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

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Title <b>State-of-the-art of wind energy in cold climates</b>		
Abstract <p>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, IEA RD&amp;D Wind 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 arctic 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 the updated version of the first State-of-the-art report published in 2003.</p>		
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## 1. Executive summary

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. Apart from lower energy production – or even no production – which directly influences a wind farm’s economy, there are legal issues, such as ice throw and increased noise, fatigue loading and O&M aspects that need to be considered. Wind turbines operating in cold climates are currently located in Asia, Europe, Oceania, and North America.

At the time of a new investment, a site assessment is carried out. Low temperature and icing climate set additional requirements for wind resource measurements. Special measurement equipment should be designed for use in low temperature and icing climate. Especially anemometers and wind vanes should be selected with care. Already a small amount of ice may reduce the measured wind speed significantly and large ice accretions may stop the entire anemometer. For example, just a small amount of rime ice on the cups and shaft of an anemometer may lead to an underestimation of the wind speed by ~30% at a wind speed of 10 m/s.

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

Suitable ice detectors can, if at all available, be used for direct measurements of icing. An increased risk for icing can indirectly be estimated with a dew point detector. The occurrence of icing may also be evaluated by using two anemometers side-by-side, of which one is properly heated and the other is unheated. An extension of the latter

method may include three anemometers. The third anemometer shall be heated only if there is a significant difference between the outputs from the two other anemometers.

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

Technical solutions for wind turbines operating at low temperature and in icing climates are 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 used, those turbines are often equipped with gearbox and pitch accumulator heaters. Some manufacturers have also developed adapted technology for icing climate. For sites where icing conditions prevail, ice detectors, hydrophobic blade coatings and anti-/de-icing systems are starting to become available to a limited extent.

Experience has been gathered from approximately 10 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 accumulated down time has been relatively low.

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 for example icing have not had that kind of effect to wind power production that it would have been recorded, even though turbines locate up to 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. Systems that keep blades free of ice have been found an interesting and probably to only solution for profitable wind power production at the areas where icing is severe. This kind of sites can be found both from Scandinavia and North America.

## 2. Introduction

In 2001, the International Energy Agency (IEA) RD&D Wind Programme initiated a new Task, number 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 or cold 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 annex is Technical Research Centre of Finland VTT and participating institutes are The Swedish Energy Agency/WindREN from Sweden, Kjeller Vindteknikk from Norway, the National Renewable Energy Laboratory (NREL) from the USA, ENCO AG from Switzerland, Natural Resources Canada and ISET from Germany [1].

When the collaboration was started there were a relatively small number of wind power projects in the cold climate. 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. The capacity at cold climate sites has increased roughly to 3 000 MW at the same time when the total installed world wide wind capacity has grown from 24GW to 94GW.

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 for 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.

Information about the installation and operation of wind turbines in cold climate conditions is poorly available. Current IEA and other international standards simply state that standard methodologies are not applicable for sites outside of normal operating conditions. Consequently, projects in such areas may risk to be carried out with inadequate knowledge.

### 3. 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 2008 there was all together approximately 3 000 MW installed at sites where wind turbines face climate conditions that are below the temperature range of standard turbines i.e. at cold climate sites. A list of identified wind energy projects that are located at cold climate sites is presented in Table 1.

Table 1. Examples of cold climate wind energy projects from Task 19 participating countries.

Site	Country	Latitude	Elevation
Guetsch, Andermatt	Switzerland	46.5	2300
Feldmoos Entlebuch	Switzerland	46.5	1020
Olostunturi	Finland	67	500
Pori	Finland	62	0
Haeckel Hill, Whitehorse	Canada	60	1430
Cambridge Bay	Canada	69	0
Nine Canyon, Washington	USA	46	200
Nygaardsfjellet	Norway	68	400
Kjøllefjord	Norway	70	320
Sandhaugen	Norway	69	420
Brandenkopf	Germany	48.2	950
Hornisgrinde	Germany	48.6	1100
Scheid	Germany	50.2	580
Hirtstein	Germany	50.3	880
Aapua	Sweden		

The latest operational experience reported by the permanent members of the IEA Task 19 on wind turbine operation in cold climates is presented in the following sections.

### 3.1 Northern Europe

#### 3.1.1 General

The atmospheric icing in Northern Europe is very much a local phenomena. 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 as can be seen in Figure 1.

Therefore icing is only occasional or nearly non-existent in the coastal areas along the Atlantic coast whereas severe icing conditions may occur at sites that are located at high altitudes. Moreover, high altitude sites at the coast are less prone to icing than sites located in the inland at similar altitude.

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.

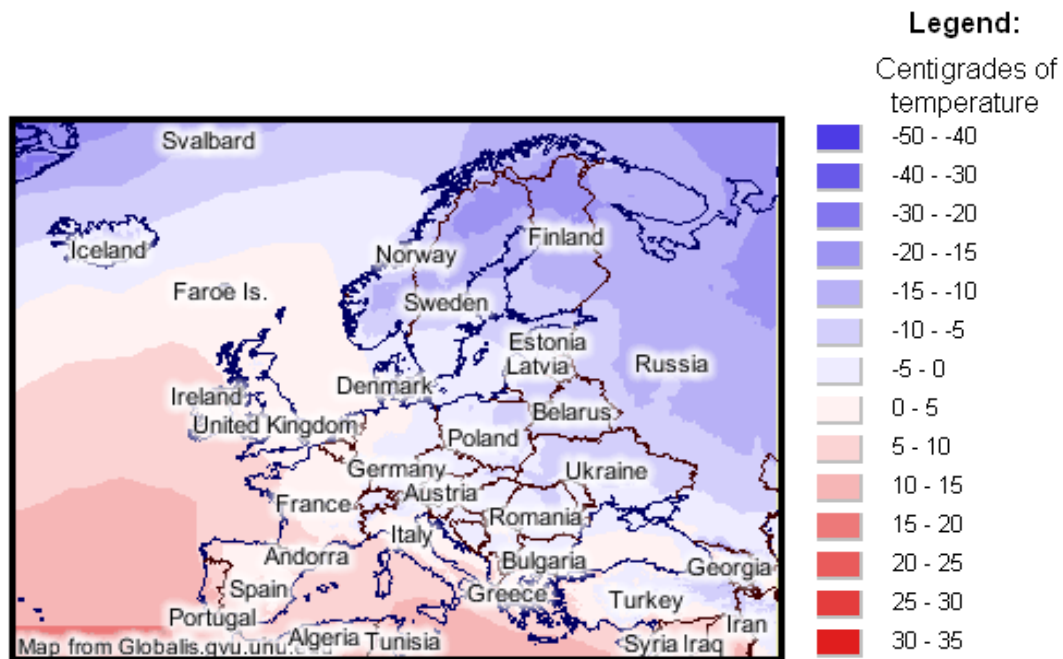


Figure 1. Temperature Europe January: Average January temperature through the years 1961–1990; Source: Climate Research Unit (CRU) – University of East Anglia, Norwich <http://globalis.gvu.unu.edu/>.

### 3. Status in different countries

#### 3.1.2 Existing capacity

The installed cold climate capacity in Scandinavian countries has been presented in Table 2.

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°C monthly average temperatures during the winter make conditions challenging.

Table 2. Existing cold climate capacity in Scandinavia.

	<b>Finland</b>	<b>Sweden</b>	<b>Norway</b>
<b>Cold Climate Capacity</b>	110 MW / 10 MW	124 MW (16% of total)	48.5
<b>Adapted cold climate technology</b>	50 MW / 5 MW	13 MW	1.5
<b>Cold Climate potential</b>	3 000 MW / 200 MW <sup>1</sup>	30 TWh (56% of all planned) <sup>2</sup>	2 000 MW <sup>3</sup>

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

<sup>1</sup>Technical and economical by 2020

<sup>2</sup>Dagens Nyheter, 2009-02-12

<sup>3</sup>Notified or applied for to the Norwegian Water Resources and Energy Directorat (NVE)

Sweden rose from 18<sup>th</sup> to 16<sup>th</sup> position world-wide during 2008 as the total installed capacity rose by 28% to 1 067 MW and an annual wind energy production grew by 2 TWh. 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. In Sweden, wind energy in cold climates has a great potential if icing and, to a lesser extent, low temperature issues can be solved. The planned production of large wind farms (over 10 turbines) in northern Sweden is listed in Table 3.

Total installed capacity in Norway was 441 MW at the end of 2008. 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

### 3. Status in different countries

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 (71°), -4°C 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.

Table 3. Planned production from wind farms larger than 10 turbines in the Northern Counties of Sweden (län = County). The planned production in the Southern part of the country is 24 TWh.

<b>Cold climate sites (incl offshore)</b>	<b>TWh</b>
Advanced planning or in operation	2,92
Norrbottens län	14,32
Västerbottens län	1,28
Jämtlands län	2,16
Västernorrlands län	1,55
Gävleborgs län	7,71
Dalarnas län	0,06
Värmlands län	0,31
<b>Total</b>	<b>30,31</b>

Norway has three small installations at or close to the altitude where icing occurs more frequent, 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. Location of large wind farms in Norway.

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

### 3. Status in different countries

#### 3.1.3 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, low air temperature has lowered turbine availability annually between 0.2% and 2.8% since 1997. Depending on the year, 5 to 18 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 2006 is 115 hours, which corresponds to 1.3% 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 9 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 96 hours per year per turbine (1.1% of annual operational hours) for those turbines that have reported icing. The figure is an average figure and thus some turbines have been down due to ice on average several hundred hours per year and some turbines report icing only occasionally few hours per year. On average 13 turbines per year has reported down time due to ice annually.

Turbine owners seem to be happy with the performance of their turbines which are operating in low temperatures and in icing conditions during winter months. The best producing turbines are located in an area where approximately 1% of the annual time can be considered icing time.

##### *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 Dec 2007, is 30 TWh of which 10 TWh is to be located offshore and 20 TWh onshore. The Swedish Wind Energy Trade Association<sup>i</sup> 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.

### 3. Status in different countries

One wind farm, Långå, has hot-air based blade heating systems. The following figure shows the energy production per sqm at Långå and 3 “nearby” locations. During the first winter, the E70 turbines were not equipped with de-icing systems.

