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State-of-the-Art of
Wind Energy in Cold Climates

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State-of-the-Art of Wind Energy in Cold Climates

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ABSTRACT

Wind turbines in cold climates refer to sites that may experience significant time or frequency of either icing events or low temperatures outside the operational limits of standard wind turbines. The potential for producing electricity at such, often inhabited, sites is vast. Consequently, the International Energy Agency Wind Agreement has since 2002 operated a working group; Task 19 Wind Energy in Cold Climates. The goal of the cooperation 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 cold climate wind energy is presented: knowledge on climatic conditions and resources, technical solutions in use and operational experience of wind turbines in cold climates. This is an updated version of the second State-of-the-art report published in 2010.

CONTENTS

1 EXECUTIVE SUMMARY

Wind Energy in Cold Climates **(WE in CC)** refers to sites that may experience, either or both, significant time or frequency of either icing events or low temperatures outside the operational limits of standard wind turbines **(WT)**. Apart from lower energy production, which directly influences a wind farm’s cash flow, legal issues, such as ice throw and increased noise, may reduce production. Additionally, fatigue loading and operation and maintenance (O&M) aspects particular to WE in CC need to be considered. WT operating in cold climates are located around the World in, for example, Asia, North and South America and Europe.

Wind resource assessment - A comprehensive site assessment is normally carried out as a basis for decision prior to each new investment. Low temperature and icing climates set additional requirements for wind resource measurements and special equipment is required in low temperature and icing climates. Anemometers and wind vanes are to be selected with care as even small amounts of ice, including accretions on support structures, may significantly disturb the wind measurements. Larger ice accretions may stop the operation of anemometers and wind vanes. The influence of ice on or near the sensors will render the measurements less bankable. Classification of sites and sensors with respect to icing has been proposed in “Expert Group Study on Recommended Practices for Wind Energy Projects in Cold Climates (2012)”, [1].

Temperature - Extensive and fairly reliable temperature data are on a regular basis produced as part of standard weather forecasts. Measured temperature recordings enable the verification of the numerical weather prediction **(NWP)** model output of extreme temperatures and the duration of these. Extreme low temperatures in stable atmospheric conditions, for example cold air in valleys, are, however, inherently difficult to forecast.

Icing measurements are rarely carried out and not part of standard meteorological observations. It is possible to estimate in-cloud icing from temperature, visibility and cloud base height measurements. The coverage and accuracy of analysis methods based on such observations can be improved by applying data from additional sources such as, for example, satellites and weather radars. It is advisable to carry out proper icing measurements alongside with wind resource measurements if icing can be expected to a) cause a significant risk of ice throw, b) an increase of noise violating the environmental permit and/or c) deterioration of power performance. Standardised methods to calculate the local icing time based on meteorological measurements are still lacking.

Dedicated ice detectors can be used for direct measurements of a) the occurrence of icing (yes or no), b) intensity, c) type of ice and d) load. An increased risk of icing can indirectly be estimated by using a properly heated dew point detector. The occurrence of icing may also be evaluated by using two anemometers side-by-side, of which one is sufficiently heated and the other is unheated. Heated sensors (and WT blades) may, however, cause melting of dry snow and trigger false icing alarms.

Modelling of atmospheric ice - Lately, NWP models have been developed to provide fairly good estimates of the timing of atmospheric icing and wet snow events. The exact amount of ice accumulating to an object, for example a WT blade, is still difficult to model as field adapted sensors for measuring Liquid Water Content (LWC) and Median Volume Diameter (MVD) aren't commercially available for verification of NWP results. In recent years, maps describing annual active icing time (icing maps) have been developed especially in Scandinavia, for example covering Sweden, [51], and Finland [52].

Theoretical models, open source computer codes and commercial software are being developed to predict the amount and shape of ice on WT rotor blades. Many of these codes originate from the aviation industry. There exists, due to the complexity of the icing phenomena combined with WT blade aerodynamics, a need for further development of more accurate models for predicting the consequences of WT icing.

Mitigation - Technical solutions for wind turbines operating in low temperatures and/or icing conditions are readily available. Low temperature specified materials and oils should be used if temperatures outside the standard limits are probable. Many wind turbine manufacturers have low temperature versions of their standard turbines. In addition to low temperature specified materials, those turbines are often equipped with heaters for critical components, such as gearbox and pitch accumulator. Some manufacturers have also developed adapted technology for icing conditions; ice detectors are available, and anti- or de-icing systems are starting to become available, but only to a limited extent.

Experience has been gathered from approximately 15 years of operation in cold climates. In Scandinavia, the down-times due to low temperature have been recorded for older turbines. Modern turbines are often adapted to the low temperatures and the recorded down time particularly due to low temperatures has been relatively low. Low temperatures in connection to another trouble, for example grid loss, might cause more down time.

The severity of icing varies depending on local conditions. In particular, the site altitude compared to the average height of the terrain has a great effect on the severity of icing. Icing has been recorded to retard the energy production at elevated sites in Scandinavia, Alpine regions of Europe as well as at elevated sites in North America in Canada and Alaska. But for example in Norway icing have not had that kind of effect to wind power production, even though turbines locate up to 200 meter level above sea level and even higher latitudes than for example in Finland. Icing and snow has also been recorded to extend the duration of maintenance and repair in wintertime considerably. Snow may even prevent access to a site. Within last years wind turbines have been installed to cold climate conditions increasingly and statistical data of performance and operational and maintenance issues is expected to be available in the near future.

Research and development of cold climate technologies, tools and methods for easier deployment of wind energy in cold climates, as well as procedures for safety issues, are done widely. The industry's interest in cold climate sites, due to the decreasing number of more easily utilizable sites, and energy policies are boosting the R&D efforts, so that many prevailed problems can soon be solved. Nevertheless, a lot of work needs still to be done; the World is not ready.

2 INTRODUCTION

In 2001, the International Energy Agency (IEA) Wind Programme initiated a new Task 19 Wind Energy in Cold Climates. This international collaboration between the participating countries has as the main objective to gather operational experience of wind turbines and measurement campaigns in icing and low temperature climates to enable a better understanding of turbine operation under these conditions. One 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. Another goal is to produce guidelines to operators and manufacturers considering the operation of wind turbines in cold climates.

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

The operating agent of the task is VTT Technical Research Centre of Finland and participating institutes among VTT are The Swedish Energy Agency/WindREN from Sweden, Kjeller Vindteknikk from Norway, the National Renewable Energy Laboratory (NREL) from the USA, ENCO AG and Meteotest from Switzerland, Natural Resources Canada and Fraunhofer IWES from Germany, and Energiewerkstatt from Austria, [1].

When the collaboration was started there were a relatively small number of wind power projects in cold climates. Yet, the global market segment was estimated to be substantial, although no real market assessments had been performed. Since 2001 the cold climate development has been slow until last years, when the installed capacity has growth rapidly. The capacity at cold climate sites has increased roughly to 10 000 MW at the same time when the total installed worldwide wind capacity has grown from 24 GW to 239 GW, [2].

Two main reasons for the slow development can be identified. First, turbine manufacturers have preferred standard projects instead of those at cold climate sites that require more advanced technology. This has meant that there have not been commercial and tested wind turbine technologies available for those project developers that have had an interest in cold climate sites. As such, the cold climate development has been similar to the situation of offshore wind. The other identified reason is lack of information regarding the operational experience and exact climatic conditions relevant to sites in cold climates, especially concerning the local risk of icing. The impact of climatic conditions on energy production and economy (reliability, O&M costs) has been difficult or impossible to assess. Typically information about the average and minimum temperatures on perspective sites is available, whereas information on icing is more difficult to obtain.

Current IEC and other international standards simply state that other than standard operating conditions have to be taken into account, but they don’t provide methodologies to do that. Consequently, projects in such areas have higher risks to be carried out with inadequate knowledge.

3 EVALUATION OF CLIMATIC CONDITIONS

Cold climate refers to sites that have either conditions favourable for icing to occur or temperatures that are lower than the operational limits of standard wind turbines. However, it is still not possible to describe a typical cold climate site as the site conditions can vary a lot. For example, at some sites there may be low temperatures, but no atmospheric icing, and at another site the annual average temperature may be mild but periods of heavy icing may be possible. Each site is individual and requires a specifically chosen set of measurements to be conducted.

Atmospheric icing can occur at temperatures below 0 °C and when there are liquid water droplets in the air. The type, amount and density of ice formations depend on both meteorological conditions and on the dimensions and type of structure or object (moving/static).

More information about atmospheric icing and cold climate can be found from standard "ISO 12494 Atmospheric icing of structures" [3], and from "Recommended practices for wind energy projects in cold climates" by IEA Wind Task 19 [4].

3.1 PUBLIC DATA AND MAPS

Meteorological community has done a considerable amount of work to present various climatic data, such as icing frequency and average temperatures, in a map format. This information is useful to a wind energy project developer as such maps indicate whether one should consider low temperatures and icing already when selecting equipment for the site assessment.

Some local maps may be detailed enough and thus give more clear indications on the local climates. Most often the maps have been made for so large areas that they can only be considered indicative. This is the case for example with the icing map of Europe. The map does not take notice on the local topography, which is very important for the local icing climate. The first versions of the European Icing Map and Frost Map were produced in the WECO EU project. The icing map of Europe is presented in Figure 1.

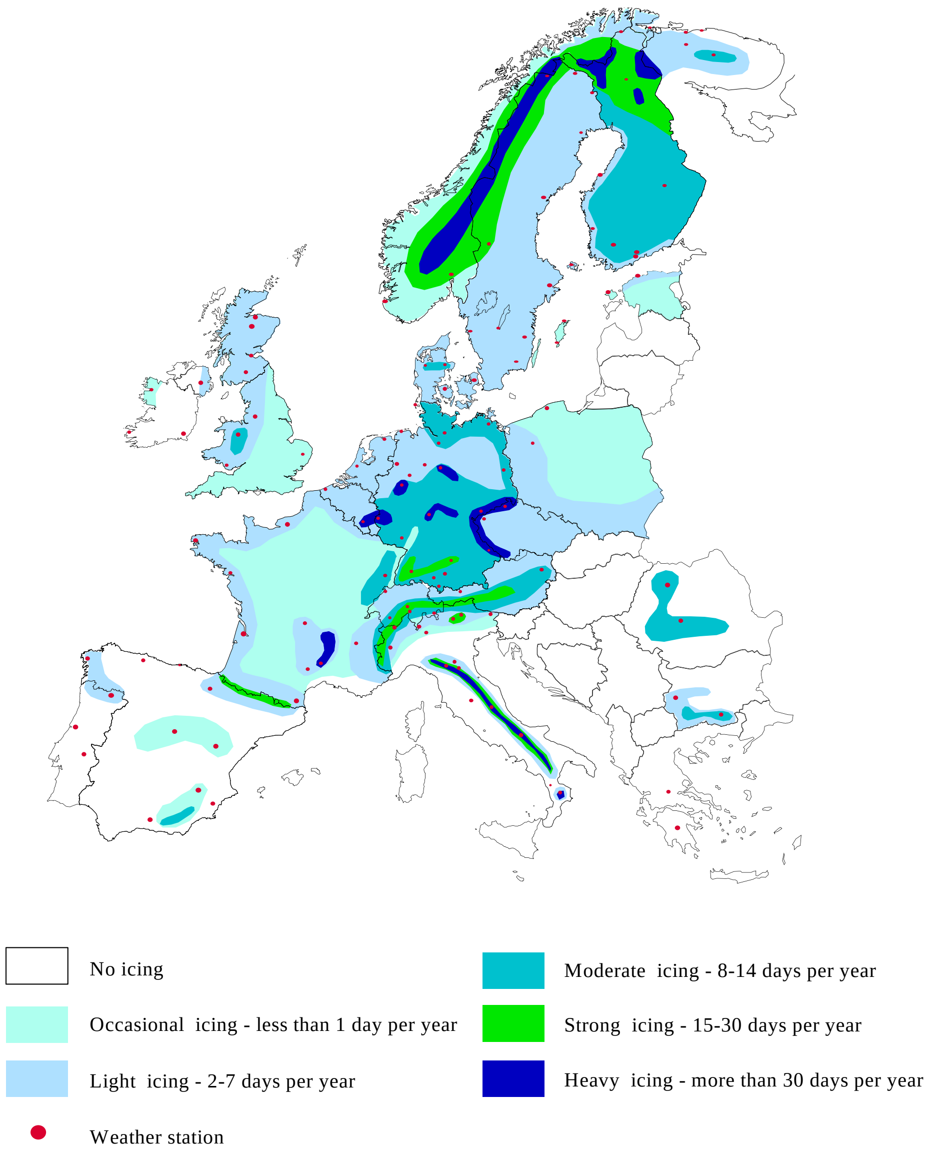

Figure 1. Icing map of Europe [5].

Improved versions of the European Icing Map, shown in Figure 2, were produced in the framework of the EU project NEW ICETOOLS [6].

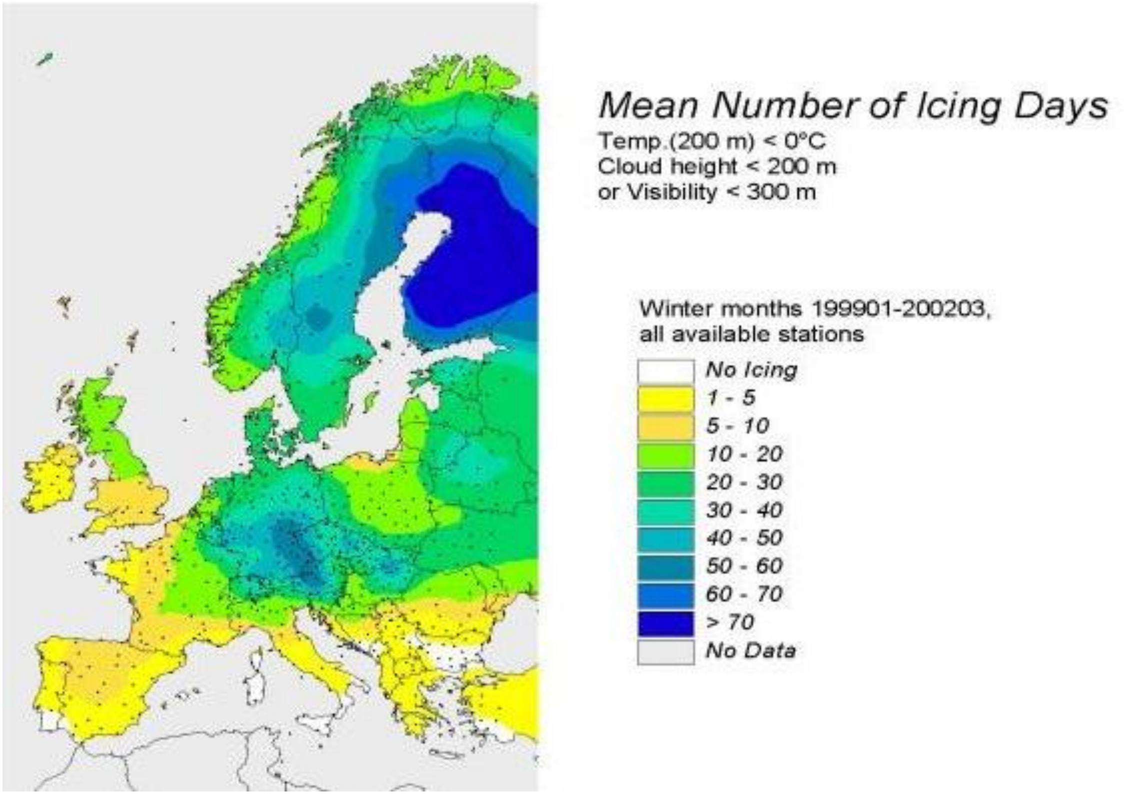

Figure 2. Icing map of Europe. Mean number of icing days at 100m above ground level.

