climate [38].

7 SUMMARY

Wind turbines have been and are located to such sites where turbines are exposed to such low temperatures outside the standard operational limit and to sites where turbines face icing, which retard energy production, at the winter time. Currently capacity of about 500MW locates on sites, which can be defined, as cold climate wind turbine sites. Such sites are often elevated from the surrounding landscape. Wind turbines have been recorded to operate in cold climate in Scandinavia, North America, Europe and Asia.

At the time of new investment site assessment is carried out. Low temperature and icing climate sets additional requirements for wind resource measurements. Selected measurement equipment should be designed for low temperature and icing climate use. Especially anemometer and wind vane should be selected with care. Already a small amount of ice may reduce measured wind speed significantly and large ice accretions may stop the entire anemometer. For example a small amount of rime on the cups and shaft of an anemometer may lead to underestimation of wind speed about 30 % at wind speed of 10 m/s. Lot of research has been done in this field and devices suitable for wind resource estimation in severe icing climate are available. In addition to the measurement instruments itself other parts of the measurement system should also be able to cope with low temperature and icing. Cables, connectors and cable ties specified for low temperature usage should be employed. Also heating for the boom of wind sensors in severe icing climates should be provided to avoid distorted results.

Extensive and reliable temperature data is commonly produced for weather forecasts. Such temperature recordings enable the estimation of extreme temperatures and duration of low temperature time. Icing measurements are however rare and are not included in standard meteorological measurement. It is possible to calculate estimation of in cloud icing from visibility observations, which include cloud base height measurements. These measurements are usually performed only at airports. Due to that coverage and accuracy of this method are only satisfactory. If icing is considered to deteriorate power production, it is advisable to add icing measurements to resource estimation measurements if such are carried out.

Several methods to detect icing are available. Ice detectors for meteorological measurements are available. It is also possible to measure icing indirectly with dew point detector. Since there is analogy between anemometer and a wind turbine, persistency of icing may be evaluated economically with a set-up of two anemometers, in which one is properly heated and the other is unheated. According to the current knowledge ice detectors are most suitable for icing time measurements and therefore also for controlling a possible heating devises.

Meteorologists have developed models for estimation of different type of atmospheric icing and the effects of icing and from other standpoint aviation industry has developed models to calculate weight and shape of ice accumulations on the leading edge of a wing. Those computer codes have been modified for wind turbines. Due to complexity of icing phenomenon and aerodynamics as well as current performance of modern personal computers, the development of more accurate models has been moderate. Maps to describe annual icing time have been developed but standardised method to calculate local icing time from meteorological measurements still lacks.

Technical solutions for wind turbines operating at low temperature or at icing climate are available. Low temperature specified materials and oils should be used if temperatures outside the standard limits are probable. Many turbine manufacturers have so called low temperature versions of their standard turbines. In addition to cold specified materials used, those turbines often are equipped with gearbox heaters. Some manufacturers have also developed adapted technology for icing climate. In addition to low temperature versions those turbines include measures against icing. Ice detectors, coatings that prevent ice to stick to the blades and different blade heating systems are available.

Wind turbines have been sited to cold climate sites for some years and today operational experiences exist. In Scandinavia down time for older turbines have been recorded due to low temperature, modern turbines instead are already adapted to the low temperatures and recorded down times have been relatively low. Low temperatures have also recorded to extend the duration of maintenance and reparation breaks during winter.

Severity of icing varies a lot depending on local parameters especially altitude compared to surrounding landscape has great effect on severity of icing. Icing has been recorded to retard energy production at elevated sites in Scandinavia, Alpine regions of Europe as well as elevated sites in North America in Canada and Alaska. But in Norway for example icing have not had that kind of effect to wind power production that it would have been recorded, even though turbines locate up to 200m level above sea level and even higher latitudes than for example in Finland. Previous underlines the fact that icing is very much local phenomenon. Similar to low temperature icing and snow has been recorded to extend the duration of maintenance and reparation breaks. Snow may even prevent accessing to site during winter. In severe icing climate of Canada and Finland systems that keep blades free of ice have been found compulsory.

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