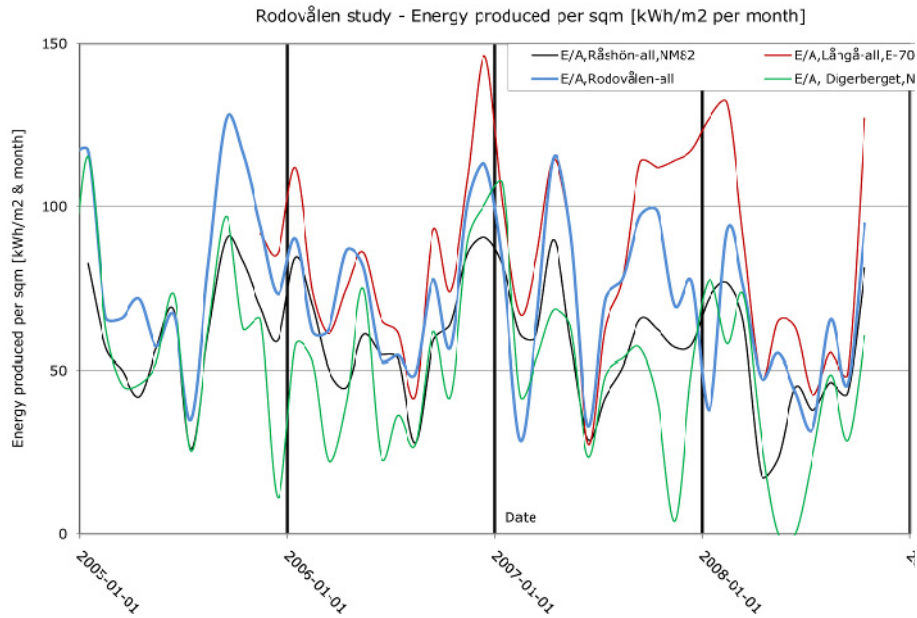


Figure 2. Monthly energy production per sqm at Råshön and three “nearby” locations.

The next figure shows the energy produced per sqm as a 12 month moving average.

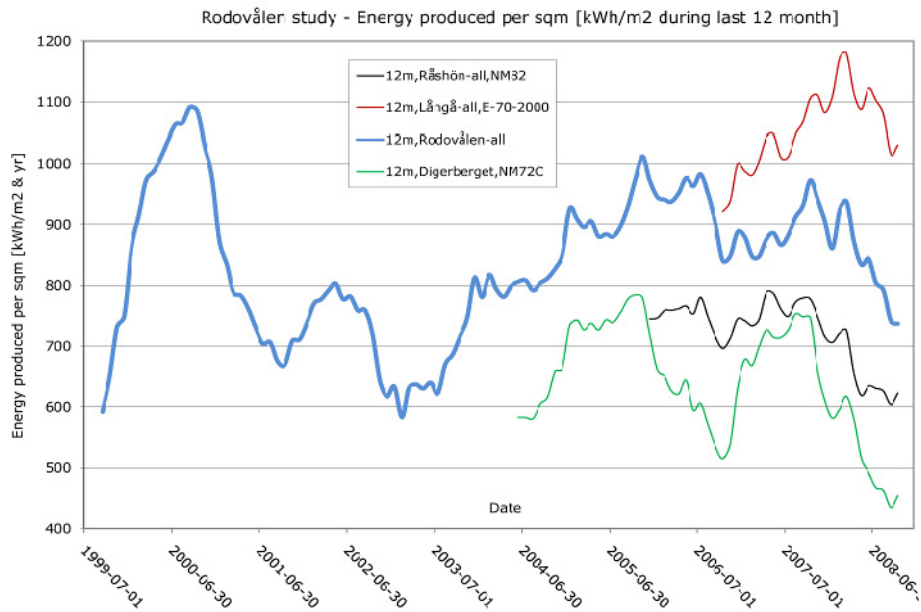


Figure 3. Moving average 12-monthly energy produced per sqm at Råshön and three “nearby” locations.



The energy production per square meter can be calculated for E-82 turbines at the four locations. Results are illustrated in Figure 4.

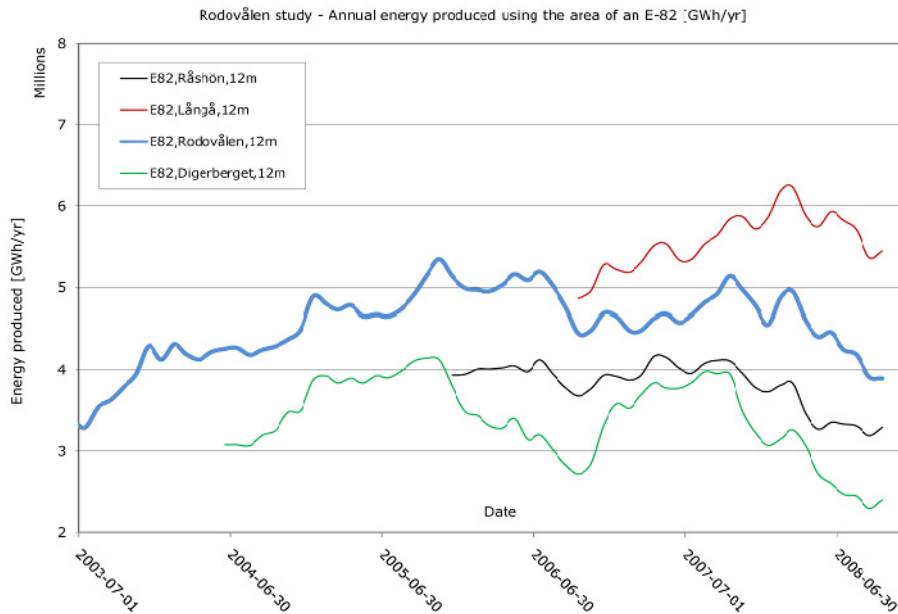


Figure 4. Annual energy moving average using the area of an E-82 at Råshön, Långå, Rodovålen and Digerberget.

Finally, the Annual Energy Production (AEP) can be calculated for the three last years of operation at Långå, Rodovålen, Råshön and Digerberget, see Figure 5. The de-icing systems at Långå seem to improve the energy production.

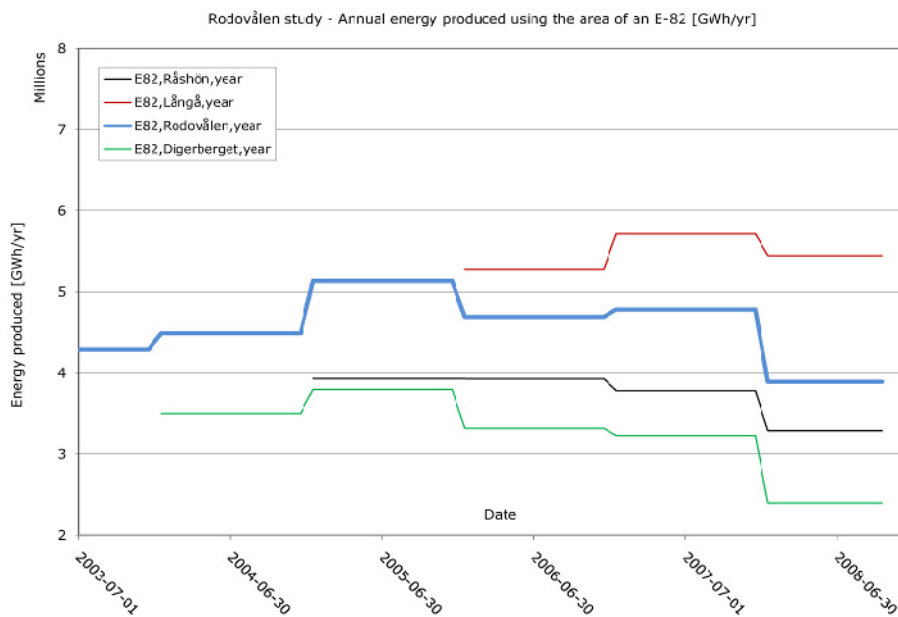


Figure 5. Annual energy produced using the area of an E-82 at Råshön, Långå, Rodovålen and Digerberget.

### 3. Status in different countries

#### 3.1.4 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 8m/s are possible. However, the icing conditions at the fjell tops are challenging. Atmospheric icing may take place up to 100 days per year.

Anti-icing technologies have been tested extensively at Olostunturi site in northern Finland. The site is on the top of the Olos fjell where harsh icing conditions and cold temperature prevail during the winter season. Turbines on the Olostunturi are equipped with blade heating system. Studies have shown that the measured power curve of the turbine under tests corresponds to the manufacturer's data when icing situations were edited out of the measurement data. Despite of the blade heating system the power performance of the test turbine suffered during the harshest icing periods. The blade heating power was found to be too low in those cases. In addition, in some cases the run back water on the blade during icing and blade heating was found to freeze after it had passed the heated area of the blade. During the years 2004 to 2006 the blade heating system energy consumption was 3.5–5.5% of annual energy production. The essential part of blade heating system is a reliable ice detector. The malfunctioning of the ice detector might lead to either excess heating or insufficient heating. Nevertheless, wind energy conversion at sites like Olosturturi without an ice removal or prevention system would be unprofitable due to long down times in winter.

Similar power performance measurements as at Olostunturi were carried out in Pori between 1999 and 2001. Pori is a coastal site located in the western part of Finland. In-cloud icing was observed to be seven times as frequent at the height of 84 meters as at 62 meters. This strongly suggests that icing becomes a more important issue to coastal wind parks at sites like Pori when the dimensions of the wind turbines increase. Still the icing at the site like Pori is occasional, and the main reason to install a blade heating system to a wind turbine is for safety of public. Power consumption of the Pori ice prevention system was measured to be 1% of the turbine's annual production. The maximum heating power of the turbines is 6% of the nominal power of the turbines. In Pori, lightning frequency is higher than in northern Finland and lightning strikes to the blade heating elements have been registered although damage to the ice prevention system could not be detected.

A need for an anti-icing system for a megawatt-size wind turbine has been identified in Finland. Therefore a new project for developing an anti-icing system for a 3 MW wind turbine has been initiated. Because of the good experiences especially of the lifetime and reliability of the anti-icing system used in Olos and Pori the new system is based on the same technology.

VTT Technical Research Centre of Finland is constructing an icing wind tunnel where it is possible to reproduce in-cloud icing conditions. The tunnel will be used for studies of

behaviour of anemometers and other meteorological instruments in icing environment. The controllable main parameters of the wind tunnel will be the air flow speed, air temperature, liquid water content (LWC) and droplet size distribution (MDV). The air speed will be in the range of typical atmospheric wind speeds at the first. In the future it will be possible to increase the speed up to the range of blade speeds of operating wind turbines.