Due to locally varying topography, variations in icing severity and intensity may vary greatly within short distances. Therefore icing maps, such as in Figure 1 and Figure 2, cannot be interpreted as exact and should be used in connection with local topographical information and with measurement statistics on the particular site.

A more exact icing map for the British Isles, where the effect of terrain has been taken into account, is presented in Figure 3. The icing map was produced by first examining the number of icing days at elevations of 0 m, 250 m and 500 m above sea level at nine meteorological measurements stations shown in the Figure 3. 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 an informative picture of areas were icing could be faced [5]. 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.

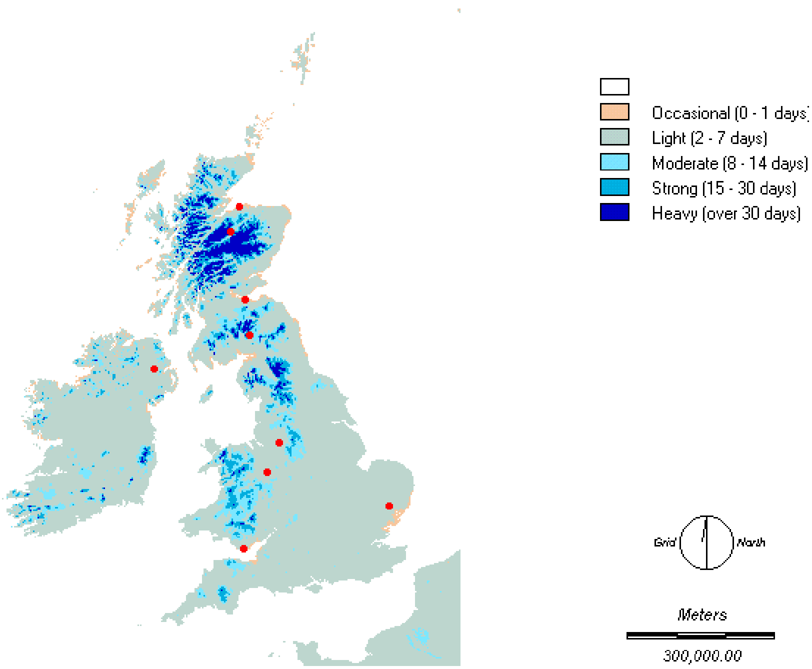

Figure 3. Annual number of in-cloud icing days in the UK and Ireland at ground level and the weather stations used in calculation [5].

Icing map of Switzerland is presented in Figure 4. The map is based on raster information on cloud water, temperature and wind from the analysis of COSMO-2, the weather forecast model of MeteoSwiss. This data is used as input for an icing algorithm that simulates the ice mass accretion on a freely rotating cylindric structure. The simulated icing frequency is given on a 2.2 km raster and was verified using measurements from the IMIS measurement network in the Alpine region and measurements in the Jura region.

Icing map of the Rogaland region in Norway is presented in Figure 5. A map for the average number of days with freezing precipitation during a year in Canada is presented in Figure 6.

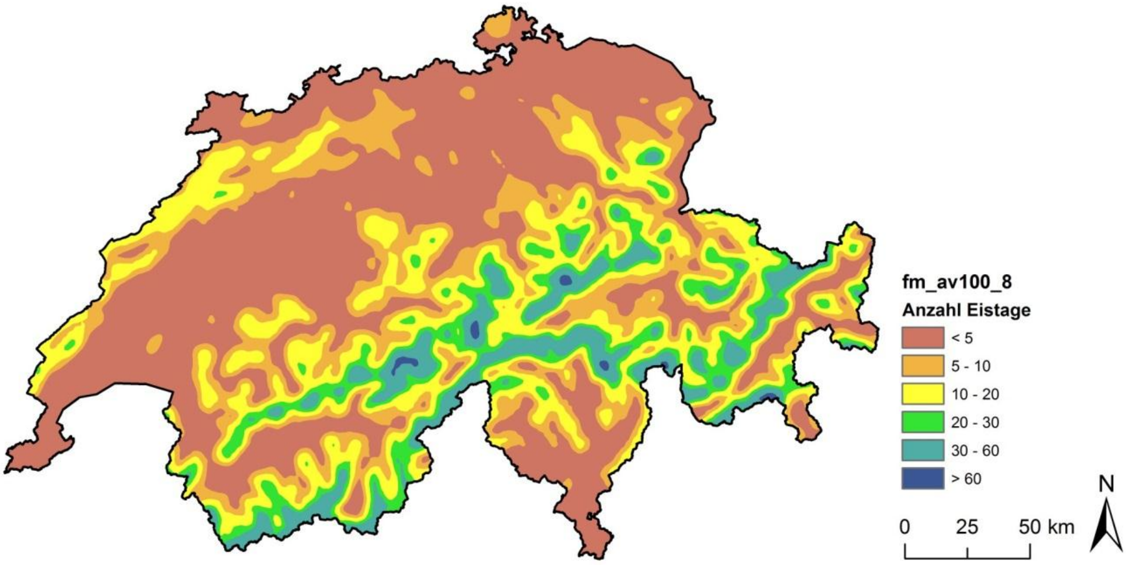

Figure 4. Icing map of Switzerland. The map shows the frequency of meteorological icing as days per year at 100 m height above ground for the period between August 2007 and July 2009. The 10-year-average value of icing frequency is about 5% lower.

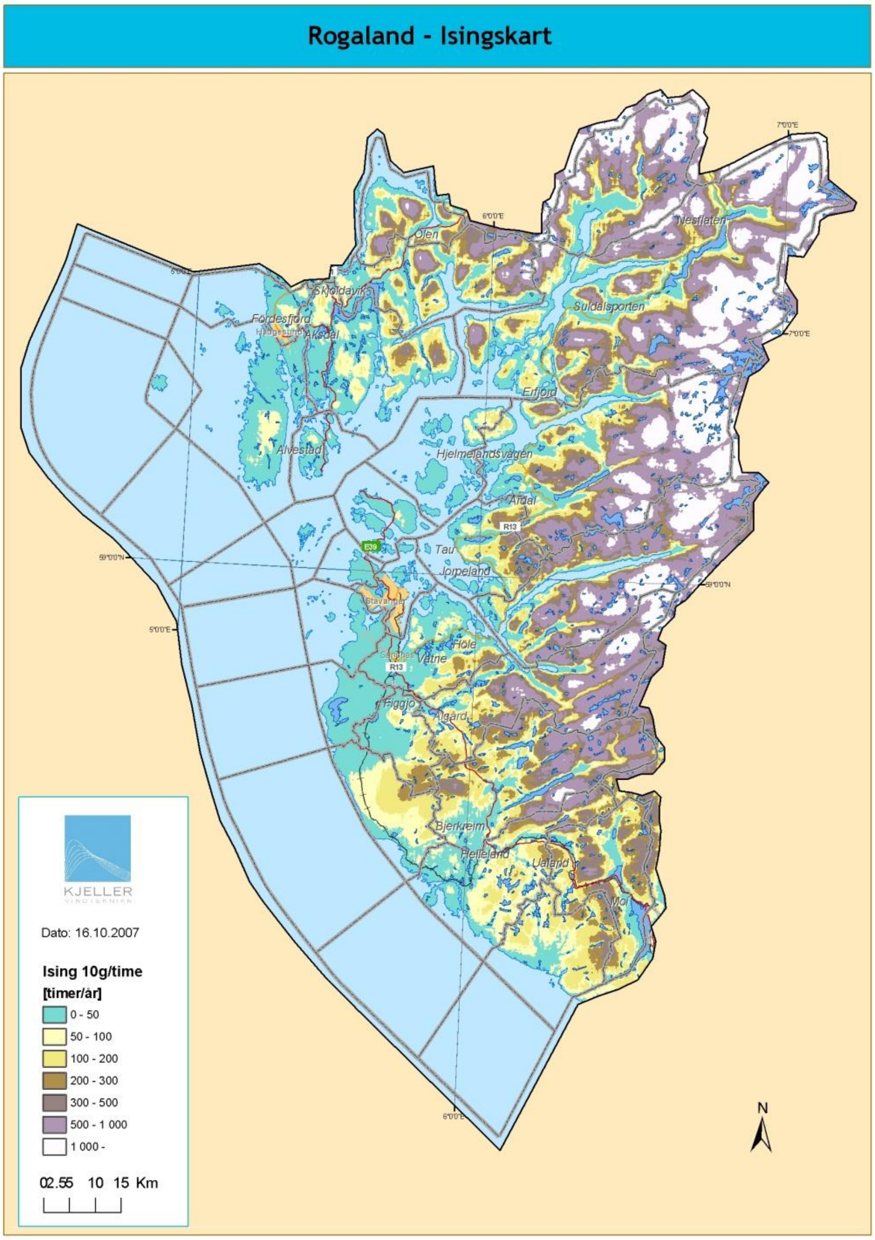

Figure 5. Icing map of a region of Norway. The map is produced with the meso-scale model WRF and shows number of hours during a year with icing rate higher than 10 g/hour on an ISO cylinder.

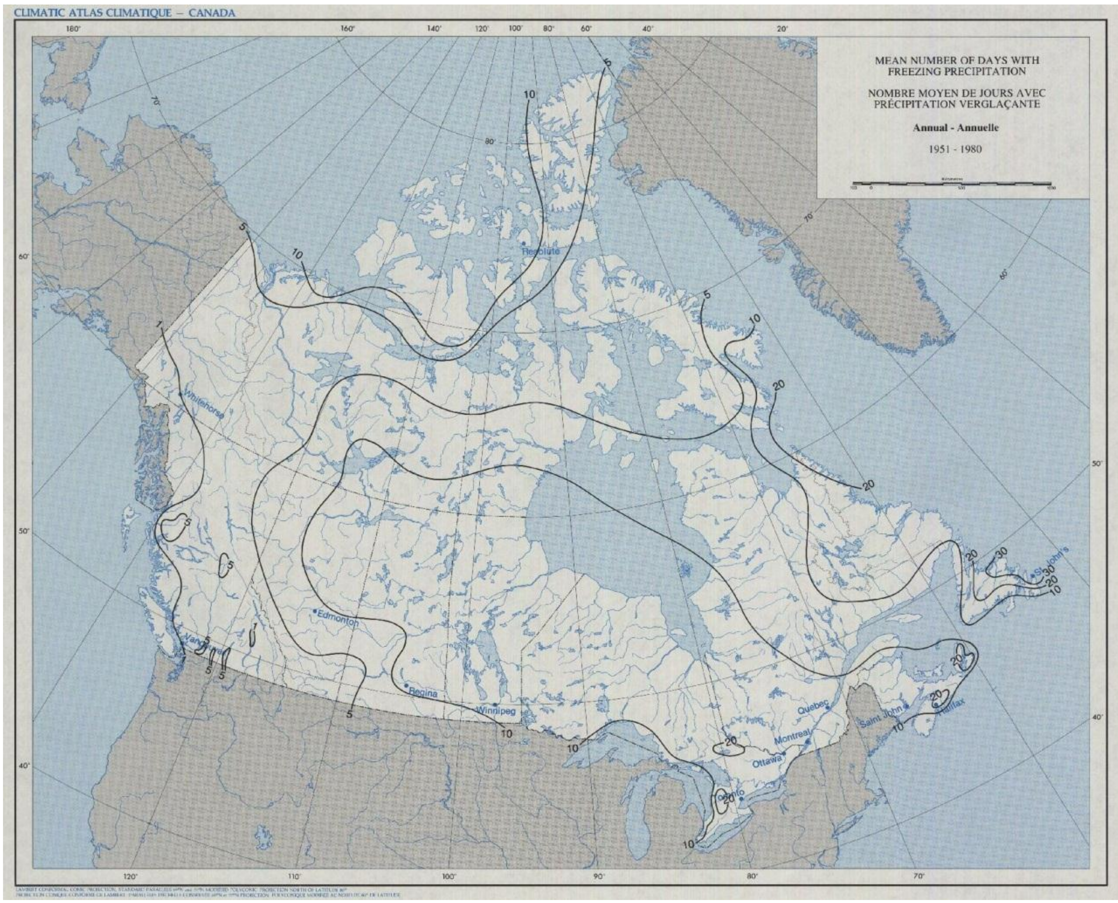

Figure 6. Mean number of days with freezing rain during one year in Canada between 1951-1980. Map from National Archives & Data Management Branch of the Meteorological Service of Canada.

An icing map from the Finnish Icing Atlas showing the number of hours per year, at 100 m height above ground level, when intensity of icing is greater than 10 g/m/h (meteorological icing, also known as active icing), is presented in Figure 7. The Finnish Icing Atlas is calculated from the same modelled data series as the Finnish Wind Atlas [7]. The basis of the icing calculations is the atmospheric model (AROME) data that is fed to the separate icing model according to ISO - 12494:2001, [3]. A preliminary verification of meteorological icing time, presented in [8], showed that the measured active icing time corresponded relatively well to the modelled active icing time. The verification was done only on one site, so the conclusions cannot be drawn to cover whole Finland. The Finnish Icing Atlas is available in http://www.tuuliatlas.fi/icingatlas/index.html.

Another icing map from the Finnish Icing Atlas is presented in Figure 8. It shows the number of hours per year, at 100 m above ground level, when ice load is greater than 10 g/m (for standard cylinder). This describes the time when turbines or components are affected by ice (instrumental icing). It has to be noted that in Finnish Icing Atlas, ice removal is only modelled by using such criteria that sublimation of ice is not taken into account, [52]. This causes overestimation of instrumental icing time.

Figure 9 shows the annual production losses for an example 3 MW wind turbine. The estimation method for production loss calculations presented in the Finnish Icing Atlas is described in detail in [8]. A short summary of the method is described below. The effect of ice on wind turbine power production was assessed in the Finnish Icing Atlas as following:

1) Three different rime ice formations on wind turbine blades were created using numerical icing simulation software TURBICE, [9]. The ice formations represented different durations of icing: less than 1 hour, approximately 3 hours, and approximately 10 hours of icing (start of icing, light icing and moderate icing respectively). The weather conditions were chosen to be equal on all three icing cases. These, so called representative icing weather conditions, were:

    a. wind speed 7 m/s (typical operating wind speed)

    b. temperature -7 °C (resulting ice type is rime)

    c. droplet size distribution, MVD (mean volume diameter), 25 μm

    d. liquid water content, LWC, 0,2 g/m^3

2) Aerodynamic properties of the iced wind turbine blades, created in step 1, were analysed with computational fluid dynamics (CFD) analysis using ANSYS FLUENT software. The flow parameters were selected to resemble representative icing conditions. The turbulence model used in CFD simulations was Spalart-Allmaras model. For all the simulated cases aerodynamic force coefficients for lift and drag were determined for appropriate range of angle of attack. Drag coefficients needed to be corrected in order to account for the ice surface roughness effects, because it could not be modelled in FLUENT sufficiently.