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 11<sup>th</sup> 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 will 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 iceload 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.

Two cold climate wind energy conferences with some 150 participants each were arranged in Sweden during 2008; a national Vintervind 2008 and an international Winterwind 2008. The presentations from both these conferences can be downloaded from <http://winterwind.se/>.

## **3.2 Central Europe (Switzerland and Germany)**

### **3.2.1 General**

Switzerland has 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 Switzerland, several wind energy projects have been carried out in icing and in low temperature climate. Wind turbines that experience icing and low temperatures locate at high altitudes, ranging from 1 300 metres to 3 000 metres above the sea level. Typically sites below 2000 metres above sea level experience light icing whereas sites at higher altitude are prone to heavy icing and low temperatures.

### **3.2.2 Existing capacity**

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

### 3. Status in different countries

Table 5. Existing cold climate capacity in Central Europe.

	Switzerland	Germany
<b>Cold Climate Capacity</b>	11.5 / 9.5 MW	1 000 MW
<b>Adapted cold climate technology</b>	1.5 MW	n.a.
<b>Cold Climate potential</b>	3 600 MW	2 500 MW est.

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 frequency of icing and reported downtimes from mountainous regions is 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.

Since most of the interesting wind energy sites in Switzerland are located above 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.

The probability of icing in the Alps is illustrated in the following figures.

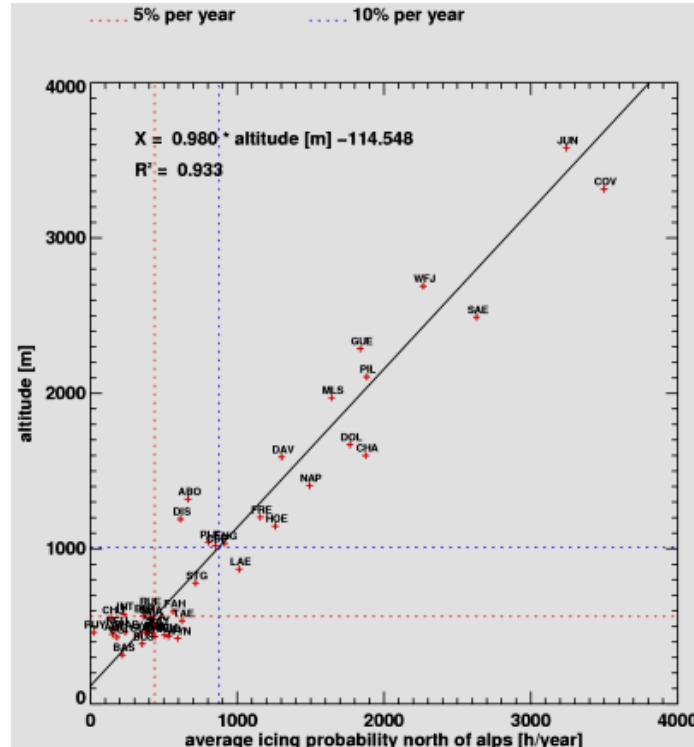


Figure 6. The average icing probability at the Swiss ANETZ stations in function of altitude in hours per year north of the Alps during the years 1999 to 2003. The red line marks a frequency of 5% per year, the blue line a frequency of 10% per year.

Altitude [m]	Icing probability north of alps [days per year]	Icing probability south of alps [days per year]
< 700	< 20	< 15
700 – 1'000	20 – 40	15 – 20
1'000 – 1'600	40 – 60	20 – 30
1'600 – 2'300	60 – 90	30 – 40
> 2'300	> 90	> 40

Figure 7. Icing probability for different altitudes in the Alps.

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)

### 3.2.3 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 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.

### 3. Status in different countries

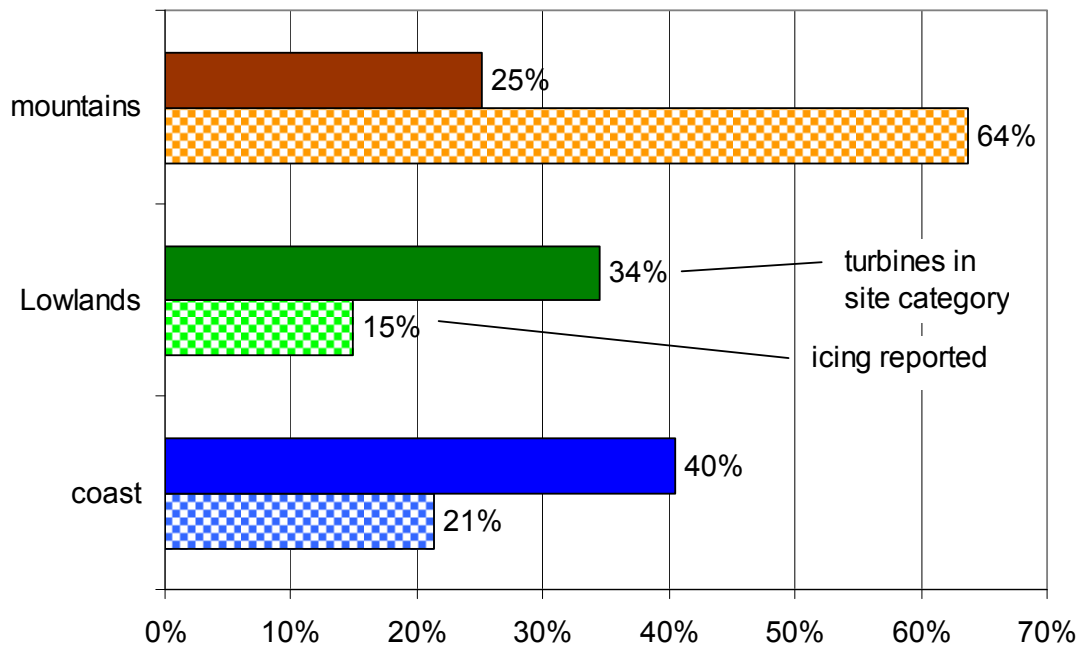


Figure 8. Turbine installations and icing reports per site categories in Germany (courtesy of Deutscher Windmonitor / ISET e.V.)

#### *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 3.2.4). For example, a web cam mounted in the turbine hub to observe the ice formation on blades, see Figure 9.

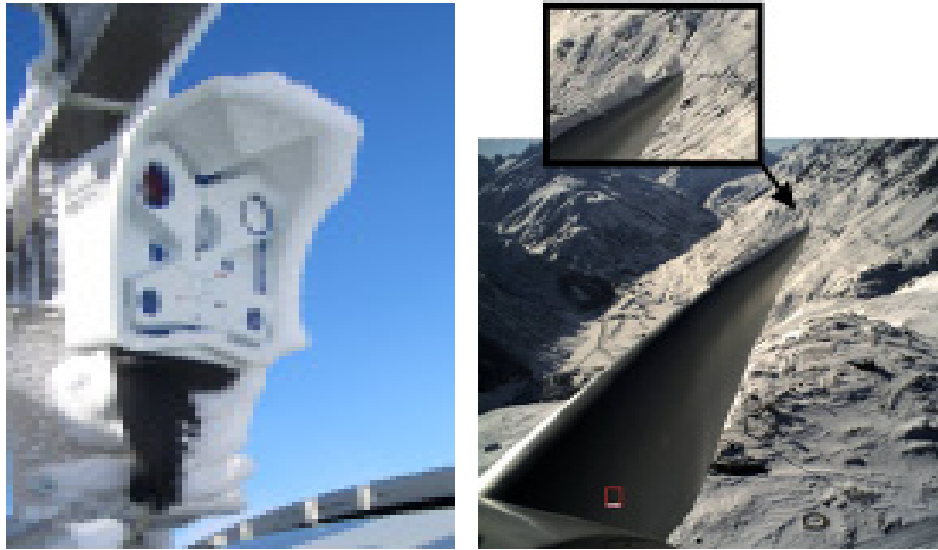


Figure 9. Webcam on Hub of E-40<sup>ii</sup>.

**Feldmoos, Switzerland NEC-Micon 52/900, Arctic Version, 1'056 m.a.s.l, see Figure 10**



Figure 10. 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.

### 3. Status in different countries

#### **Grenchenberg, Switzerland, Bonus 150 kW, 1'300m.a.s.l., in Figure 11**



Figure 11. Grenchenberg turbines.

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

#### **3.2.4 Technology development taken place**

Important experience on the use of wind energy under climatically extreme conditions will be gained with the 800 kW plant on the Guetsch near Andermatt (2 300 m above sea-level) which was commissioned in spring 2002. This is the first wind turbine in Switzerland that uses technology adapted for icing and low temperatures. Further projects, such as St.Moritz (2 200 m above sea-level) as well as Crêt Meuron (1 300 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. A photo from the Gütsch site is in Figure 12.



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 Guetsch occurs mainly as in-cloud rime icing, mostly when winds from the north lift the humid air of passing fronts over the Guetsch 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 annex XIX "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")
- Development and publication of a manual “Operating wind turbines under freezing conditions in the alpine region”.

The project includes an intercomparison 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 intercomparison 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. A distribution of ice throws from Gütsch wind turbine is in Figure 13. Furthermore, a simple meteorological ap-

### 3. Status in different countries

proach to identify icing conditions was tested with fairly good results. Finally, modeling of two icing events with the NWP model WRF was accomplished, showing promising agreement with on-site observations.



Figure 12. Installation on Mt. Gütsch with Enercon E-40 and test bench of the Swiss Met Institute.

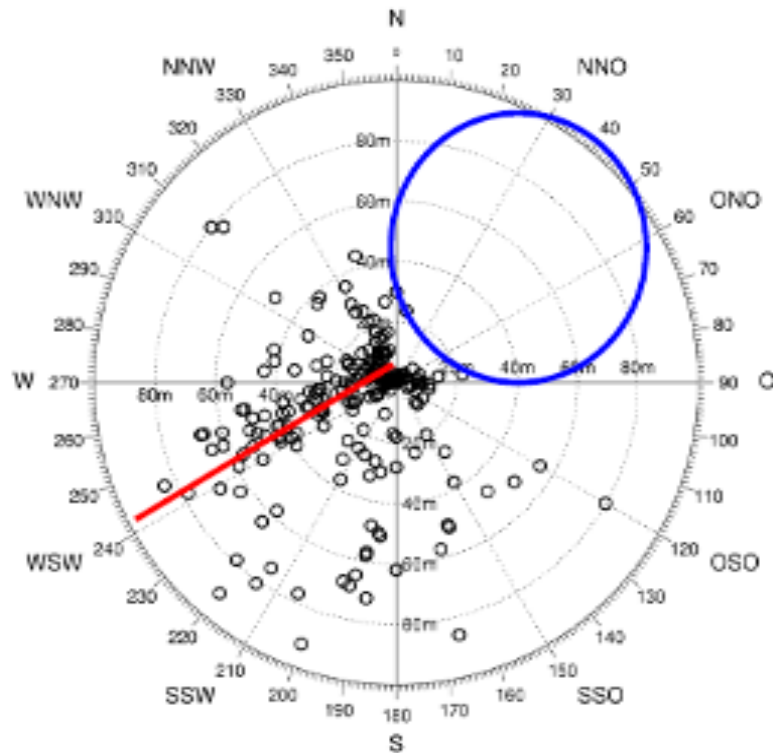


Figure 13. Distribution of ice throw around the Enercon E-40 on the Guetsch. In the northeast sector hardly any pieces of ice were found (blue circle); in the northwest sector is an amassment to recognize (red line).

### 3.3 Northern America

#### 3.3.1 General

Canada offers what is generally considered cold climate conditions. In areas where cold air temperature is not an issue such as along the coasts, atmospheric icing becomes 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. A map of average temperatures in January over North America is shown in Figure 14.

### 3. Status in different countries

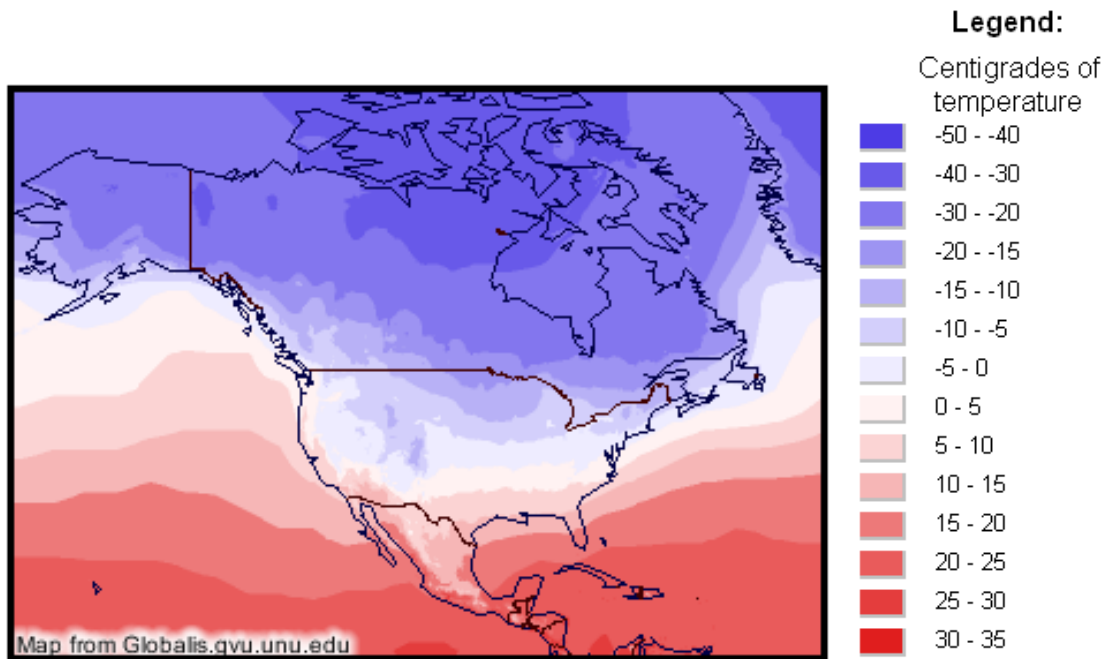


Figure 14. Average January temperature through the years 1961–1990; Source: Climate Research Unit (CRU) – University of East Anglia, Norwich <http://globalis.gvu.unu.edu/>.

### 3.3.2 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 1 876 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.

	<b>USA</b>	<b>Canada</b>
<b>Cold Climate Capacity</b>	Data not available	1 823 MW / 2 239 MW
<b>Adapted cold climate technology</b>	Data not available	1 500 MW / 220 MW
<b>Cold Climate potential</b>	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.

### 3.3.3 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 been installed in three general climatic regimes effected by cold weather. In the north central region, such as the 200 MW wind plants in the Lake Benton, Minnesota area, snowfall and cold temperatures are common but turbine icing is uncommon due to the low humidity. Operators in these regions have not reported down time due to either cold temperatures or icing events. In the north-east and north-west parts of the US, such as the 6 MW plant in Searsburg, Vermont, turbines are located on low altitude mountain ridges or in coastal regimes where icing is common, but is not usually severe 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 does 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 [13]. Also on a 65 kW Bonus machine located in Kuujuaq (58° N), a 5-minute average power output of 89 kW was recorded [13].

Yukon Energy Corporation has a significant amount of experience in operating wind turbines in low temperatures and severe in-cloud icing environment. The company owns two turbines: one 150 kW Mark III Bonus and one 660 kW V47 Vestas in Haeckel Hill, Yukon (altitude 1 430 meters). They were installed in 1993 and 2000, respectively [32]. Maissan [32] reports that low temperature steels, synthetic lubricants and heating systems for items like gearbox, generator and electrical cabinets have worked well. However, anemometers and aerial power lines proved to be adversely affected by in-cloud icing.

### 3. Status in different countries

In addition, problems were encountered with the ice detector that controls the heating strips installed on the first turbine. The ice detector was removed and the heating strips controlled manually. Another ice detector was installed but outside the control loop of the heating strips. It recorded approximately 800 hours of rime icing at the site [32].

Based on the experiences of Yukon Energy, Maissan identifies icing as probably the most significant issue. Yukon has experimented with a protective coating on their first turbine. They covered the blade surfaces with a black low adhesion type of paint 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  $-40^{\circ}\text{C}$  [32].

#### **3.4 Central 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 15.

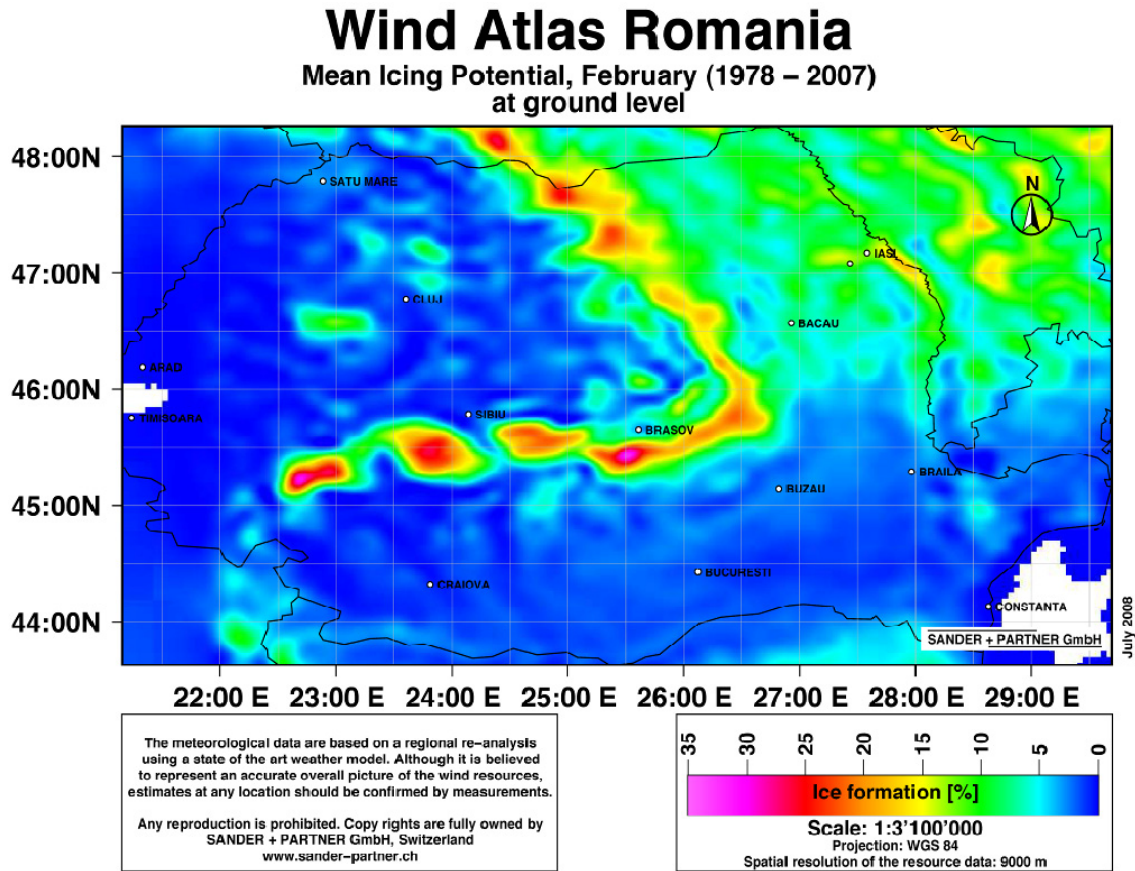


Figure 15. Icing map by Sander for Romania and Moldavia in February.

## 4. Evaluation of climatic conditions

Cold climate refers to sites that have either icing events 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 not be icing nearly at all but low temperatures might be annual and on other site annual average temperature may be mild but still periods of heavy icing may be possible.

Icing can occur at temperatures below 0°C and when there is humidity in the air. The type, amount and density of ice formations depend on both meteorological conditions and on the dimensions and type of structure (moving/static). There are also different icing climates, such as in-cloud icing, when small water droplets in the cloud impact and freeze on the surface of structures, or cold and extreme low temperature icing. It can be said that each site is different and requires independent measurements regarding icing and temperature in a similar way as wind requires.

This is demonstrated in Figure 16 which shows examples of three different cold climate sites, two coastal sites and one more extreme in terms of low temperature.