3) Power curves of iced wind turbines were simulated using wind energy specific multibodydynamic (MBS) software FAST, [10], and the aerodynamics of iced blades, from step 2, as input.

4) The power curves of iced wind turbine, from step 3, were linked in weather data time series to weather conditions resulting similar ice formations as were created in step 1.

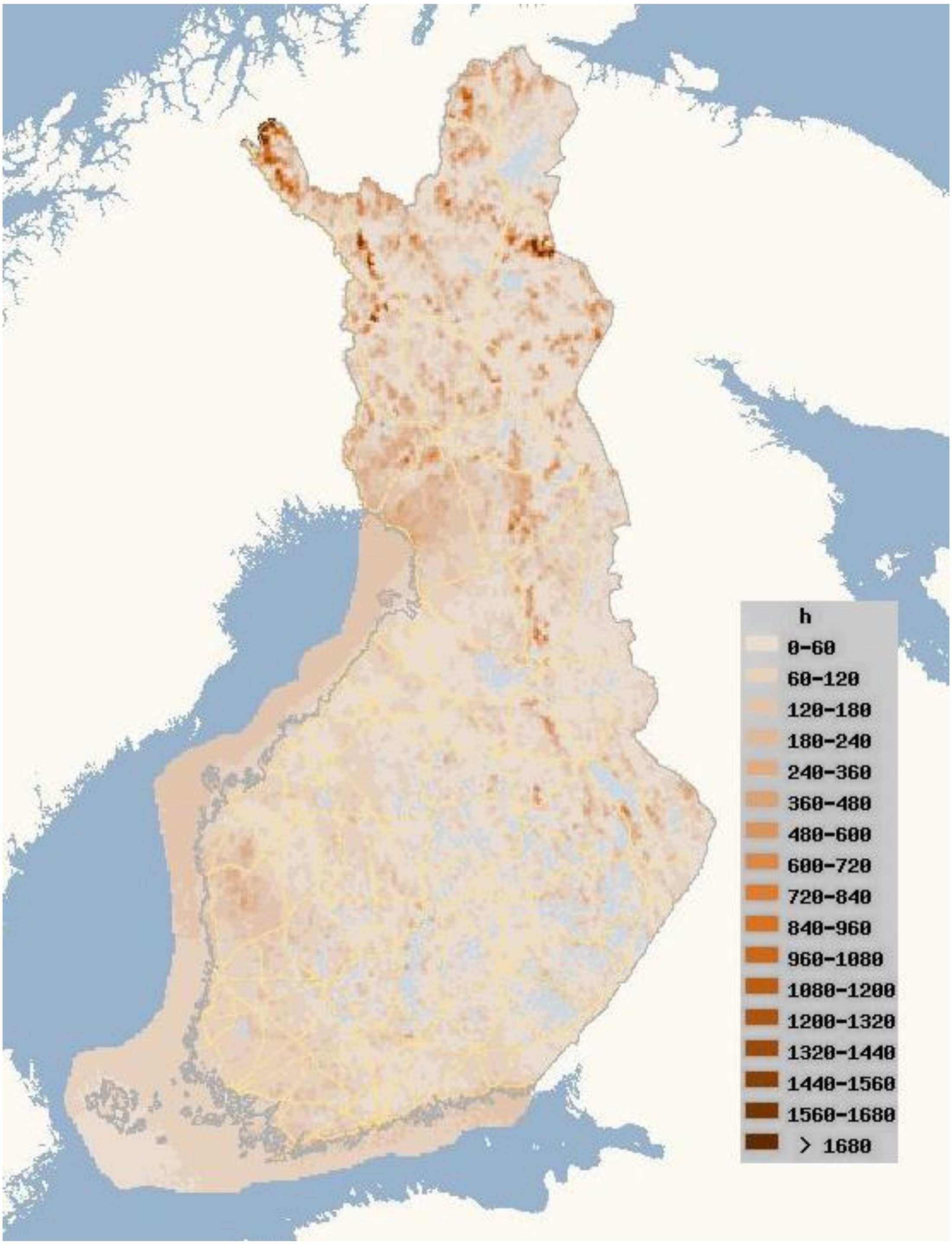

Figure 7. Icing map from the Finnish Icing Atlas showing the number of hours when intensity of icing is greater than 10 g/m/h (meteorological/active icing time) for a stationary cylinder as defined in ISO 12494.

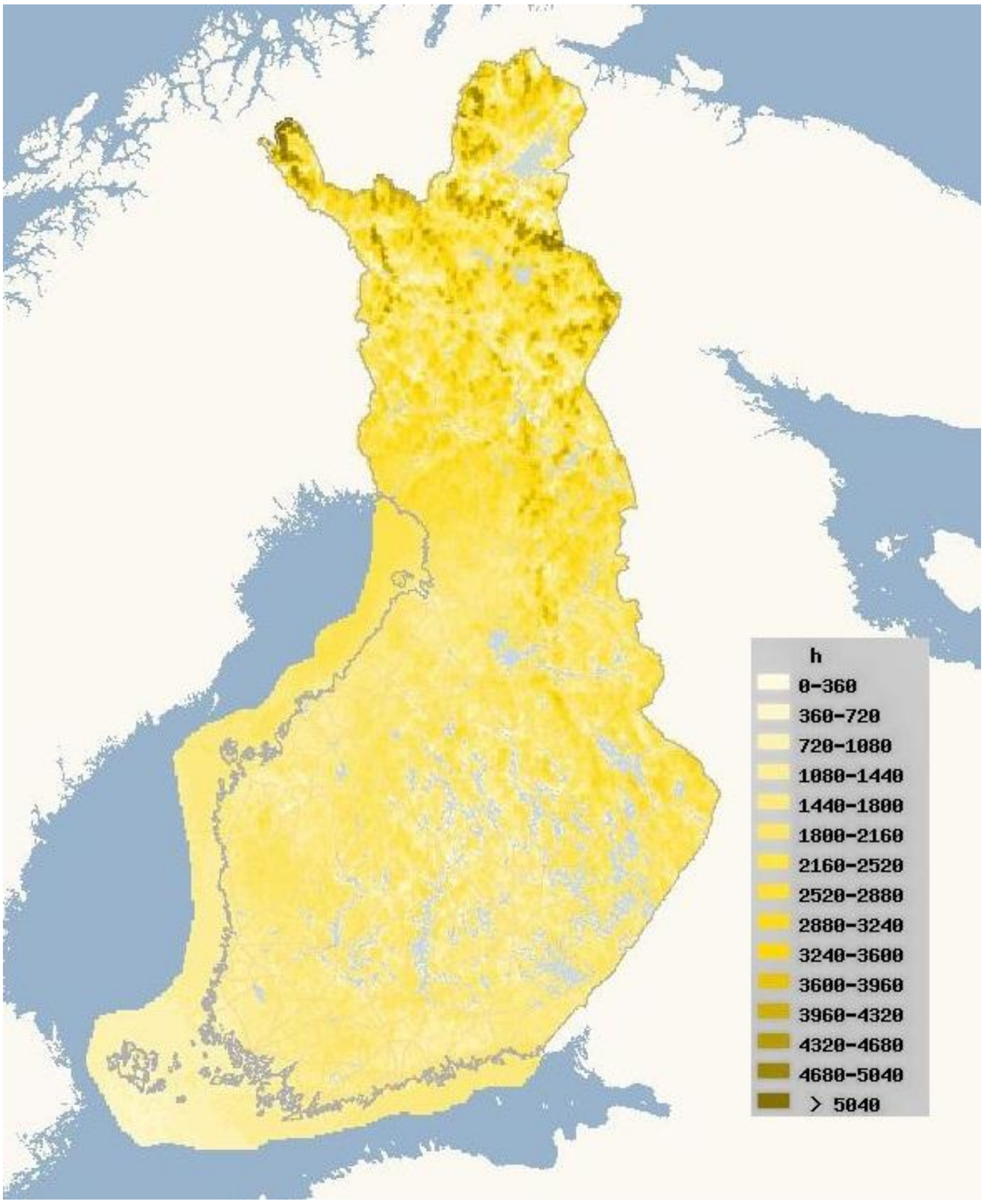

Figure 8. Icing map from the Finnish Icing Atlas showing the number of hours when ice load is greater than 10 g/m for a stationary cylinder, as defined in ISO 12494, which describes the time when structures are iced up or turbines or components are affected by ice, also called instrumental or passive icing time.

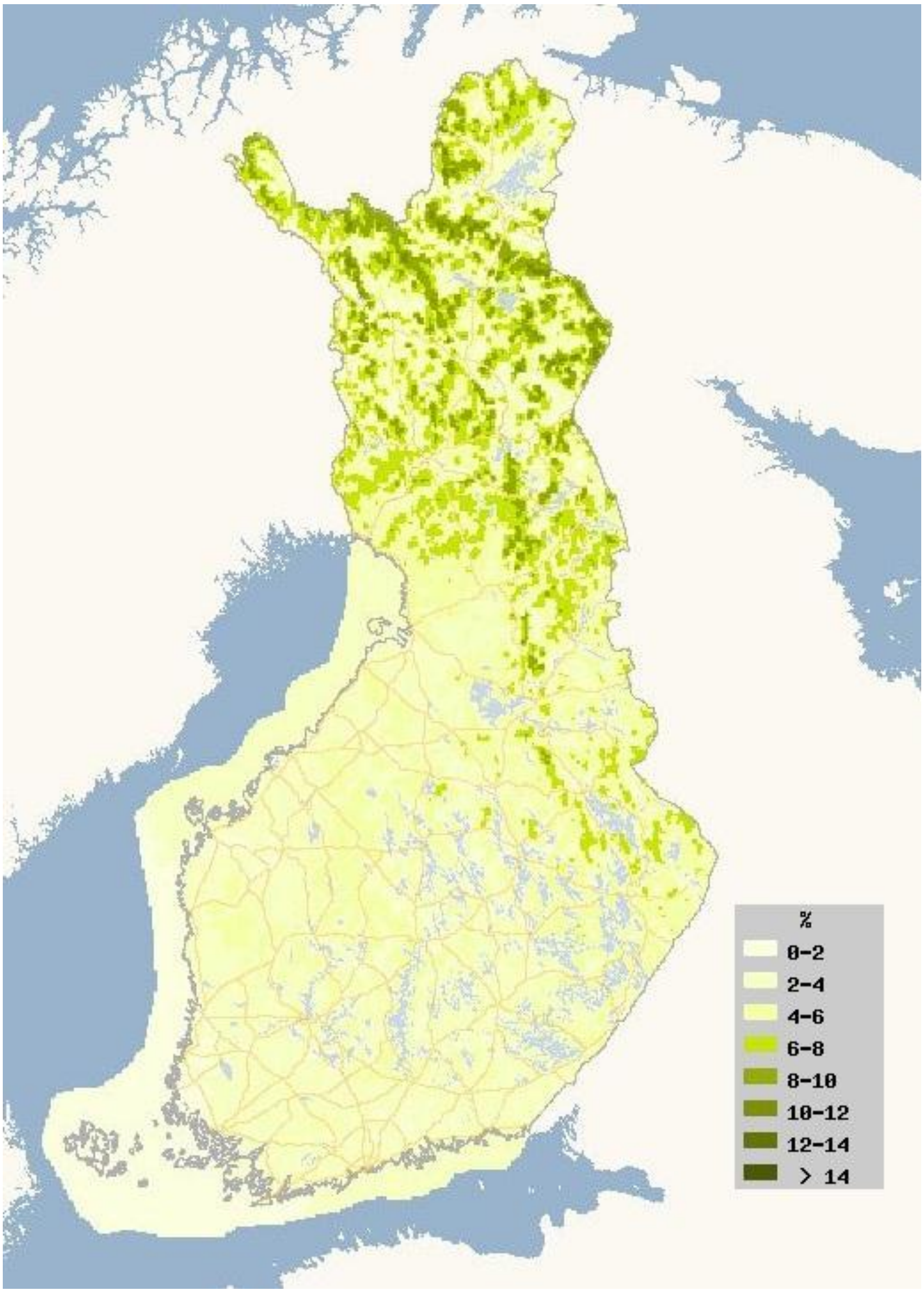

Figure 9. Icing map from Finnish Icing Atlas showing the estimated annual production losses of an example 3MW wind turbine.

Icing maps similar to those presented above are generally available from the weather service agencies of most countries where it is relevant.

As seen in the examples above, the usefulness of an icing map increases when the resolution improves. Figure 10 illustrates further the importance of high grid resolution with respect to the mapping of rime icing [11]; the terrain effect on flow and cloud physics can be modelled more precisely with increasing vertical and horizontal resolution.

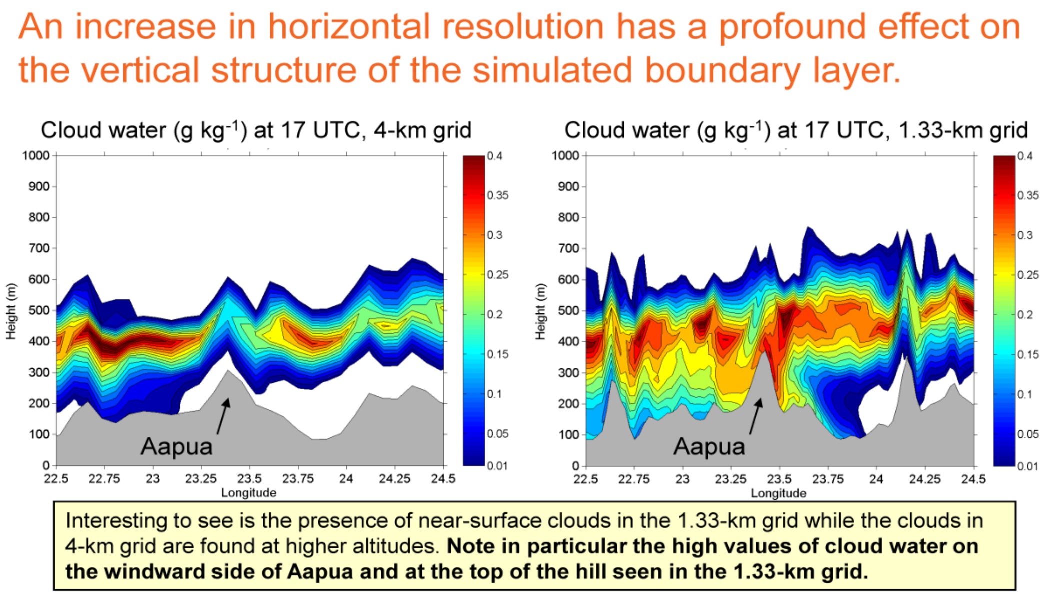

Figure 10. High horizontal resolution is required to simulate icing in complex terrain.