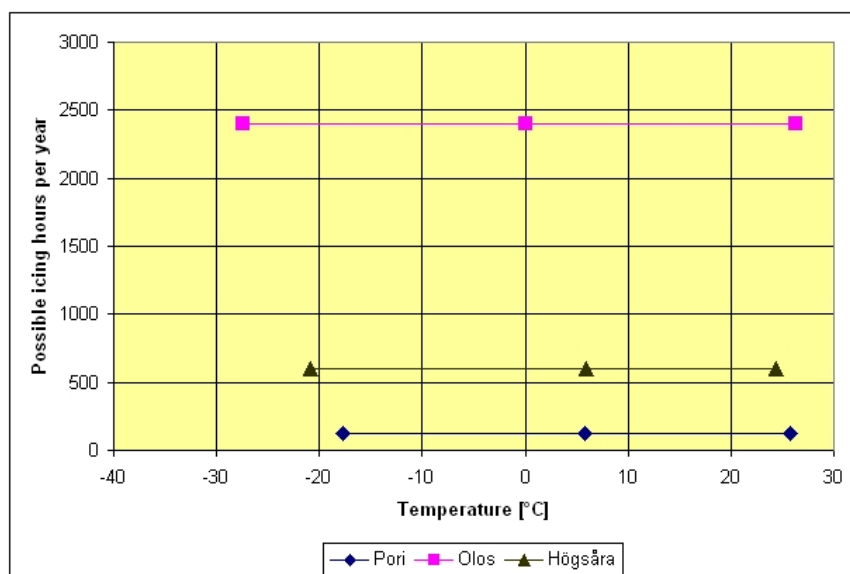


Figure 16. Different kind of cold climate sites icing vrs. low temperature.



## 4.1 Public data and maps

Meteorological community has done considerable amount of work to present various climatic data, such as icing frequency and average temperatures, in 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 equipments for the site assessment.

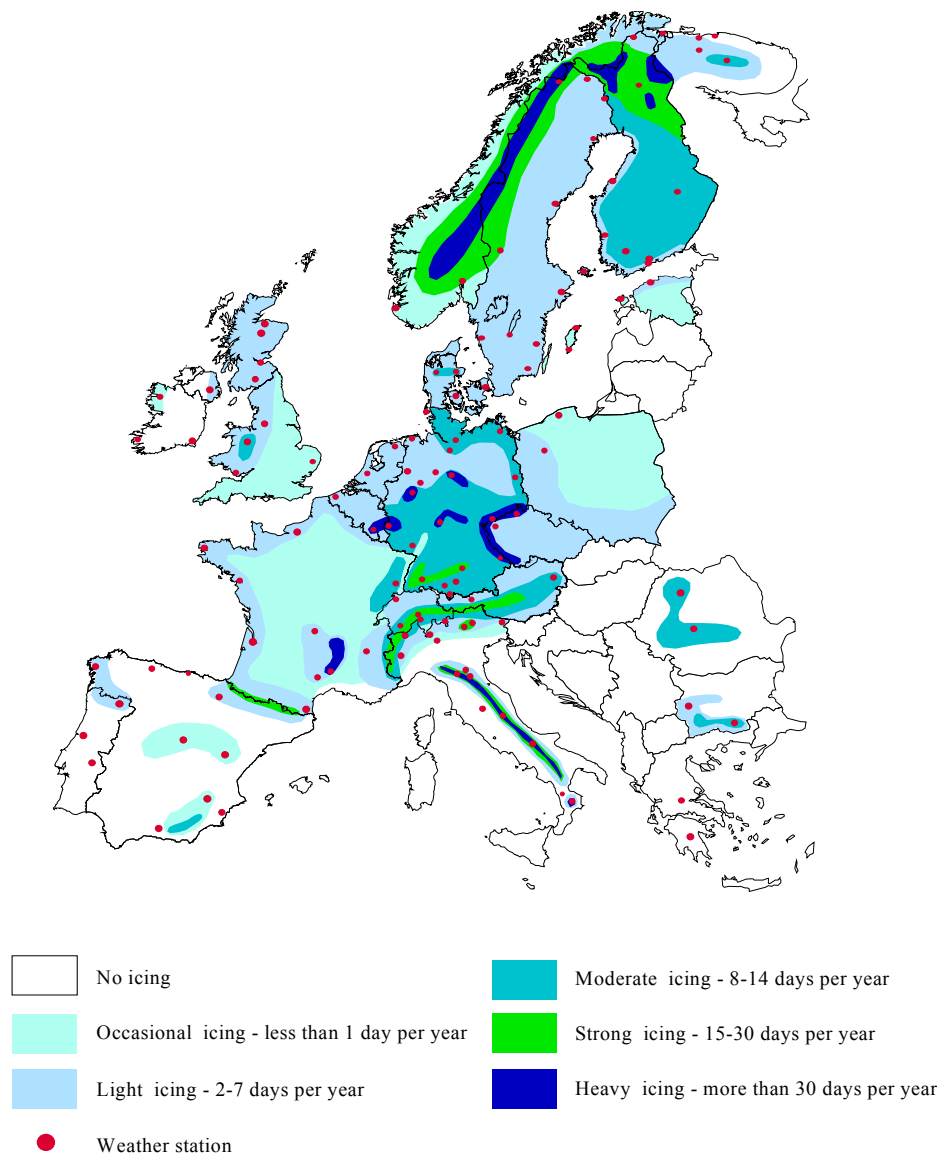


Figure 17. Icing map of Europe. [19]

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 such large areas that they only can be considered indicative. This is the case for example with icing map of Europe.

#### 4. Evaluation of climatic conditions

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 17.

Improved versions of the European Icing Map were produced in the framework of the EU project ICETOOLS. However, a tool for estimating the number of icing days and icing intensity at a given site is needed but still missing.

Due to the local topography, variations in icing severity and intensity may vary greatly within short distances and therefore icing maps, such as in Figure 17, cannot be interpreted as exact and must be used in connection with local topographical information and, if possible, with measurement statistics.

A more exact icing map for the British Isles, where the effect of terrain has been taken into account, is presented in Figure 18. That 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. Those three levels were interpolated to cover the entire land mass. Local and detailed estimation of the number of icing days was then interpolated and extrapolated by using the previous three levels and digital terrain models. The result is a clear picture of areas where icing could be faced. [50] Due to the local climatic conditions and low number of weather stations used in the production of the map, the actual number of icing days experienced at some site may differ from the amount presented in the map.

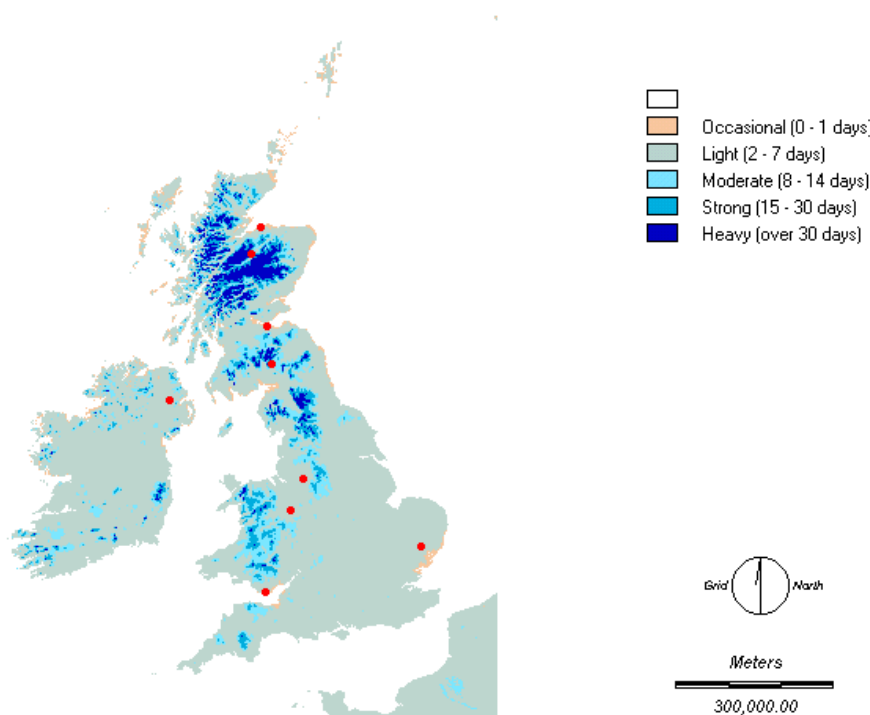


Figure 18. Annual number of in-cloud icing days in the UK and Ireland at ground level and the weather stations used in calculation [50].

#### 4. Evaluation of climatic conditions

Icing map of Switzerland is presented in Figure 19. As with all such maps, the severity and intensity of icing may vary greatly within short distance and the map also should be interpreted as indicative only. Icing map of the Rogaland region in Norway is presented in Figure 20. A map for the average number days with freezing precipitation during a year in Canada is presented in Figure 21.

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

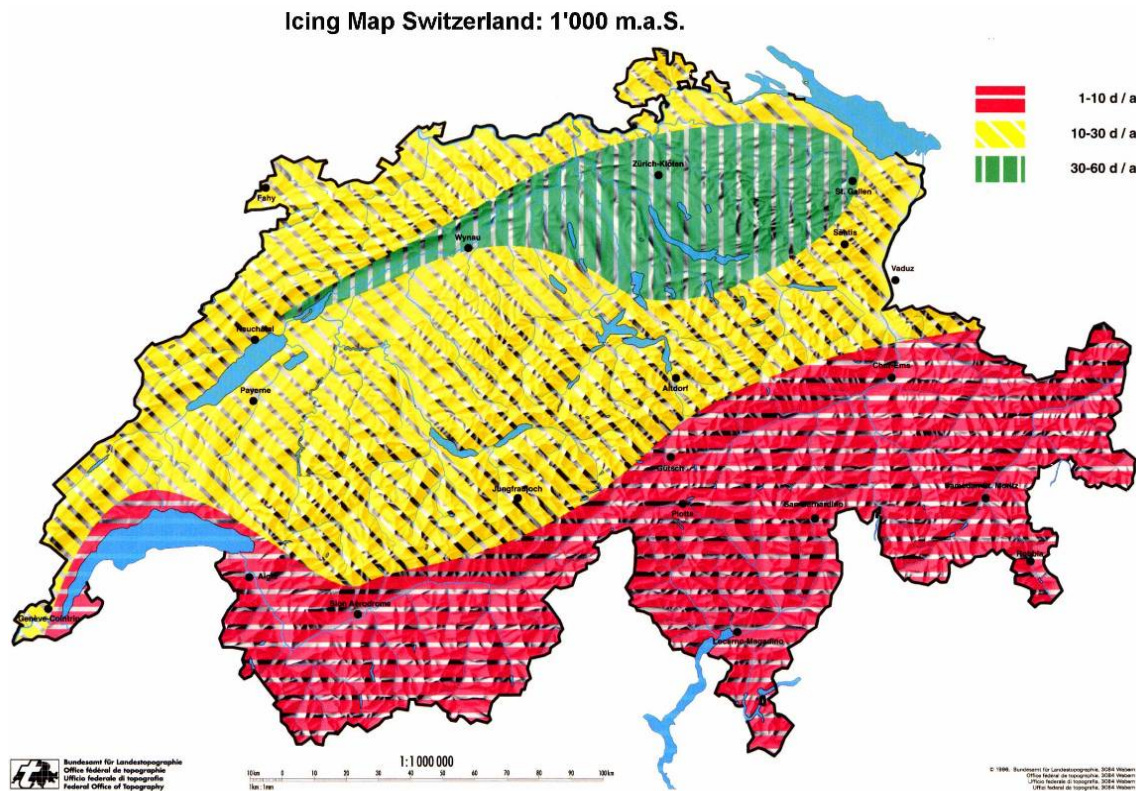


Figure 19. Icing map of Switzerland for 1 000 meters above sea level.