3.2 METEOROLOGICAL MODELS

Meteorological meso-scale models are used on a worldwide basis to create weather forecasts on regional scales. The meso-scale models are based on mathematical formulations of the atmospheric dynamics and physics. This includes formulations on the microscale physics which describes the formation and development of clouds and precipitation.

The key elements for calculating icing include air temperature, wind speed and air moisture, either as water vapor, liquid cloud droplets or snow. These are all parameters that are calculated by the meso-scale meteorological model and can be utilized in calculating icing at a certain location.

For parameters such as wind speed, temperature and mass fields the uncertainty in the model data is relatively low, while for the parameters like precipitation, evaporation and clouds the uncertainty in the model results is much higher. The reasons why a large uncertainty is found for the quantification of clouds and precipitation are listed below:

1. Complicated processes that are not fully understood and that are difficult to describe mathematically. The processes cannot be described explicitly in a model and must be parameterized.

2. Insufficient or too excessive vertical mixing in the planetary boundary layer is a common problem for meteorological models and is related to the parameterization of turbulence in the lower atmosphere. The vertical mixing

processes are important in describing the vertical moisture profile and thus also the formation of low clouds.

3. Lack of observations of vertical profiles of moisture and clouds. This will often give an initial error in moisture fields in the models.

4. The processes of cloud formation and precipitation appear on a micro-scale level, which cannot be fully resolved by a coarser meso-scale.

Calculations that involve the use of atmospheric moisture content from the model will be associated to a relatively high degree of uncertainty. This includes the calculation of accumulated ice mass during an icing episode. For the identification of periods when icing may occur, the model data will be related to lower uncertainty.

3.3 ICE ACCRETION MODELLING

Numerical models, which are used to calculate ice accretion, ice masses and blade heating demands in different icing conditions, are described in this section. In addition, the basis of the methods that are used to calculate different types of icing from standard meteorological observations is presented.

The rate of icing is dependent on the flux of particles (concentration multiplied by 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 the object while other smaller ones, which have less inertia, follow the air stream and pass the object. Some particles also bounce when colliding with the 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, or form a thin water film on the surface of the 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 physical icing models cannot model all icing processes with good agreement to experimental ice accretion results. Physical descriptions, including heat transfer of different icing processes are presented in detail in ref. [36], [37], [38], [39], [40], and [41].

TURBICE is a numerical model which simulates ice accretion, amount and shape of ice, on wind turbine blades. The development of the software has started in 1991 at the Technical Research Centre of Finland (VTT). The model simulates both rime and glaze icing. All angles of attack experienced by a wind turbine blade may also be calculated. 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 [9]. The model can also simulate ice accretion when the blade is heated, which makes it suitable for designing anti- and de-icing of wind turbine rotor blades. In the development of the ice prevention technology in VTT, 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.

Another software that can be used for ice accretion and heating demand is LEWICE [34] and [57], the newest version is LEWICE 3.0. LEWICE 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 evaluates the thermodynamics of the freezing process that occurs when super cooled droplets impinge on a body. Its primary use is for evaluating icing on aircraft but it has been adapted to work on other applications too. LEWICE can model both dry and wet (glaze) ice growth. In addition to simulating the ice accretion, LEWICE 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. The heat source for the anti-icing capability can be specified as being electro thermal 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.

Recent studies, [58], showed that TURBICE and LEWICE codes are using little bit different models of heat transfer on the leading edge when ice is present, both highly influenced by empirical correlations. Neither one can be kept more correct than other. According to the study, more research on the physical processes of icing and heat transfer is required in order to model heat transfer on iced rotor blade better.

Newest ice accretion code for wind turbine applications is FENSAP-ICE, developed by Newmerical Technologies, [59]. The origins of the software are in the aviation industry, but lately it is being applied also to wind turbine rotor blades. FENSAP-ICE applies 3D Navier-Stokes CFD-like models to calculate flow, droplet impingement, ice accretion, anti- and de-icing loads, and aerodynamic penalties.

3.4 MEASUREMENTS

The site assessment of cold climate sites is more laborious compared to the standard undertakings. It is important to use measurement instruments that are suitable for the climate conditions that prevail on the site. Thus, a fair amount of information on the site climate conditions is beneficial for a successful measurement campaign at a cold climate site. Suitable instruments are commercially available and, moreover, the technology is continuously being developed and evaluated by manufacturers and users. Same goes for the measurement set-up as icing and low temperatures may necessitate additional arrangements such as boom heating in extreme icing conditions.

3.4.1 Measurement set-up

Met masts are usually very thin and slender constructions. The slenderer the met masts are, the less will they influence the measurements. Met masts are exposed to atmospheric icing. For example, in heavy icing conditions, a mast with a mass of around 1 000 kg can collect 5 000 kg of ice. This is a problem for the mast, especially if the ice load is combined with high wind speed. Therefore compromises between robustness and accurate measurements need to be done when choosing a met mast for cold climate site.

Before erecting a met mast in a region with icing conditions, calculations of the highest ice load and the highest wind load should be performed. For permanent masts the standard ISO 12494 states that a combination of ice load with a 3 year return period should be combined with a wind speed with 50 years return period. For the non-permanent constructions, where the probability of people being close is small, the return periods can be reduced. This type of calculations will usually show that it is a problem to use tubular towers in icing climates. A properly designed lattice tower is usually the only solution. This might increase the cost for non-permanent met masts significantly compared to climates without icing.

In order to avoid heavy lattice met mast construction in site with icing conditions, using SODARs and LIDARs may become an option. The current SODARs and LIDARs are not yet capable of operating in harsh conditions with as little maintenance as appropriately designed and built lattice met mast. Experiences with SODAR units in Switzerland and LIDAR units in Finland have demonstrated that the technology may be used in harsh climates, but careful or regular oversight of the equipment is necessary.

Sufficient power supply system is needed for thorough cold climate site assessment and measurement campaign. In the best case access to an electricity grid is available and if not, stand-alone power supply arrangement that is sufficient for sensor and other heating is a must. Such power supply systems are available. Typically the power supply system consists of diesel generator and additionally solar panels, small wind generators or possibly fuel cells which charge battery pack. Solar panels or other weather dependent power generation means are not sufficient power supply alone for properly heated instruments that will maintain their accuracy, as power requirements up to 1 500 W are needed. Icing and snow in cold climate sites might block or otherwise hinder also the operation of power supply system, which have to be taken care of. Regular maintenance visits, for example for fuel filling, are probably needed.

3.4.2 Wind

Special attention has to be paid to wind measurements in icing climate, as cup anemometers and vanes are sensitive to icing. Recent tests have repeatedly shown that a small amount of ice reduces the measured wind speed significantly and large ice accretions may stop the anemometer entirely. 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 the severity of icing conditions [24], [25], [26], and [27]. This decrease is insidious, as without other monitoring equipment there is no way to determine if a given anemometer is reading an accurate wind measurement or operates affected by ice. This may lead to a significant underestimation of the wind speed.

Solution for accurate wind measurements in icing climate is the use of a properly heated anemometers and wind vanes. If cup or propeller type anemometers are used, both the anemometer's cup shaft and post should be heated in order to prevent ice from accumulating and impacting measurement quality. Heated sonic anemometers, without moving parts, are typically more robust sensors in icing conditions. Heated sensors tend to be less accurate than unheated sensors, because those are usually less sensitive to low wind speeds and to changes in wind speed. Some of the sensors are also sensitive to flow that is not horizontal [19].

The state-of-the-art solution is simply to use heated and unheated sensors; unheated sensors provide accurate data during non-icing periods and heated sensors provide data availability during harsh conditions. The reading of the heated sensor can be correlated with the unheated sensor during periods where ice is not present to obtain more precise measurements during periods when ice is present.

At the sites where sufficient power supply is difficult or impossible to arrange, one alternative may be 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.

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. Heating cables for mounting booms are needed for sites with severe icing.

3.4.3 Icing

Ice detection is a critical measurement for developing wind energy in cold climates. The purpose for using ice detectors needs to be defined for choosing the right type of ice detector. There are two type of icing events to detect:

- The time period when ice is accumulating to structures due to the weather conditions. This is called meteorological icing.
- The time period when ice is on the structure. This is called instrumental icing (or component icing). Instrumental icing event means the time when ice affects to wind measurements or power production of wind turbine.

For a more comprehensive definition of icing events, see reference [4].

For wind power use, ice detectors are used to assess the icing conditions at the site during site assessment campaign and to control anti- or de-icing systems, for example blade heating, as well as to control the operation of turbine to prevent ice throw.

The detection of ice and icing is a rather complex task. In the past, considerable deviations between the results of ice detectors of the same type and even similar ice detectors have been reported [20], [6], and [21]. However, the ice detector technology has improved and is expected to improve in near future due to the increased wind energy markets and activities in CC sites.

Many ice detectors detect ice from the sensing part, for example a probe or a thin wire, which has collected ice. After detection the accreted ice is typically removed by heating. When the ice detector is free of ice, it is again ready for ice detection. This type of cyclical ice detection is suitable for detecting meteorological icing event. One of the main problems of the ice detectors is the melting cycles. The heating power can be insufficient to remove all the accreted ice or the already melted ice freezes again after heating period. It is also possible, that ice detector is able to clear itself from ice, but ice accumulating on the surroundings of ice detector, for example on mounting boom, start to block the detector. Occasions has been observed where ice detectors have been completely trapped inside ice accumulated on a mounting boom and in the same time the detector has indicated that it is clear of ice and icing is not happening.

Other problem is the response time of detectors. It is important to detect icing as soon as possible because the rotor blades collect ice more due to higher flow velocity compared to typical ice detectors mounted on the top of nacelle.

Due to the unreliability of older ice detectors and problems of ice detection, other approaches to observe ice have been developed. It is possible to identify icing using heated and unheated anemometers and comparing differences in wind speeds. The logic and signal processing for this kind of a solution should be designed and carried out with care to avoid operational problems. This method enables well the estimation of production losses due to icing if used during site assessment.

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 [22]. One of the heated anemometers was kept ice-free and the other was heated 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 time of the icing event that a wind turbine would experience in an icing climate (meteorological icing). It was also demonstrated that one could estimate the time when the turbine or anemometers are iced with this method (instrumental/component icing).

Adequate results on information on icing have been achieved also by combining an ice detector and a humidity and temperature sensors. Dew point detectors or humidity sensors designed for sub-zero operation have been used in indication of icing. This is possible as theoretically icing takes place when relative humidity of water vapour over ice is 100 %. Another, a more robust and straightforward way, is to decide e.g. 97 % RH limit and assume that when temperature is lower than zero and RH is over the decided limit, icing might occur. The use of such a dew point measurement for the purpose of ice detection was studied at the Pori site in Finland [12] and is discussed in greater detail in the paper by Makkonen et al. [13]. Unfortunately, using this kind of measurement set up, the question of reliability of measurements still exists. 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. It has to be remembered that in-cloud icing, most relevant icing type for wind turbines and measurement equipment's, is mainly caused by super cooled water droplets colliding with the blades or measurement instruments. But high humidity enable condensation of droplets, and thus the relative humidity could be kept as indication of icing conditions.

Actual power production of the wind turbine compared to the presumed power production according to the nacelle anemometer may also be used to ice detection since a turbine with ice on the blades will produce less compared to the turbine free of ice. Care must be taken when interpreting lower production values as sign of ice on the rotor blades, because other aspects for example wake or terrain effects can cause lower production values, especially for turbines with large rotors where wind measurement covers tiny area compared to the rotor swept area.

Automatic visibility sensors may also be used as ice detectors. However, the entire instruments, especially the lenses, must be heated in low temperatures and icing climate to ensure the appropriate operation of the devices.

Cloud height data from airport ceilometers has been used to estimate the cloud height over large regions. To improve the energy production assessment with respect to icing, cloud base sensors should be considered to be deployed also at proposed wind farm sites. Also SODARs and LIDARs could be used for detecting the cloud base by analysing the back scattering of the measurement signal. This is not done automatically yet, but could be incorporated to an extra feature of coming SODAR or LIDAR devices.

3.4.4 Other meteorological parameters

Measuring of other meteorological parameters than wind speed and icing is more straightforward as there is more experience from measuring for example temperature and humidity. It is known that the temperature measurements are impacted by the surroundings, vegetation and design of the radiation shield. The performance of thermometers in icing conditions has also been studied extensively. The results of those studies have shown that errors of several degrees are possible when thermometers not designed for icing conditions are used in such conditions. An ice layer on a thermometer or on a radiation shield insulates the probe from the surrounding air and causes delays and dampening of errors to the temperature measurements. In the worst case, the closed measurement conditions inside the radiation shield may continue until the ice has melted [28]. 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 [28].

Measuring humidity reliably in icing and low temperatures climate is not a trivial 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, on which the calculation of dew point is based. Standard hygrometers designed for temperatures over 0 °C will give unreliable results at low temperatures [28], therefore devices designed for sub-zero operation should be used as described in [13].

Measurement instruments for icing conditions including humidity, temperature, wind speed, wind direction, precipitation and radiation, have to be properly designed and heated under icing conditions to maintain their accuracy. Classification of meteorological instruments for cold climate and icing conditions can be found from the COST727 report [45].

4 TURBINE TECHNOLOGY FOR COLD CLIMATE

There is a wide array of solutions that have been used to reduce the impact of low temperatures and ice conditions on wind turbine design and operation. The following section of this document reviews current experience.

4.1 SENSORS

Sensors for measuring wind speed (anemometer) and wind direction (wind vane) are key components in wind energy technology. They are being used for site assessment and turbine operation. State-of-the-art techniques in the wind energy technology for measuring wind speed are cup anemometers and ultrasonic anemometers. The ultrasonic instruments measure so-called vector wind speed, so they usually provide information on both the wind speed and the wind direction, while a wind vane is additionally needed to detect the wind direction, if wind speed is measured with cup anemometers.

For turbine operation in cold climate the following sensors, combination of sensors or sensors and procedures are used for wind measurements and ice detection:

For wind measurements:

- Fully heated anemometers:
  Fully heated anemometers, both cup anemometers and ultrasonic, are available on the market. Ultrasonic anemometers are typically more robust sensors in icing conditions than cup anemometers. Despite of the full heating (cups and shaft or measurement probes and main body), these sensors cannot always keep their promised specifications in heavy icing conditions. The advantage of using ultrasonic sensors, which typically measure the wind speed and direction at the same time, is that no separate wind vane is needed.

For ice detection:

- A combination of one heated and one unheated anemometers:
  Under normal conditions both sensors measure nearly identical values of wind speed. Under icing conditions the data of the two sensors deviate from each other. These incidents can be processed by the control system and the deviation in measurements can be used to ice detection. The lack of this method is that the ice detection does not reflect the actual condition of the blades.

- Nacelle anemometer, ambient temperature combined with performance data:
  Wind measurements from a nacelle anemometer in combination with ambient temperature and analysis of wind turbine performance. Deviation of actual power output from the reference power curve indicates operation under icing conditions for ambient temperatures below 0 °C. The benefit of this method is that the measured quantity (power) reflects the real condition of the blades.

- Ice detectors: Different systems are available; piezo-electric, optical and measuring of eigen-frequencies of blades:
    - The measuring principle of mainstream sensors is the analysis of piezoelectric oscillations. Under icing conditions the frequency or amplitude changes and this deviation can be processed by a computer. Tests of these sensor types under severe weather conditions have shown that the accuracy of the output signals (ice / no ice) is not always reliable. In some cases the sensitivity of the sensor can be fine-tuned to obtain higher accuracy. The lack of this method is that the ice detection does not reflect the actual condition of the blades.
    - Optical ice detectors emit infrared light to a photo sensor. Interpretation of variations between emitted light and light received by the photo sensor. The lack of this method is that the ice detection does not reflect the actual condition of the blades.
    - Rotor blade monitoring systems measure the oscillations of blades. The typical frequencies for normal operation, which means ice free operation, change if damage has happened or ice has built up on the blade. Interpretation of the blade sensor signals indicates whether the blades are iced or clear of ice. The benefit of this method is that the measured quantity reflects the real condition of the blades.

4.2 ANTI- AND DE-ICING OF WIND TURBINE ROTOR BLADES

4.2.1 Thermal anti- and de-icing systems

Blade heating may be necessary or profitable at sites which experience frequent icing or have high safety requirements for example due to 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. A simple approach to estimate the break-even conditions has been developed by Peltola et al. [15]. 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.

Recent experiences from Uljabuouda wind farm in Sweden have shown that energy consumption of anti-icing systems of 3 MW wind turbine can be as low as 0.5 % of annual energy production of the wind turbine [48].

A number of different approaches for anti-icing 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 anti- and de-icing options available.

The Finnish blade heating system, where carbon fibre elements are mounted to the blades near the surface, has operating experiences from 40 turbines at various sites, with a total of nearly 250 operating winters. The system operates as anti-icing system during turbine operation [49]. The technology is known as VTT Ice Prevention System.

Siemens Wind Power have tested a blade heating system, operating as de-icing of non-rotating rotor, originating from the same technology as the Finnish system. Results have been promising and future development will include increase in heating power to be able to operate as anti-icing [46].

Warm air circulation inside the wind turbine rotor blades is another method for de-icing. It is adequate in light icing conditions, but might not be enough for harsh climate. Typically the turbine needs to be stopped during de-icing of blades. Warm air circulation is created with a hot air blower in the blade root and thus no wiring is required further in the blade. Wind turbine manufacturer Enercon offers this kind of system as a standard feature [47]. On the performed tests approximately 50 % increase in energy yield on the 5 month testing period were achieved compared to turbine without de-icing.

An overview of known anti- and de-icing system is presented in Table 1.

Table 1. An overview of known anti- and de-icing systems.

Turbine manufacturers offering anti- or de-icing	
Enercon – Rotor blade de-icing system	Warm-air circulation
Nordex – Anti-icing for rotor blades	Electro-thermal heating elements
Siemens – BDI (Blade De-Icing)	Electro-thermal heating elements
WinWinD – Blade Ice Prevention System	Electro-thermal heating elements
Independent system/solution providers	
EcoTEMP	Electro-thermal heating elements
Kelly Aerospace – Wind turbine ice protection system (WTIPS)	Electro-thermal heating elements
VTT Ice Prevention System	Electro-thermal heating elements

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

Blades painted black is not a solution for anti- or de-icing. In the winter time solar intensity might not be enough and in the summer time the solar energy might heat the blades to too high temperatures for blade materials.

4.2.2 Anti-freeze coatings for rotor blades

Antifreeze coatings have been investigated widely in the last years. Many coatings have been promising in the laboratory tests, but none of them has proved to be functional or enough wear resistant in field conditions.

Researcher from the Institute of Materials and Process Engineering of the Zürcher Fachhochschule Winterthur from Switzerland has investigated antifreeze coatings based on proteins – known from arctic fish. Contrary to the traditional antifreeze compounds, the effect of the anti-freeze proteins is not proportional to their concentration. Anti-freeze proteins inhibit crystal growth and ice formation starts at much lower temperatures. Synthetically prepared polymers can mimic the effect of the anti-freeze proteins. Coatings of such polymers could prevent icing.

Various polymers were investigated in order to explore their freezing point depression properties. Polymers were coated on glass and the resulting coating was subjected to varying air humidity and cooling ramps in a cold chamber. The formation of ice on the coating was compared with the formation of ice on the glass. It was observed that ice forms on some of the coatings at lower temperatures than on the glass.

Two effects can be distinguished: 1) Freezing point depression. Water freezes at lower temperatures on the coating. 2) Delay of condensation. Water condenses only at lower temperatures on the coating. Hence, the apparent freezing point depression on the polymer surface is in reality a delayed condensation of water at the surface.

Compounds were developed which suppress the freezing temperature of water on glass surfaces. This effect could be based on the antifreeze effect of arctic fish.

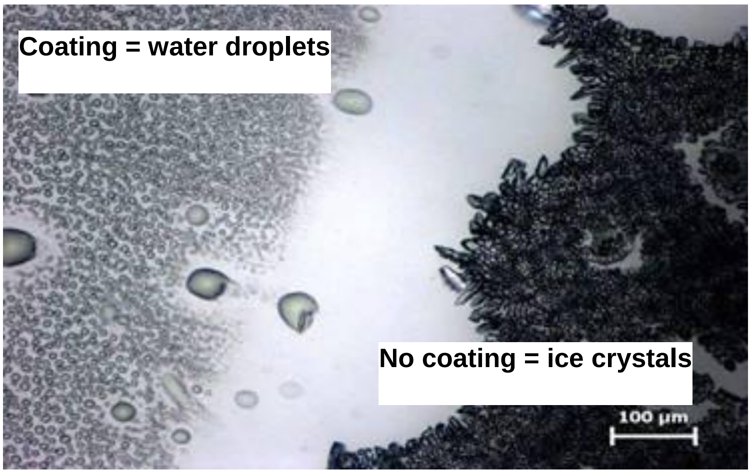

Figure 11. Formation of ice on a non-coated surface illustrated alongside with the situation of a coated surface [44].

4.3 LOW TEMPERATURE MATERIALS AND LUBRICANTS

Most turbine manufacturers 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.

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 [18].

Tests at the National Wind Technology Centre, USA, have 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" [53]. These tests, one of the few being conducted specifically to look at issues related to wind turbine construction, show that operation in cold temperatures does not always result in damage, but may actually improve the performance of the system.

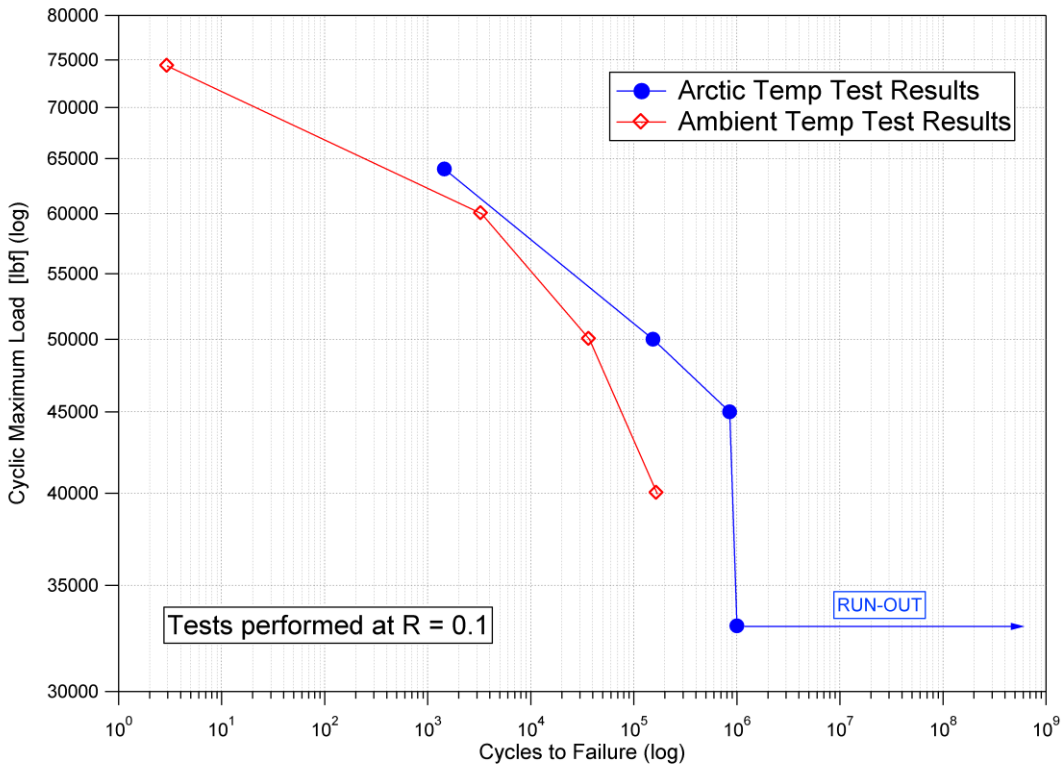

Figure 12. Cyclic fatigue pull tests on blade studs conducted at NREL comparing studs at standard (20 °C) and arctic(-48 °C) temperatures.

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.

4.4 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 in the Alps. The gearboxes and yaw systems need to be heated and kept free of ice, as do any disk breaks or separators.

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 [18], [29]. Especially important is the protection of control electronics against moisture and condensation at the sites where low temperatures during the winter is frequent.

4.5 O&M

Turbines may locate at remote sites and the access to the sites may be difficult or even impossible during part of the winter. It is possible that the access to a site may be limited to snowmobiles, which only allows 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 the 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 STATUS IN DIFFERENT COUNTRIES

Wind farms have been installed to cold climate sites since the early nineties. At the present moment there is thus a number of sites with either existing or projected wind parks in cold climates: Northern and Central Europe, Northern America and Asia (China and Russia). Task 19 estimated that at the end of 2011 there was all together approximately 10 000 MW installed at sites where wind turbines face climate conditions that are below the operational temperature range of standard turbines i.e. at cold climate sites. An example list of identified wind energy projects that are located at cold climate sites is presented in Table 2.

Table 2. Examples of cold climate wind energy projects.

Site	Country	Latitude	Elevation
Aapua	SWE	66.5	423
Aqcua Spruzza	ITA	41	1 360
Ajos	FIN	65.7	0
Bliekevare	SWE	64.37	743
Brandenkopf	DE	48.2	950
Cambridge Bay	CAN	69	0
Feldmoos Entlebuch	CH	46.9	1 020
Gütsch, Andermatt	CH	46.6	2 300
Haeckel Hill, Whitehorse	CAN	60	1 430
Hirtstein	DE	50.3	880
Hornisgrinde	DE	48.6	1100
Kjøllefjord	NO	70	320
Nine Canyon, Washington	US	46	200
Nygaardsfjellet	NO	68	400
Olostunturi	FIN	67	500
Pori	FIN	62	0
Sandhaugen	NO	69	420
Scheid	DE	50.2	580
St. Brais	CH	47.4	1 100
Tauernwindpark, Oberzeiring	AUT	47	1 900
Uljabuouda	SWE	65.58	800
Windy Standard	UK	55	600
Viscaria	SWE	67.52	620

The latest operational experience reported by the permanent members of the IEA Wind Task 19 on wind turbine operation in cold climates is presented in the chapters of this document.

5.1 NORTHERN EUROPE

5.1.1 General

Atmospheric icing in Northern Europe is very much a local phenomenon. Icing may occur at all existing wind farm sites in Finland, Sweden and Norway but the icing climate of different regions varies considerably. Due to the warming effect of the sea, the average temperatures at the Atlantic coast and in Lapland differ greatly even though the areas are located at the same latitude; monthly average temperatures during the winter are between about 0 °C near Atlantic Ocean and -20 °C in the inland of Lapland. Therefore icing is only occasional or nearly non-existent in the coastal areas along the Atlantic coast, whereas severe icing conditions may occur at inland sites, especially those that are located at high altitudes. In spite of the challenging climate conditions in most parts of the Northern Europe, wind power has considerable potential. Especially coastal areas and elevated inland areas are attractive sites for wind turbines due to their good wind resources; annual average wind speeds up to 10 m/s are possible.

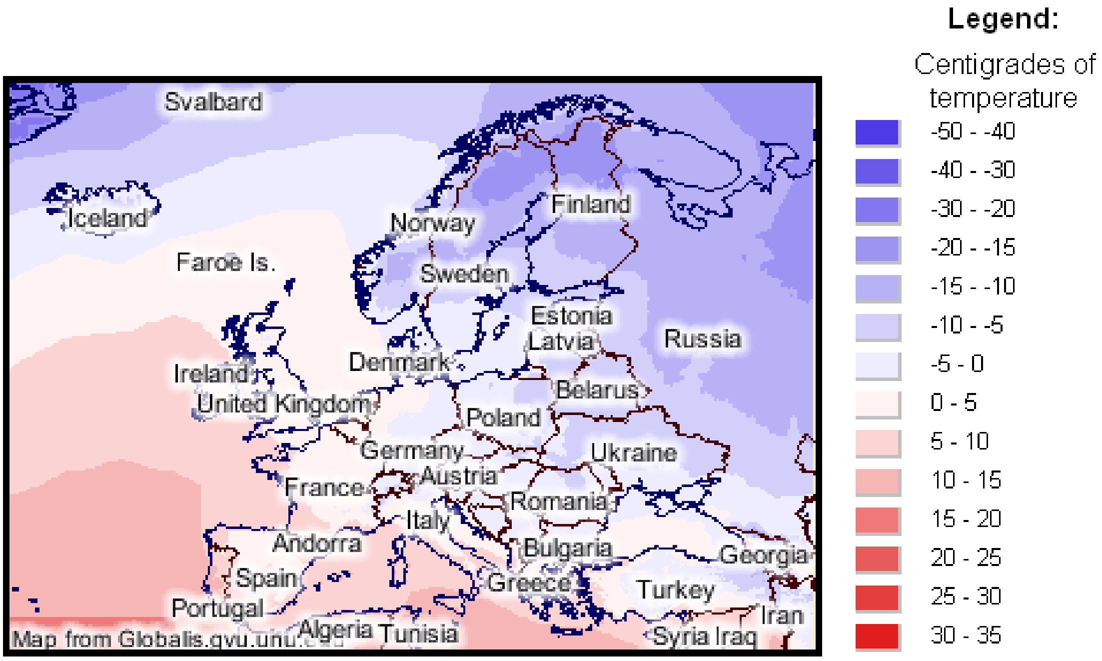

Figure 13. Temperature Europe January: Average January temperature through the years 1961-1990; Source: Climate Research Unit (CRU) - University of East Anglia, Norwich http://globalis.gvu.unu.edu/.

5.1.2 Existing capacity

The installed cold climate capacity in Scandinavian countries is presented in *Table 3*.