#### 4. Evaluation of climatic conditions

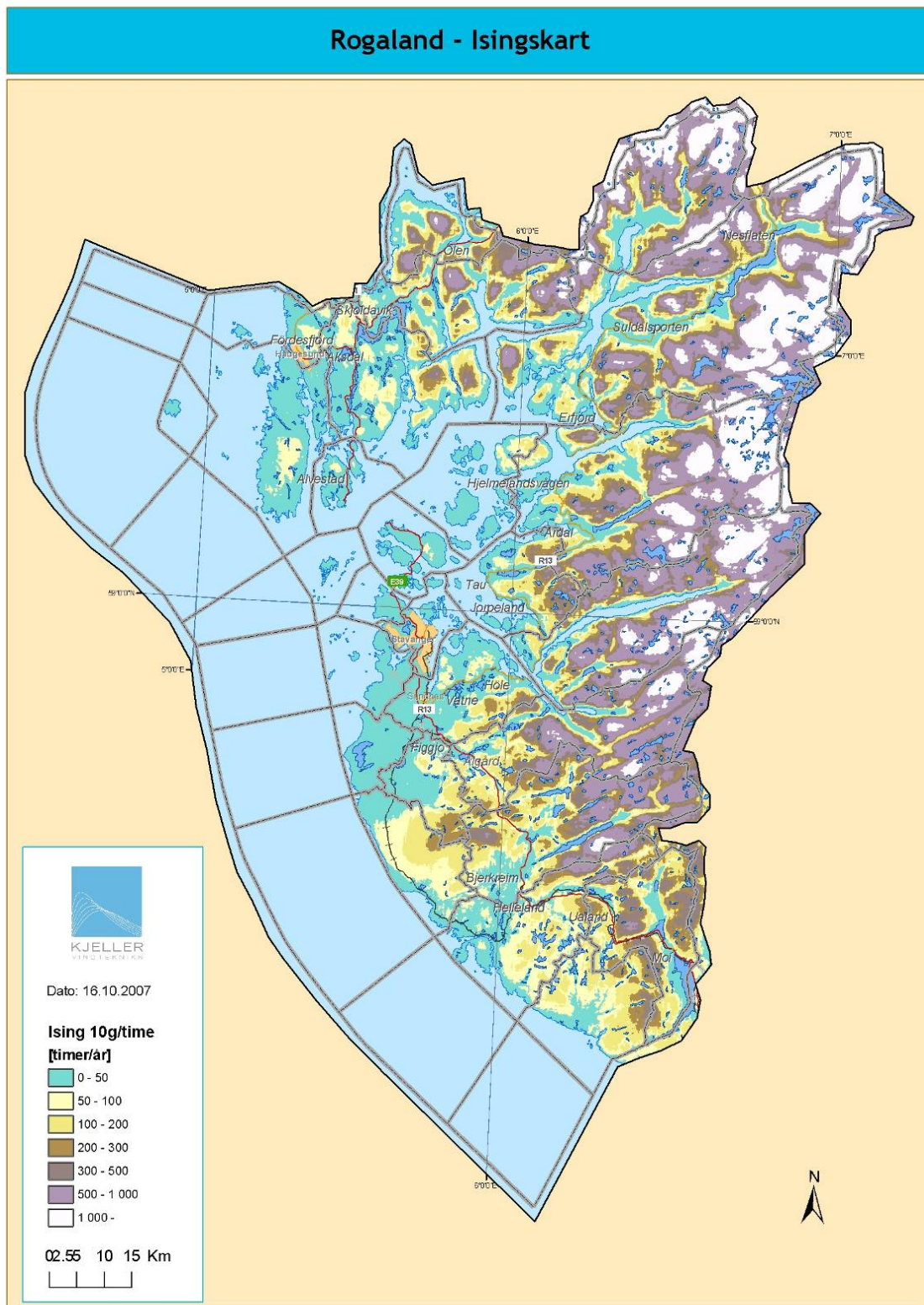


Figure 20. Icing map of a region of Norway. The map is produced with the meso-scale model WRF and shows number of our during a year with icing rate higher than 10 g/hour on an ISO cylinder.

#### 4. Evaluation of climatic conditions

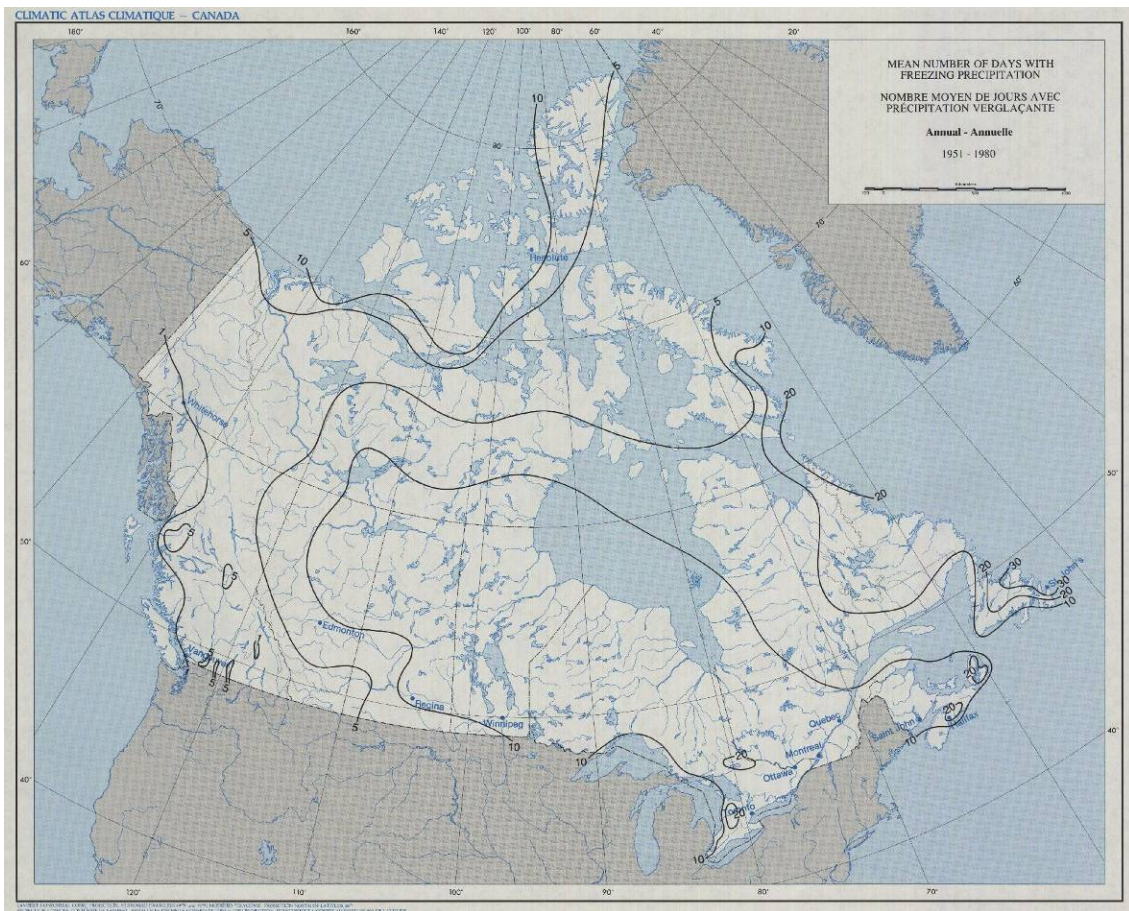


Figure 21. Mean number of days with freezing rain during one year in Canada between 1951–1980. Map from National Archives & Data Management Branch of the Meteorological Service of Canada.

Figure 22 illustrates the importance of high grid resolution with respect to the mapping of rime icing.<sup>1</sup>

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<sup>1</sup> Söderberg & Bergström, Winterwind 2008, see p. 9.

#### 4. Evaluation of climatic conditions

An increase in horizontal resolution has a profound effect on the vertical structure of the simulated boundary layer.

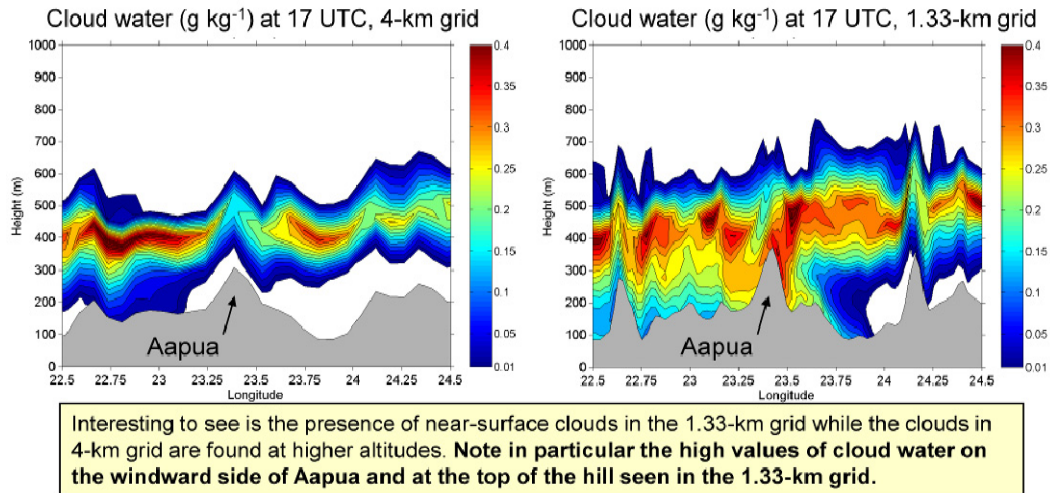


Figure 22. High horizontal resolution is required to simulate icing in complex terrain.1.