In Finland the entire wind capacity can be considered to be located in cold climate as all the wind turbines face temperatures outside the limits of standard wind turbines. On the other hand, icing is severe only in Lapland, where high elevation combined with icing and as low as -13 ºC monthly average temperatures during the winter make conditions challenging.

Table 3. Existing cold climate capacity in Scandinavia in 2010.

	Finland	**Sweden**	**Norway**
Cold Climate Capacity	197 MW	124 MW (16 % of total)	48.5 MW
Adapted cold climate technology	50 MW	13 MW	1.5 MW
Cold Climate potential	3 000 MW [1]	6 400 MW (56 % of all planned)[2]	2 000 MW[3]

Defining criteria: Low temperature = more than 9 days below –20 per year / Long term atmospheric icing annually

[1]Technical and economical by 2020
[2] Dagens Nyheter, 2009-02-12
[3]Notified or applied for to the Norwegian Water Resources and Energy Directorate (NVE)

O2 Vindkompaniet studied the wind power potential by mapping the areas that fulfil the requirement of an annual mean wind speed at hub height of 7 m/s. They found sites in cold climate regions where 10 times more energy could be produced compared to easily accessible offshore. The interest for wind energy in cold climates took off in March 2007 when E.ON declared that in spite of a $10M subsidy, the proposed offshore wind farm Utgrunden II could not be built. Presently, the investment and O&M costs for offshore wind energy are more than 50 % higher than for onshore [61]. In Sweden, wind energy in cold climates has a great potential if icing and, to a lesser extent, low temperature issues can be solved.

Total installed capacity in Norway was 487 MW at the end of 2011. Nearly all the wind farms are situated at an altitude below the limit where icing starts to be a problem. This limit varies with latitude, distance from the shore line and the local topography.

Norway has a long shoreline facing the warm waters of the eastern part of the North Atlantic Ocean. 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), -4 ºC is the lowest monthly average temperature at sea level.

On the highest coastal mountains the icing can get very severe with ice loads of more than 50 kg/m on a ISO cylinder. Due to the complex topography, the icing conditions will also vary locally. Super-cooled cloud droplets tend to dry out when they are transported over a hill or a ridge.

Norway has three small installations at or close to the altitude where icing occurs more frequently, Nygaardsfjellet, Sandhaugen and Mehuken.

The large wind farms are mainly installed at 200-300 m above sea level as shown in Table 4. The listed wind farms represent 392 MW or 89 % of the total installed capacity. The down time and production losses at all these wind farms are minor.

Table 4. Locations of large wind farms in Norway.

	Height above sea level	Latitude
Kjøllefjord	300	70°
Havøygavlen	280	70°
Hundhammerfjellet	200	64°
Bessaker	360	64°
Hitra	300	63°
Smøla	30	63°

5.1.3 Cold climate sites/experiences

Finland

Finland's national wind energy statistics contain reports of the operation of wind turbines, including turbine down time. Down time due to ice and low temperatures has been reported since the starting of the reporting.

According to the statistics [50], low air temperature has lowered turbine availability annually between 0.2 % and 2.8 % since 1997 to 2010. Depending on the year, 1 to 27 turbines have been forced to be shut down due to low air temperature per year. The average down time per turbine due to low temperature between 1997 and 2010 is 123 hours, which corresponds to 1.4 % of the annual operational hours. Turbines that report down time due to the low air temperature are mainly located in the northern part of the country. During years colder than average, turbines suffer from low temperature in the entire country. On average 10 turbines per year has been shut down due to low temperature per year. Typically the duration of shutdown is short in southern Finland.

Icing has lowered turbine availability approximately 114 hours per year per turbine (1.3 % of annual operational hours) for those turbines that have reported icing between 1996 and 2010. The availability decrease due to icing has varied between 0.3 % and 4.1 % per year per turbine. On average 16 turbines (varying between 4 and 30) per year has reported down time due to ice annually.

Norway

Norway does not have a centralized system for collection of operational experience from wind farms. Data for downtime and production loss due to icing or low temperature is therefore generally not available.

Based on a general analysis of the wind farm sites, none of the sites is in the zone where heavy icing is expected. Four of the installed wind farms are located in areas where light icing is expected.

The highest elevated wind farm in Norway is the Nygaardsfjellet wind farm. It consists of three 2.3 MW turbines and is located at 68° north and 430 meters above sea level. At this site the owner, Nordkraft Vind AS is using one of the turbines for R&D purposes. Ice detectors and two web cameras are installed on the turbine. The experience with the turbine so far is that the production losses are small, approximately 3 % on an annual basis.

At Sandhaugen, close to the city of Tromsø at 69° north, a single GE 1.5 MW wind turbine is installed. The base of the turbine has an elevation of 410 m above sea level. The turbine is a private R&D installation. No figures indicating down time or production losses are known to the public. According to the owner of the turbine, the problems due to atmospheric icing are small.

Kvalheim Kraft owns a wind farm consisting of five Vestas 850 kW turbines. They are located at latitude 62° and about 410 meters above sea level. The only arctic adaptation made is the use of heated sonic anemometers. The turbines 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 standstill 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.

There is a 40 MW wind farm at Kjøllefjord at latitude 70° and 300 meters above sea level, and a 40 MW wind farm at Havøygavlen at latitude 71° and 275 meters above sea level. In addition, there is a 6.9 MW wind farm at Nygaardsfjellet at latitude 68° and about 400 meters above sea level. No publicly available reports on experiences of cold climate are published from these wind farms.

A test turbine was erected at Sandhaugen close to the city of Tromsø in January 2004 at latitude 69 and 420 meters above sea level. 20-25 icing days a year is reported at the Sandhaugen test turbine. No detailed statistics on failures or energy loss are reported publicly.

Sweden

As production reporting has been largely automated, operation and maintenance reports are scarcer than before. Additionally, since the investment subsidies were scrapped in 2005, turbine owners of newer turbines are not even required to report their production to http://www.vindstat.nu/. It should, however, be possible to obtain this information via the green certificate system. The Swedish Energy Agency needs to consider what measures it has to take to obtain production statistics after 2012 and 2014 when the early installed wind turbines are no longer eligible for green certificates. The planning goal for wind, as proposed by the Swedish Energy Agency in December 2007, is 30 TWh of which 10 TWh is to be located offshore and 20 TWh onshore. The Swedish Wind Energy Trade Association collects wind energy project information in categories A-D depending on how far the process has come for a particular project. Only projects in category A are made publicly available. In addition, many developers and manufacturers claim they don't report all their projects to the Swedish Wind Energy Trade Association. A recent survey by Dagens Nyheter indicates 54 TWh of projects, including offshore, of which 30 TWh are planned in areas where cold climate conditions will occur.

5.1.4 Technology development taken place

Anti-icing technologies has been developed and tested in Finland since 1995. This is due to the fact that northern Finland is mainly uninhabited and the fjell peaks between 350 meters and 600 meters above sea level provide good wind resource; annual average wind speeds up to 8 m/s are possible. However, the icing conditions at the fjell tops are challenging. Atmospheric icing may take place up to 100 days per year.

The anti-icing technology used in Olos and Pori, which is based electro-thermal heaters assembled on blades, has been developed for multi-megawatt size turbines, up to 100 m rotor diameter. VTT Technical Research Centre has developed ice prevention solutions based on this technology together with wind turbine manufacturers and more than 20 turbines has been installed to Sweden, in Uljabuouda, Jokkmokksliden and Storliden wind farms. The energy consumption of the systems has been less than 1 % of annual energy production of the wind turbines. The owner of the wind farms, Skellefteå Kraft Ab, has reported to be satisfied with the performance of the ice prevention systems and is planning to equip all turbines to be built in Blaiken wind farm with the particular system.

VTT Technical Research Centre of Finland has developed an icing wind tunnel which is capable to reproduce in-cloud icing conditions. The tunnel has been used for studying the behaviour of anemometers in icing conditions, ice detector development and experimental research and development of ice prevention solutions. The weather parameters to be simulated in the wind tunnel can be adjusted to be suitable for most of the relevant conditions in wind energy.

Sweden has participated in COST 727 – Atmospheric icing of structures since 2004. Activities include icing measurements at four different elevations (15, 70, 155 and 240 m) in a telecommunication mast and on the nacelle of a nearby wind turbine. Evaluation of the power performance indicates a loss of 5 % in energy production due to icing between December 11th 2007 and the end of April 2008.

A de-icing system based on an external heating foil on the leading edge of the blades has recently been installed on a Vestas V90 2MW turbine in Bliekevare. Ten WinWind turbines on Uljabuouda were be equipped with de-icing systems by 2010. The latter project starts with four turbines in 2009. The de-icing systems in Bliekevare and Uljabuouda are financed by the Swedish Energy Agency in the frames of wind pilot projects.

Saab Security has developed an ice-load sensor, the IceMonitor, and HoloOptics is continuing the development of its T20-series of ice detectors. Both sensors have been tested during the course of COST 727 – Atmospheric Icing of Structures.

Cold climate wind energy conferences, called Winterwind, with participants from 150 up to 400 each were arranged in Sweden since 2008. The Winterwind conference has become the number one event of cold climate wind energy. The presentations from these conferences can be downloaded from http://winterwind.se/.

5.2 CENTRAL EUROPE

5.2.1 General

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

In those three countries, 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, ranging from 1300 metres to 3000 metres above the sea level. Typically sites below 1500 metres above sea level experience light icing whereas sites at higher altitude are prone to heavy icing and low temperatures.

5.2.2 Existing capacity

The installed cold climate capacity in Switzerland, Germany and Austria is presented in Table 5**.**

Table 5. Existing cold climate capacity in Central Europe.

	Switzerland	**Germany**	**Austria**
Cold Climate Capacity	35 MW	1 000 MW	200 MW
Adapted cold climate technology	20 MW	n.a.	2 MW
Cold Climate potential	1 200 MW	2 500 MW est.	1 000MW (estimated)

Defining criteria: Low temperature / Atmospheric Icing

In Germany, atmospheric icing has been observed and reported from all site categories, i.e. from coastal sites, the plains of northern Germany and from low mountain regions. However, the frequencies of icing and reported downtimes from mountainous regions are significantly higher than in the other parts of the country. The figures in Table 5 refer to the sites with a minimum altitude of 500 meters above sea level.

The same situation applies for the wind farm sites in Austria. Most of the wind turbines have been installed in the East of the country, in the flat regions of Burgenland and Lower Austria. In those regions, meteorological icing happens only 1 to 3 times per year. When it comes to wind farm locations in the Austrian Alps with elevations up to 2.000m above sea level, meteorological icing happens quite frequent (<30 days per year) and large ice accretions.

Since most of the interesting wind energy sites in Switzerland are located over 800 meters above sea level, about 90 % of the entire wind potential of 4 000 MW can be considered to be in cold climate or at icing sites. Among the actual installations, only the wind turbines in Collonges (Enercon E-82) are not affected by rime, ice and cold temperatures.

In Switzerland, cold climate technology is implemented at the installation in Mt. Gütsch (1 Enercon E-40, 600 kW, Class 1, 2 350 meters above sea level) and in Rengg (1 NEC-Micon 52/900, Arctic Version)

5.2.3 Typical cold climate sites/experience

Germany

In-cloud icing with accretion of rime ice and wet snow are the most often observed situations of turbine icing in Germany. Freezing rain is possible yet rare. Due to the moderate climate conditions and frequent changes between cold (continental climate) and relative warm air (maritime climate) the downtimes caused by icing usually don't last longer than about week. However, in mountainous regions in altitudes above 800 meters above sea level downtimes of up to two months have been reported. The following chart compares the percentage of wind turbines and the equivalent share of reported icing incidents per site category (coastal, lowland plains and mountainous regions). The total number of wind turbines in the data pool is ~1,650 while the number of icing reports is ~1,050. It is obvious that the small share of turbines in Germany which are operated in mountainous areas are affected significantly stronger by turbine icing than the majority of the existing installations. However, the number of installations affected by icing is expected to increase in the future as more and more wind turbines are planned to be erected in mountainous areas.

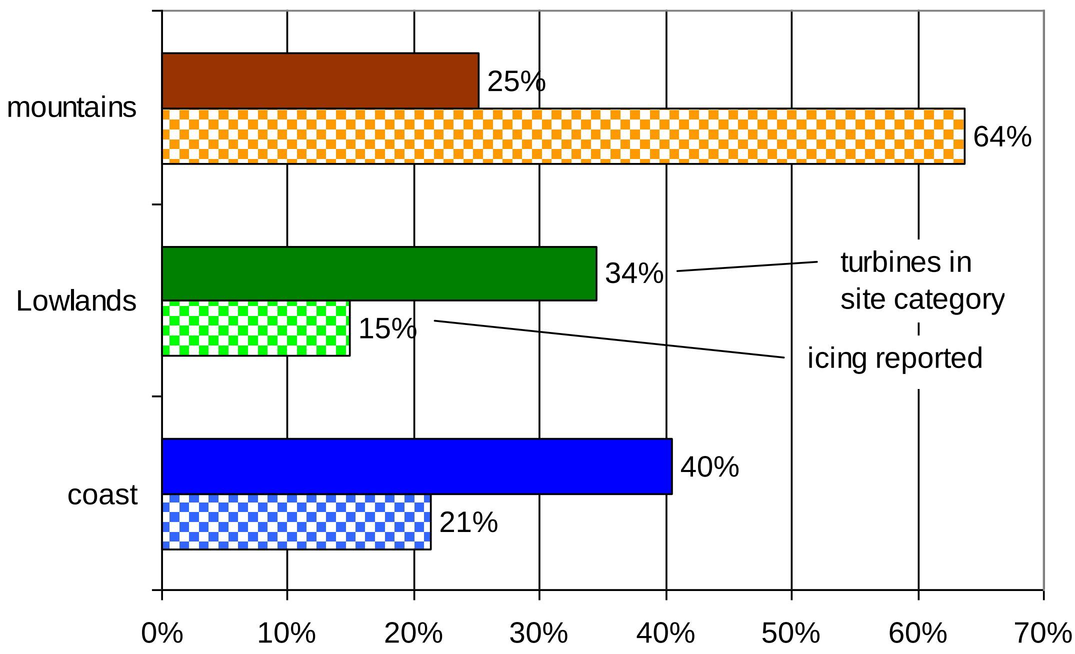

Figure 14. Turbine installations and icing reports per site categories in Germany (courtesy of Deutscher Windmonitor / ISET e.V, 2009.).

Switzerland

Apart from one installation, all the current wind turbines in Switzerland are imposed to cold temperatures and icing.

Mt. Gütsch, Switzerland, Enercon E-40, 600kW, Class 1, 2 350 m.a.s.l

Thanks to the set-up with measuring instruments from the Swiss Met Institute and a well-equipped E-40, various research projects have delivered results from this particular wind energy site (see also "Alpine wind test site in Switzerland" in chapter 5.2.4).