## 4.2 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 the 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 are much higher. The reasons why a large uncertainty is found for the clouds and precipitation:

1. Complicated processes that are not fully understood and which 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 a meso-scale model cannot resolve.

Calculations that involve the use of atmosphere 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.

### **4.3 Measurements**

The site assessment of cold climate sites is more laborious compared to the standard low land undertakings. It is important to use measurement instruments that are suitable to the climate conditions that prevail on the site. Thus fair amount of information on the site climate conditions is prerequisite for successful measurement campaign at cold climate sites. It is outmost important to select measurement instruments that are suitable for the site conditions. Such instruments are commercially available and, moreover, the technology is continuously being developed and evaluated by manufacturers and users [11]. Same goes for the measurement set-up as icing and low temperatures may necessitate additional arrangements such as boom heating in extreme icing conditions etc.

#### **4.3.1 Measurement set-up**

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 often not directly available but need to be tailored for the purpose. Solar panels are not sufficient power supply for properly heated instruments that will maintain their accuracy, as power requirements up to 1 500 W are needed. Where no electricity grid is available, alternative measurement setups should be considered.

Icing and high winds also cause higher loads on masts and measurement booms. In these regions wind measurements are often performed at lower levels; 30 m instead of 50 m for example. As a result, it may be difficult to extrapolate the measurement results to the hub height of a future wind turbine. If electricity grid access is available, SODARs suitable for harsh climates may become an option. Experiences with SODAR units in Switzerland have demonstrated that the technology may be used in harsh climates, but careful oversight of the equipment is necessary.

#### 4. Evaluation of climatic conditions

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.

##### 4.3.2 Wind

Special attention has to be paid to wind measurements in icing climate as anemometers and vanes are sensitive to icing. Recent tests have repeatedly shown that a small amount of ice reduces 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 severity of icing conditions. [Refs. 23–26]. 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. 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. Instruments suitable for cold and icing climate are available and new devices are actively being developed and evaluated by manufacturers and users [11].

Heated sensors tend to be less accurate than unheated sensors. Heated sensors are usually more compact and are therefore 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<sup>2</sup>. Some companies use both heated and unheated sensors at sites where ice builds up on the sensors. The unheated can then be used to calibrate the heated sensor on the site during periods where ice is not 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.

As masts are expensive to build and they tend to fall in severe icing conditions, SODAR and LIDARs are starting to become popular for wind speed assessments in

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<sup>2</sup> EUMETNET SWS II



cold climate regions. It is not currently known if the severity of icing can be estimated by analyzing the backscatter.

### 4.3.3 Icing

Ice detection is a critical measurement in arctic wind power. The purpose for using ice detectors needs to be defined for choosing the right type of ice detector. For wind power use, ice detectors are used for controlling the anti-icing system, for example blade heating, as well as to control the operation of turbine to prevent ice throw near populated environment.

The detection of ice is a rather complex task. Unfortunately at the present there are no verified and fully reliable ice detectors for heavy icing conditions on the market. Considerable deviations between the results of ice detectors of the same type and even similar ice detectors can be found [[8], [60] and [61]]. However, the ice detector technology has improved and is expected to improve in near future due to the increased wind energy business. In addition to improved technology research, commercial organisations are also conducting and sharing extensive research on ice accretion due to temperature, humidity, radiation, wind direction, wind speed and precipitation.

Many ice detectors detect the ice from sensing part, for example a probe or a thin wire, which has collected ice. After detection the accreted ice is removed usually by heating. When the ice detector is ice free it is again ready for ice detection. One of the main problems of the ice detectors is due to 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. Other problem is the response time of detectors. It is important to detect the ice as soon as possible if the ice detector is controlling a blade heating system, because delayed ice detection increases the heating power demand of the anti-icing systems due to the increased heat transfer as a consequence of turbulent airflow over a rough iced blade surface.

Due to the unreliability of ice detectors and problems of ice detection, other approaches to observe ice have been developed. Adequate results on information on icing have been achieved by combining an ice detector and a humidity and temperature sensors. Dew point detectors or humidity sensors designed for subzero 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 occurs. The use of such a dew point measurement as an ice detector was studied at the Pori site in Finland [9] and is discussed in greater detail in the paper by Makkonen et al. [29]. 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

#### 4. Evaluation of climatic conditions

for calibrating ice detectors because even the most up-to-date ice detectors are not 100% accurate.

For wind turbine applications it is possible to identify icing using 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. An example of the challenges in signal processing is that how much slower should the unheated anemometer read compared to the heated one to be interpreted as an icing signal? Possible wakes on the top of the wind turbine nacelle should be taken care by either right placing of the anemometers or by other means. However, this “multiple anemometers” method enables the estimation of energy losses that a wind turbine would experience at that specific site in icing conditions, especially if unheated anemometers are to be used for turbine control.

In an experiment on measuring icing in northern Canada, two heated and one unheated anemometers were used to measure the actual wind speed, icing time and sublimation time of ice [33]. 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. It was also demonstrated that one could estimate the time when the turbine or anemometers are iced with this method.

Actual power production of the wind turbine compared to the presumed power production according to the nacelle anemometer may also provide a hint on icing conditions since a turbine with ice on the blades will produce less compared to the turbine free of ice. However, it is still unclear what conclusions can be drawn from the reduced production levels. In Finland, if the turbine is located in a remote site and no visual observations are possible, reduced power production is often interpreted as an “anemometer error” when the cause of such error is icing.

Automatic visibility sensors may also be used as 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.

#### **4.3.4 Other meteorological parameters**

Measuring of other meteorological parameters than wind speed and icing is more straightforward as there is more experience from measuring parameters like temperature and humidity. It is known that the temperature measurements are impacted by their surroundings, vegetation and design of the radiation shield. The performance of thermometers in icing conditions has also been studied extensively. 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 of the air inside the radiation shield may continue until the ice has melted, [31]. In icing climates the radiation shields for thermocouples should be heated or the instrument protected from being covered in ice. Thermometer itself should be designed for icing and low temperature operation [31].

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

Instruments for cold climate and icing conditions measurements including humidity, temperature, wind speed, wind direction, precipitation and radiation, have to be properly designed and heated under icing conditions to maintain their accuracy. Instruments that are suitable for cold climate measurements are continuously being developed and evaluated by manufacturers and users [11]. Classification of meteorological instruments for cold climate and icing conditions can be found from the COST727 report [62].

#### **4.3.5 Measurement setup**

Met masts are usually very thin and slender constructions. The slenderer the met masts are, the less will they influence the measurements. When the wind transports supercooled droplets towards the mast they will freeze on the tower. If the tower is thick, a higher percentage of the droplets will follow the wind flow around the mast and not stick to the mast. 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.

Before erecting a met mast in a region with ice, a calculation 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.

The other critical instruments in addition to wind sensors are ice detectors or sensors used in measuring the icing intensity or duration of icing events. The best results for icing measurements can be achieved by combining traditional humidity and temperature

#### 4. Evaluation of climatic conditions

sensors and available ice sensors as at the present moment there is no verified and fully reliable ice sensor on the market.

Detection of ice is complex. Traditional ice-detectors used to be extremely unreliable, however, this technology has improved and ice detectors are expected to improve considerably in near future due to ongoing technology development. In addition to the improved technology research, commercial organisations are also conducting and sharing extensive research on ice accretion caused by temperature, humidity, radiation, wind direction, wind speed and precipitation.

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

## 5. Turbine technology for cold climate

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

### 5.1 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. States of the art in the wind energy technology for measuring wind speed are cup anemometers and ultrasonic anemometers. The ultrasonic instruments usually already provide information about the wind direction while a wind vane is additionally needed to detect the wind direction when wind speed is measured with cup anemometers.

For turbine operation in cold climate the following sensors, combination of sensors or sensors and procedures are possible:

For wind turbine without de-icing systems:

- 100% ice-free sensors:

Heated sensors are available on the market. However, these sensors cannot always keep their promised specifications. Under severe ambient conditions they can fail.  
→ FMI, measurements at Luosto, Säntis, and Mt. Aigoual. [75, 76, 77]

- 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, e.g. to shut down the turbine.

- Nacelle anemometer, ambient temperature combined with performance data

Wind data from the nacelle anemometer in combination with ambient temperature and analysis of wind turbine performance. Deviation of actual power output from

## 5. Turbine technology for cold climate

the reference power curve indicates operation under icing conditions for ambient temperatures below 0°C.

- Ice detectors

Different systems are available; piezo-electric, optical and measuring of natural frequencies of blades.

The measuring principle of mainstream sensors is the analysis of piezoelectric oscillations. Under icing conditions the frequency 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.

Optical ice detectors emit infrared light to a photo sensor. They interpret variations between emitted light and light received by the photo sensor. The manufacturer claims that the sensors can distinguish clear and rime ice.

Rotor blade monitoring systems measure the oscillations of rotating blades. The typical frequencies for normal operation, i.e. 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.

## 5.2 Blades for icing conditions

### 5.2.1 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. Therefore, when the financial benefits of a blade heating system are evaluated, icing time, severity of icing and wind resources need to be known. Blade heating system may also be required as a safety precaution in connection to the planning or permission granting process. One of the limitations of blade heating systems is their energy consumption, which can be quite high. A simple approach to estimate the break-even conditions has been developed by Peltola et al. [12].

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

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

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

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

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

### 5.2.2 Antifreeze coatings for rotor blades

Researcher from the Institute of Materials and Process Engineering of the Zürcher Fachhochschule Winterthur from Switzerland 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, see an example in Figure 23.

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.