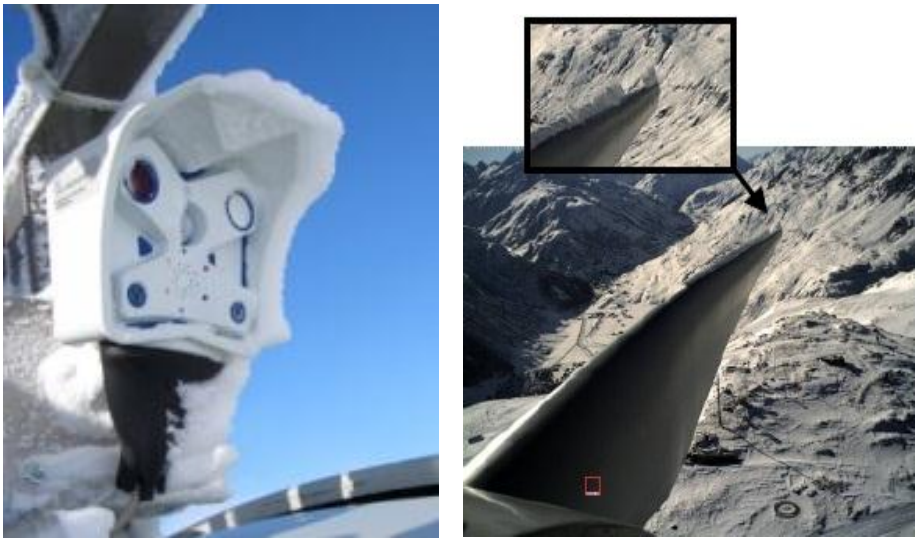

Figure 15. Webcam on Hub of E-40[1]*.*

Feldmoos, Switzerland NEC-Micon 52/900, Arctic Version, 1 056 m.a.s.l

Figure 16. Feldmoos turbines.

Icing is not a big problem on this site. The turbine has typically been shut down two or three times during winter due to icing. There is no blade heating device; the turbine shuts down automatically if the turbine control anemometer doesn't send any signal. De-icing takes place with the sun. In practice, turbine will stand still and the sun will melt the ice and thus the ice throw occurs only within about 30 m distance from the turbine.

Grenchenberg, Switzerland, Bonus 150 kW, 1 300 m.a.s.l.

Figure 17. Grenchenberg turbines.

On this site heavy rime ice occurs, but there are no possibilities to remove it – besides by the radiation from the sun. This means down time up to one week.

Austria

In the Wind Farm Moschkogel (Figure 19. Wind farm Moschkogel in the Austrian Alps) located at 1 600 m.a.s.l. in the Austrian Alps, five ENERCON E70 wind turbines have been equipped with rotor blade heating systems. During the first two years of operation a heating system was used that provided warm air from electrical heating transistors placed along the inner side of the leading edge (Figure 18). Due to disappointment with this initially used heating system, all blades of the 5x 2,3 MW turbines were exchanged in summer 2008 and equipped with an amended heating system based on warm air circulation inside the blade. The total heating power of that new system is 70 kW per turbine.

Figure 19. Wind farm Moschkogel in the Austrian Alps.

To assess the reliability of the two different heating systems, in a first step a detailed analysis of the operation mode during the last four years has been performed:

The ENERCON turbines automatically shut down as soon as ice accretion on the blades is detected. The detection of ice happens via the power curve method, which is based on the sensitivity of rotor blade profiles against change in contour and roughness. The resulting significant change in a WEC´s operating performance is used to detect ice build-up (interrelation of wind / rotational speed / power / blade angle). This power curve method is able to detect ice formation even in a situation when ice detectors on the nacelle are not detecting ice because WEC´s with large rotor blades may dip into clouds and thus be affected by icing conditions. A disadvantage of the power curve method is that it is not able to detect ice during standstill of the rotor.

The monitoring of blade heating is based on 10 min time series data, recorded by the wind turbines, i.e. wind speed, temperature, power output and status data (Figure 20. Operational data (example January 2008)). No additional measurements of pressure, humidity or ice-detection have been performed.

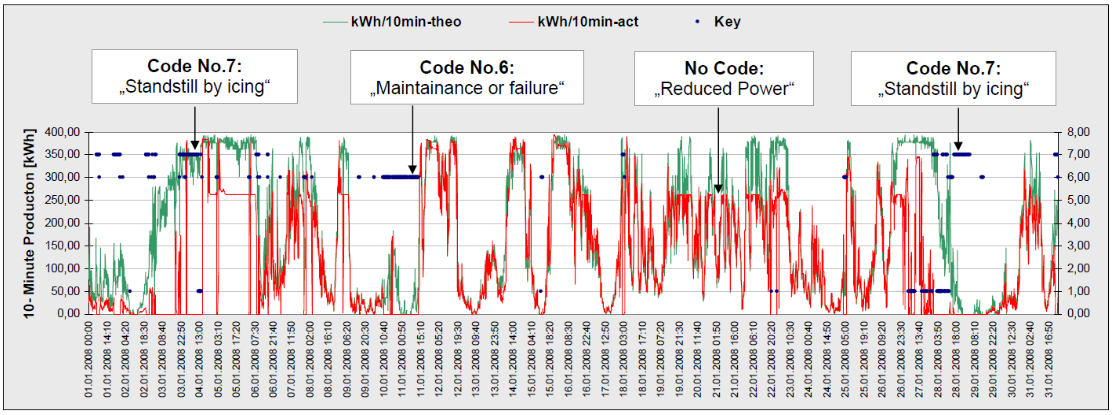

Figure 20. Operational data (example January 2008).

The calculation of production losses due to icing (and other turbine errors) is based on comparison of the actual 10-minute energy production against the theoretical energy production calculated from the power curve and the wind speed data of the anemometers on the turbine nacelle. Through that approach statistics have been prepared regarding the reasons for operational standstills, which (amongst others) reveal how high the energy loss of individual turbines is due to icing. Additionally the two different rotor blade heating systems used at WF Moschkogel have been compared and assessed using that approach.

RESULTS

As a result of the analysis (Figure 21. Technical availability with and without ice) the theoretical availability of the turbines (without losses due to icing) has been plotted against the actual availability (including standstill due to icing).

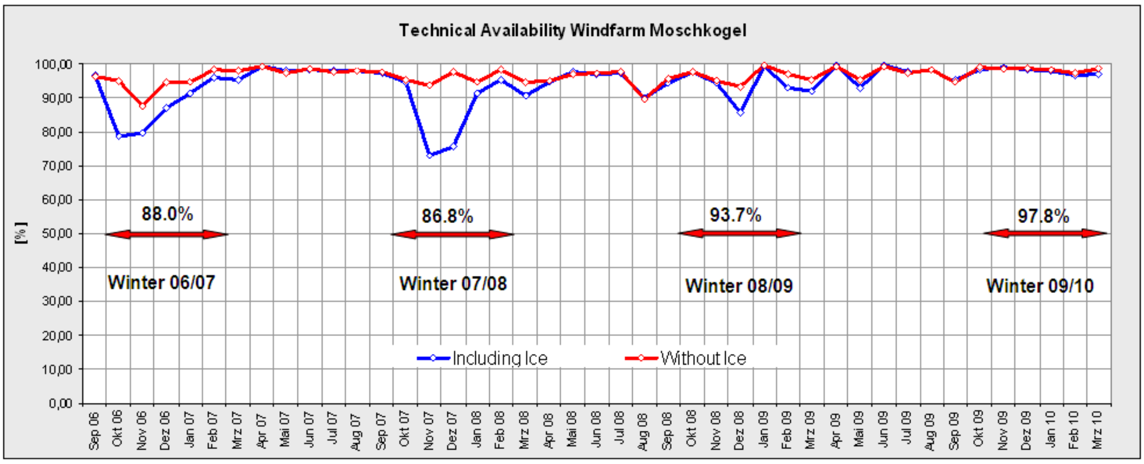

Figure 21. Technical availability with and without ice.

From the result above the following conclusions can be drawn:

- The heating system using warm air circulation leads to an improved availability
- 'De-Icing' & automatic re-start works in principle, but no technical verification is available
- 'Anti-Icing' during operation is possible, but no technical verification is available
- Detection of ice on rotor blades during stand still is not possible
- Operator has to carry the risk for automatic operation and 'Anti-Icing' during operation
- ENERCON heating system has to been accredited by the authorities.

5.2.4 Technology development taken place

Important experience on the use of wind energy under climatically extreme conditions has been gained with the 800 kW plant on the Gütsch near Andermatt (2300 m above sea-level) which was commissioned in spring 2002. Even though the turbine has been in operation many years, it still provides valuable information about cold climate wind energy. This is the first wind turbine in Switzerland that uses technology adapted for 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 the alpine region in harsh climatic conditions.

Alpine wind test site in Switzerland

At Mount "Gütsch", 2'350 m.a.s.l near Andermatt in Switzerland, an interesting set up was installed in 2002 in order to investigate the problems of icing on wind turbines under alpine conditions. The test site is located on a ridge in a highly complex terrain.

Next to a test bench for anemometers and ice detectors from the Swiss Met Institute, there is an Enercon E40 class 1 wind turbine installed, equipped with various additional data collecting instruments.

The research will be done in collaboration with COST 727 and IEA Wind Task 19.

The prevailing wind directions are north and south (Foehn). Winds are very variable and during strong Foehn events wind speeds can easily reach 120 km/h or more. The long term average monthly temperature varies from -6.9 °C in February to 7.3 °C in July and drops below 0 °C from November to April. The main icing periods are late autumn and early spring when the temperature frequently lies around 0 °C. Icing can occur throughout the year. In midwinter the temperature may fall below -20 °C.

Icing on Gütsch occurs mainly as in-cloud rime icing, mostly when winds from the north lift the humid air of passing fronts over the Gütsch ridge. Icing occurs regularly during winter time but the ice loads are usually not very high (up to 6 kg/m). The duration of the ice accretion is in the range of hours and the persistence of the ice on the unheated structures lies in the range of hours to single days.

The goal of the Swiss project "Alpine Test Site Gütsch" is to expand the knowledge base on atmospheric icing specifically in the Alps. Tasks of the research on this site are:

- Studying icing process on rotor blades and other structures
- Analysing quality of icing detecting devices
- Improvement of the de-icing strategy Enercon E-40
- Verification of the recommendations from the IEA Wind Task 19 "WECO" for the alpine area
- Verification of the “Guidelines for the security of wind-power installation in Switzerland“
- Optimization the operating strategy of the wind turbine E-40 Gütsch under icing conditions (from "De-Icing" to "anti- Icing") l
- Development and publication of a manual “Operating wind turbines under freezing conditions in the alpine region "

The project includes an inter-comparison of ice detectors, the performance monitoring of a wind turbine and recommendations for the estimation of icing conditions at sites not equipped with ice detectors.

The ice detector inter-comparison has shown surprisingly poor results so far; no device has been able to measure icing correctly for a whole winter season. The monitoring of the wind turbine pointed out deficiencies in ice detection as well as blade heating performance. An extensive observation of the wind turbine's ice throw proved that a significant safety risk has to be taken into account at this site. Furthermore, a simple meteorological approach to identify icing conditions was tested with fairly good results. Finally, modelling of two icing events with the NWP model WRF was accomplished, showing promising agreement with on-site observations.

Figure 22. Installation on Mt. Gütsch with Enercon E-40 and test bench of the Swiss Met Institute.

5.3 NORTHERN AMERICA

5.3.1 General

Canada offers what is generally considered cold climate conditions. But in areas where cold air temperature is not an issue, such as along the coasts, atmospheric icing may still become a concern. For instance, rime ice occurs at high elevations on the West Coast and on the Appalachian mountains while glaze prevails in Central and Atlantic Canada. Rime can also take place at lower elevations near areas of high evaporation. Either in grid-connection or in remote communities, wind turbines in Canada are impacted by cold climates issues.

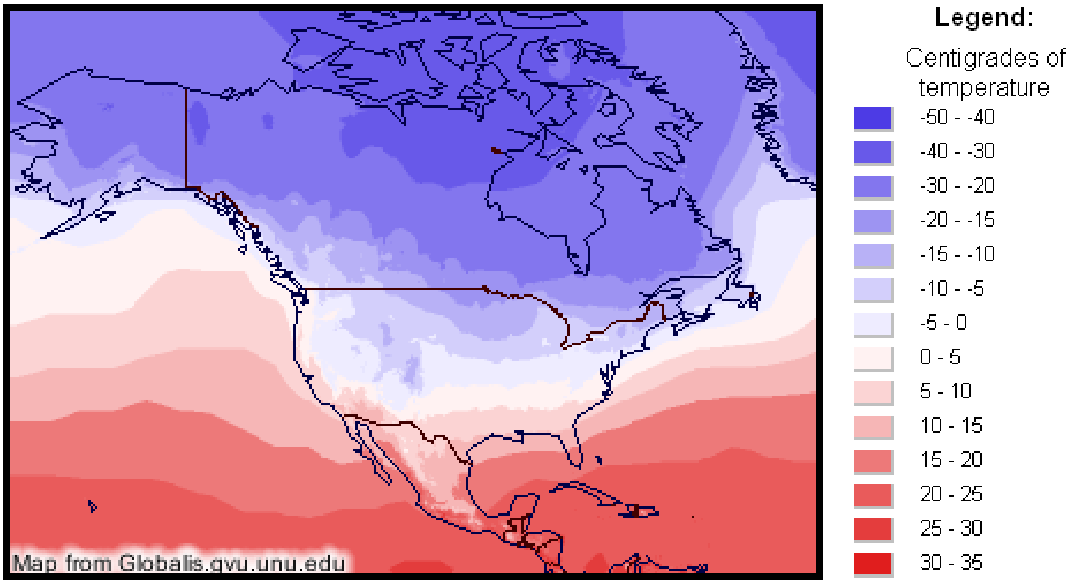

Figure 23. Average January temperature through the years 1961-1990; Source: Climate Research Unit (CRU) - University of East Anglia, Norwich http://globalis.gvu.unu.edu/.

5.3.2 Existing capacity

The installed cold climate capacity in the USA and Canada is presented in Table 6.

In Canada, the installed capacity in utility wind energy went from 137 MW in 2000 to 1876 MW in mid-2008. For the year 2007, the amount of wind-generated electricity has been estimated to be around 4.3 TWh. This represents approximately 0.8 % of the national electric demand. The Canadian Wind Energy Association calls for an ambitious growth in installed capacity in order for wind to meet 20 % of the electricity demand by 2025.

Table 6. Existing cold climate capacity in the USA and Canada in 2010.

	USA	**Canada**
Cold Climate Capasity	Data not available	1 823 MW / 2 239 MW
Adapted cold climate technology	Data not available	1 500 MW / 220 MW
Cold Climate potential	Data not available	45 000 MW / 55 000 MW

Defining criteria: Low temperature / Atmospheric Icing
Note: it is difficult to evaluate the wind turbines fitted with cold climate technology as the information is usually kept proprietary. The figures shown are considered gross estimates.

5.3.3 Typical cold climate sites/experience

Operational experience of wind turbines in cold and icing climates in the USA 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 affected 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 severe 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 is along the arctic coast, such as the 0.5 MW plants 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 than 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.

One operator in Canada has identified overproduction in cold temperatures 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 [16]. Also on a 65 kW Bonus machine located in Kuujjuaq (58° N), a 5-minute average power output of 89 kW was recorded [16].

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 [29]. Maissan [29] 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 [29].

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 and noticed an improvement in turbine output. In addition to the more obvious solutions for cold weather climates, he recommends that turbines are 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 [29].

5.4 EASTERN AND SOUTHERN EUROPEAN COUNTRIES

Several of the countries in the eastern and south-eastern Europe have significant wind energy resources in areas that are prone to icing. The process to develop such sites in this part of the world has barely started. Turkey, for example, has a goal of installing 20 GW until 2020. Applicants were invited to submit their proposals during one day only and the result was 71 GW. Romania and Bulgaria are other countries with significant wind energy potential and a desire to lower the dependency on natural gas from Russia. An icing map for Romania in February made by Sander is shown in Figure 24.

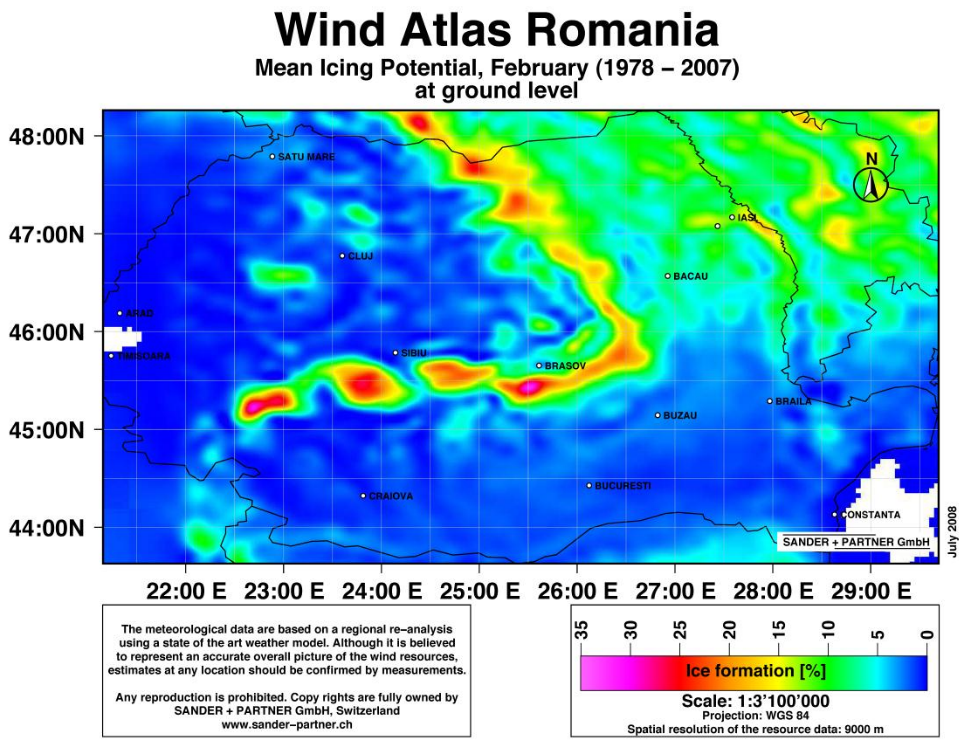

Figure 24. Icing map by Sander for Romania and Moldavia in February.

6 OPERATIONAL EXPERIENCE

6.1 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 stall controlled wind turbines [42]. In most cases this will be detected by the wind turbine controller resulting in a turbine shutdown. Any operation on overrated 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 aerodynamic and mass induced forces. In addition, ice usually sheds from the blades unevenly resulting in further loading on the turbine [14] 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. Since other extreme load sources, 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 [43], [54].

Ice thrown off the blade may also pose a safety risk even in areas where icing is infrequent, especially when the turbines are situated close to the public, such as roads 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 the 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. Iced wind vane may lead to operation in a misaligned yaw or to a production stop due to the misalignment.

6.2 OPERATIONAL EXPERIENCE IN LOW TEMPERATURES

Low temperatures have an effect on materials and 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 a 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. The start-up procedure of turbine should include a heating of gearbox oil before starting the power production in order to get the viscosity of the oil in the right level.

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 for the wires and other turbine parts not considered in most system impact assessments. Wires for which the insulation becomes brittle may fracture, leading to shorting, have caused many problems in turbines that have been otherwise 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 % on top of the 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 [16]. This leads to production losses and probably has led to generator failures [17]. 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.

6.3 SAFETY – ICE THROW

6.3.1 Background

It is important to assess the risk of ice throw with respect to health and safety (H&S) as well as public safety. Previously, it was sufficient with respect to the public to install warning signs indicating the risk of ice throw at a safe distance[1] from each wind turbine. A current trend is for the authorities to require a risk analysis using measured wind speed, direction and icing data to define the risk area around each turbine.

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[1] According to WECO [5] project; d=1.5(H+D).

6.3.2 Examples

In order to better estimate the safety risks, the ice throw of the Enercon E-40 (600 KW, hub height 50 m, rotor diameter 40 m) was observed and documented in the framework of the project "Alpine test Site Gütsch" starting from 2005. After every de-icing event by the turbine, the area around the turbines was searched for pieces of ice.

Figure 25. Examples of ice pieces, the heaviest ice piece was 1.8 kg.

Figure 26 illustrates the distribution of the ice found under the turbine on Mt Gütsch. Most pieces of ice were found directly under the turbine. Hardly any pieces were found in the northwest sector. This is because on Gütsch, the prevailing winds during freezing events frequently are from north and therefore the most pieces of ice were thrown towards west. These results show clearly that the ice throw risk in the periphery of the turbine depends strongly of the wind statistics during the icing events.

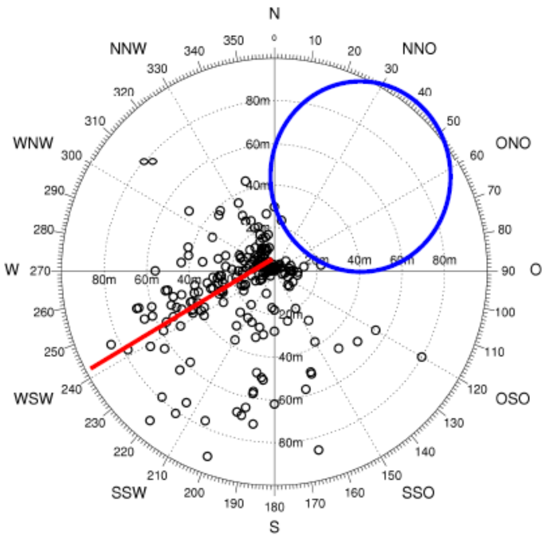

Figure 26. Distribution of found ice pieces on Mt Gütsch.

The following results from the evaluation of over 220 pieces of ice were found:

- On the Gütsch ice throw occurs regularly, also during the summer months

- Ice pieces were found in distances up to 92 m of the turbine. The theoretical maximum distance of 135 m (in accordance with the formula from H. Seiffert, [5]) was not reached.

- The maximum weight of a piece of ice was 1.8 kg

- About 50 % of the pieces were found in a distance of 20 m or less (radius of the rotor blade: 20 m).

- The pieces of ice had not necessarily been thrown away by the rotating blades, often they just drop straight downward.

- The largest ice throw risk exists during the heating procedures of the blades or during the re-start directly after the heating

Figure 27. Warning sign on Mt Gütsch.

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 with the distance of 1.5*[hub height+rotor diameter] from turbine in all directions. Tammelin et al [5] 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 28*.

Figure 28. Warning against shedding ice fragments at Tauernwindpark in Austria. Photo from http://www.tauernwind.com.

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

Canadian Wind Energy Association (CanWEA) ordered from Garrad Hassan Canada Inc. (GHC) a study including firstly recommendations for assessing the risk of ice fragments shed from wind turbines striking members of the public in the vicinity of wind farm projects in Ontario and secondly a literature review of wind turbine rotor blade failures based on publicly available information, [55].

In the publication, [55], "RISK ANALYSIS OF ICE THROW FROM WIND TURBINES" the authors came to the following conclusions. The experience and the results of many calculations show that during operation small fragments are hitting the ground at a longer distance than large pieces, whereas from stopped turbines the larger pieces can be transported further than small ones. However, when the turbine is operating, the area of risk is larger than at standstill. In both cases, the wind direction is an important parameter for the assessment of possible risk and for the behaviour of the control systems during icing events. Ice sensors or ice detection by using power curve plausibilisation or two anemometers – one heated, one unheated – are not reliable enough for desired automatic shut down and restart of turbines during icing events at the moment and needs to be improved.

7 EXISTING STANDARDS AND REQUIREMENTS

7.1 WIND TURBINE CERTIFICATION

Certifying wind turbines for cold climate 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 Turbines -Design Requirements recommends taking ice loads into account, but a special load case is not given and no minimum ice requirements are given for standard wind turbines, [56]. However, standardization work is going on and the maintenance group for revising the IEC-61400-1 version 3 to version 4 has recently started working and is planning to include ice load cases to standard.

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 30 mm for all exposed parts must be taken into account. Simple formula for calculating the design ice loads is given [30], [31].

The standard IEC 61400-3 Design requirements for offshore wind turbines, [32], gives in its informative Annex E recommendations for design of offshore wind turbine support structures with respect to sea ice.

7.2 POWER PERFORMANCE MEASUREMENTS

The international standard IEC-61400-12-1 Power performance measurements of electricity producing wind turbines [33] states mostly indirect requirements and restrictions to power performance measurement in cold or icing climate:

- The standard requires that measurement data is obtained during normal operation of the turbine; data sets where external conditions other than wind speed are out of the operating range of the wind turbine shall be excluded from the power performance data set. This means that during cold weather or icing event, the power performance measurements might be invalid depending on the specification of the turbine.
- The standard allows setting up a special data base for power performance measurements collected under conditions other than normal operation conditions. The special data base can be used when the purpose of the power performance measurements is to represent other than normal operational conditions. This data base and power performance calculations based on it shall be clearly marked to prevent confusion with figures of normal operation of turbine.
- The standard requires that anemometers used in power performance measurements are classified. The classification of anemometer should allow cold

climate usage when operating in cold climate region. Anemometers which are classified for cold climate usage can be difficult to find.

- The standard sets requirements for air density measurements: both instruments and mounting suitable for cold climate and icing conditions shall be used when air temperature and pressure are measured for air density calculations. Instrument has to be mounted in a way that possible ice and snow do not lead to malfunctioning of the instrument.

One, but maybe not so novel, way to deal with these issues is simply to exclude all the data where temperature is for example below +2 °C. The problem is that many times the winter is the windiest time in a year and because of such data exclusion the time period needed for complete power performance measurements might become too long or even impossible because of the lack of the highest wind speeds.

Another possible way to manage these problems is the use of reliable ice detector. If operator can be sure that neither the turbine nor the instruments are iced, power performance data can be included in the data base. This requires that the conditions are inside of the turbines normal operation conditions and instruments are suitable to these conditions. Extra care shall be taken when this method is utilised.

In addition, a new informative appendix for the IEC-61400-12-1 has been proposed which would describe how to include temperatures below 0 °C to the power performance measurement data base.

8 TOPICS OF ACTIVE RESEARCH

8.1 ICE DETECTORS

Since April 2004, the EU-program COST has hosted COST Action 727 – Atmospheric Icing of Structures. State-of-the-art reports are available since 2005 on http://cost727.org/ and the project has since implemented the proposed icing measurements at six different locations. The test sites are located in Switzerland, Finland, Germany, The Czech Republic, Sweden and UK. It was initially believed that the greatest progress would be made in sensor development.

Instead, significant progress has been made in weather modelling and the need for verification of the icing models applied to the output from the weather models is urgent if regional and national mappings of icing are to be enabled.

The liquid water content of air and the droplet size distribution ought to be measured, in addition to temperature and wind speed. But this is challenging as there are currently no commercial and automated sensors available for measuring the liquid water content of the air and the droplet size distribution. These two parameters may, for rime ice conditions, be approximated by visibility and vertical velocity. But in order to verify the models there is real need for field measurements of the critical weather parameters liquid water content of air and droplet size distribution.

Ice detectors are used also in operation of wind turbines; it is important to know whether rotor blades are iced or not because of public and labour safety but also to avoid turbine operation in conditions yielding higher than expected loads. For this purpose, ice detection from blades would be most useful. Many ideas of measuring ice directly from blades have been presented, but commercial blade ice detectors are not available.

8.2 ANTI-ICING COATINGS AND MECHANICAL ICE REMOVAL

8.2.1 Materials and coatings

Research in Switzerland has shown that antifreeze coatings are could be developed. Much development must still be carried out, before the found compounds will lead to useful coatings, which protect rotor blades against icing.

• The antifreezing effect of the coating must be tested under more realistic conditions (i.e. in a climatic wind tunnel)

• Coatings must be developed which fulfill the requirements such as adhesion and abrasion resistance, UV stability, longevity, etc.

A research project TOPNano has started in 2010 and is about to end in 2014, [60]. The objective of the project is to develop anti-icing coatings based on nanotechnology.

8.2.2 Mechanical ice removal

Mechanical removal of ice has been proposed by means of cranes, skylifts and ropes. At the international cold climate wind energy conference Winterwind 2008, a crane was parked outside the conference hall for the attendants to remember this alternative way of removing ice.

8.3 ICE THROW RESEARCH

Ice throw constitutes a risk for professional H&S as well as for public safety. In some areas, wind turbines have to be shut down when there's an increased risk of ice throw. It's, however, not a straight forward task to detect small amounts of ice on wind turbine blades. In other regions, a wind turbine is considered as any other tall building and operation may continue in spite of an increased risk of ice throw.

Experienced maintenance staff is well aware of the risk of ice throw and may therefore shut down wind turbines prior to arrival. Completely stopping a turbine doesn't completely eliminate the risk of falling ice. Ideally, staff ought to be able to park their vehicles beneath a shelter connected to the wind turbine entrance.

Actively shutting down wind turbines is normally not an option for the public. Instead, the public can be warned by means of signs. Sirens and flashing lights are other options to warn the public of an increased risk of ice throw prior to startup after the wind turbine has been shut down due to iced up blades.

Current and past activities: Fragments of ice have been collected beneath a few wind turbines. Risk analyses have been carried out based on largely unverified assumptions regarding size, density, shape and trajectories of ice fragments. Iced up wind turbine blades have been documented by means of cameras.

Future activities: Observation of the blades by means of cameras has proven to be a valuable tool for monitoring ice throw. Measurement methods based on, for example, radar and laser techniques might be developed to capture ice throw events. A risk analyses is to be based on verified statistics. The calculation methods, as well as the assumptions made for the ice fragments, need to be improved and validated against observations. Benchmark tests of ice throw trajectories ought to be carried out for computer code candidates. Furthermore, after the validation of the models, parameter studies need to be performed in order to improve simplified assumptions for international standards and recommendations. To enable research, operators and wind farm owners can assist the scientific society by providing icing event related data including reports and statistics of ice throw. Maintenance staff ought to have access to instruments, making it possible to determine the risk of ice throw in complete darkness.

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