## 5. Turbine technology for cold climate

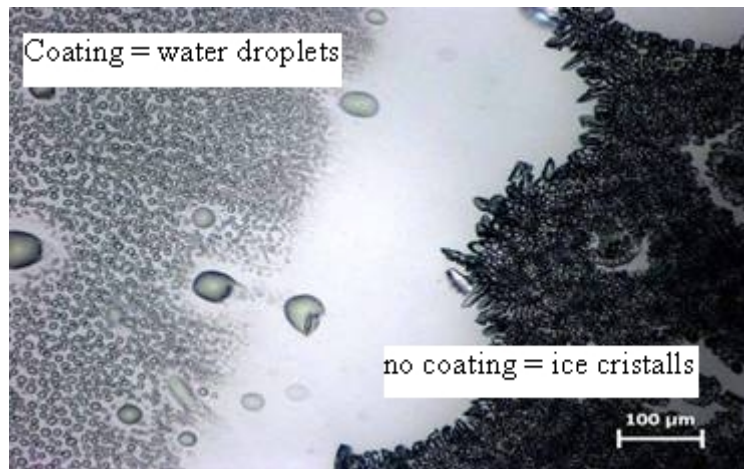


Figure 23. Anti freeze coatings.

### 5.3 Low temperature materials and lubricants

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

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

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

Recent testing at the National Wind Technology Centre, USA, has looked at the cyclic loading of wind turbine blade root studs at ambient and extreme cold temperatures,  $-45^{\circ}$  to  $-51^{\circ}\text{C}$  ( $-50^{\circ}$  to  $-60^{\circ}\text{F}$ ). Testing considered 4 140 steel root studs, a Vinyl Ester / E-glass laminate with an epoxy annulus to pot the root stud inserts into the fibreglass. In the limited tests “all of the cold temperature samples tested exceeded the life of the room temperature control group, though none of the cold temperature samples exhibited any evidence of superior construction over the room temperature samples” [16]. These tests, one of the few being conducted specifically to look at issues related to wind turbine construction, show that operation in cold temperatures does not always result in damage, but may actually improve the performance of the system, as can be seen in Figure 24.



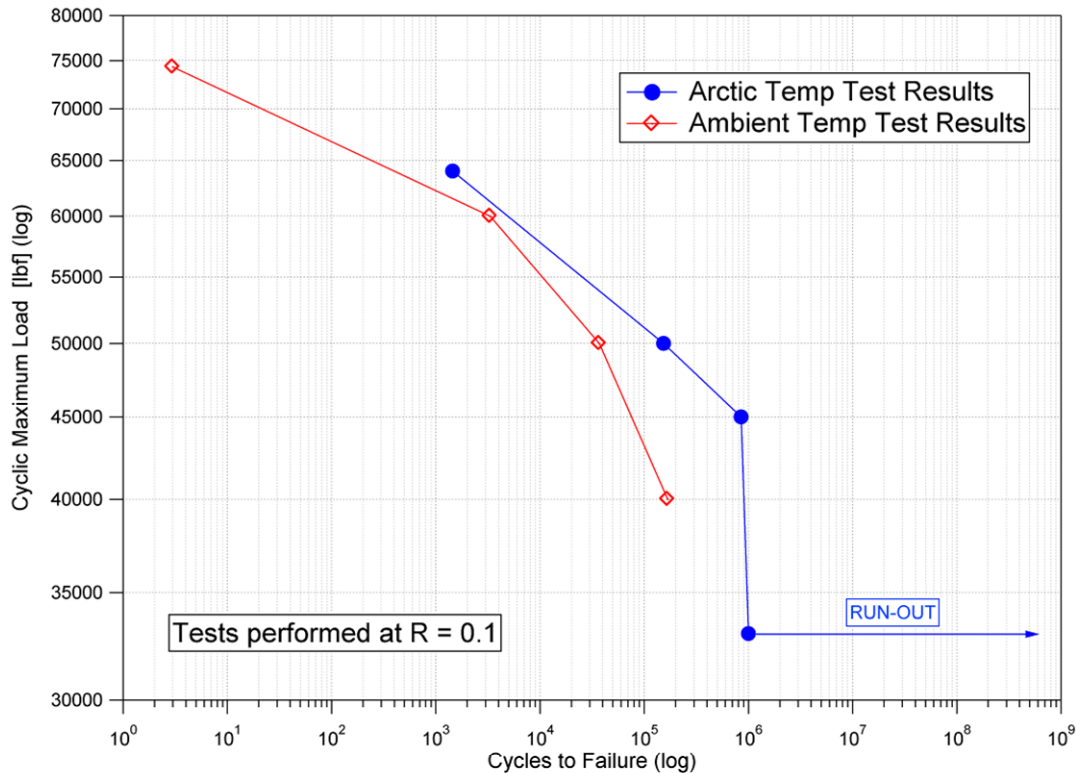


Figure 24. Cyclic fatigue pull tests on blade studs conducted at NREL comparing studs at standard (20°C) and arctic(-48°C) temperatures.

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.

## 5.4 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 [15, 32]. Especially

## 5. Turbine technology for cold climate

important is the protection of control electronics against moisture and condensation at the sites where low temperatures during the winter is frequent.

### **5.5 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 motor sledge, 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.

## 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 passive pitch controlled wind turbines [57]. In most cases this will be detected by the wind turbine controller resulting in a turbine shutdown. Any operation 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 either aerodynamic or mass induced forces. In addition, ice usually sheds from the blades unevenly resulting in further loading on the turbine [10] due to the mass imbalance, especially if it is allowed to operate. These forces result in two basic load types; extreme loads and fatigue loads, depending on the turbines structural design and the icing event. A properly designed control system should address issues of extreme loads, irrespective of their origin. 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. [58]

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.

## 6. Operational experience

Ice shedding off the tower or the nacelle can also pose a similar though a more limited risk than ice that sheds off 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. Increased loads are caused if a pitch control system is based on information of an iced anemometer. Iced wind vane may lead to operation in 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. Due to high viscosity of standard oils in low temperatures or different properties of cold temperature oils, turbine start-up may be delayed to higher wind speeds which will impact overall turbine performance.

When going to very low temperatures, the need for cold weather or weather resistant materials extends for both the steel and plastics used in the system fabrication but also 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 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 [13]. This leads to production losses and probably has led to generator failures [14]. Impacts on the gearbox and braking 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

In order to better estimate the risk, 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 Gütisch” starting from 2005. After every de-icing event by the turbine, the area around the turbines was searched for pieces of ice. Examples of ice pieces can be seen in Figure 25.



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

Figure 26 illustrates the distribution of the ice found under the turbine on Mt Gütisch. Most pieces of ice were found directly under the turbine. Hardly any pieces were found in the northwest sector. This is because on Gütisch, 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.

## 6. Operational experience

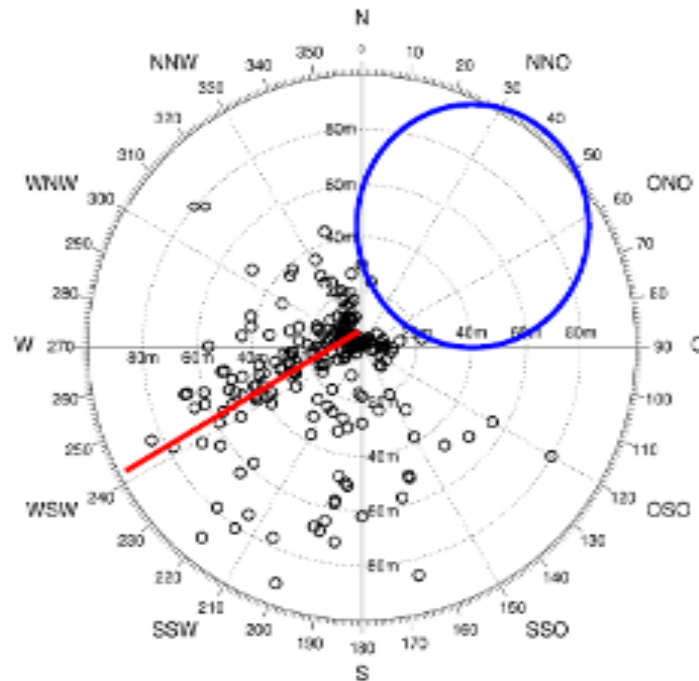


Figure 26. Distribution of found ice pieces on Mt Gütsch.

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

- On the Guetsch 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, [19]) 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 150 meters from turbine in all directions. Tammelin et al. [19] provides a method to estimate the risk that results from ice fragments that are thrown off a wind turbine. An example of a warning sign is shown in Figure 27 and in Figure 28.

## 6. Operational experience



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

As a general recommendation 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.



## **7. Existing standards and requirements**

### **7.1 Wind turbine certification**

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

### **7.2 Power performance measurements**

The international standard IEC-61400-12-1 Power performance measurements of electricity producing wind turbines [38] 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

## 7. Existing standards and requirements

power performance measurements might be invalid depending on the specification of the turbine.

- The standard allows also 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 might be hard 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 needed for 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.

### 7.3 Safety

Garrad Hassan Canada Inc. (GHC) has been contracted by the Canadian Wind Energy Association (CanWEA). Two tasks include firstly providing 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. Secondly, GHC shall provide a literature review of wind turbine rotor blade failures based on publicly available information.<sup>3</sup>

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<sup>3</sup> [http://www.canwea.ca/images/uploads/File/GH-RiskAssessment-38079or01a\(1\).pdf](http://www.canwea.ca/images/uploads/File/GH-RiskAssessment-38079or01a(1).pdf)

In the publication “RISK ANALYSIS OF ICE THROW FROM WIND TURBINES”<sup>4</sup> the authors came to the following conclusions.

The experience and the results of many calculations show that during the operation small fragments are hitting the ground in a longer distance than large pieces whereas from stopped turbines the larger pieces can be transported wider 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 – is not reliable enough at the moment and needs to be improved.

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<sup>4</sup> <http://web1.msue.msu.edu/cdnr/icethrowseifertb.pdf>

## 8. Topics of active research

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

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

### 8.1 Sensors

#### 8.1.1 Ice detector

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.

Icing has been a challenge to measure and so far it can be concluded that it still is. 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.

There are at least five parameters that are of interest with respect to icing:

- Active icing – yes or no?
- Intensity of icing
- Duration of icing
- Type of ice (freezing wet snow, glaze, rime, hoar frost)
- Ice load.

The relative humidity is only an indication of the risk of icing. Instead, the liquid water content of air and the droplet size distribution ought to be measured, in addition to temperature and wind speed of course. As there are currently no sensors available for measuring the liquid water content of the air and the droplet size distribution, these may, for rime ice conditions, be approximated by visibility and vertical velocity.

### **8.1.2 Sensors for the cloud data**

Rime icing is likely to occur if a wind turbine is operating in a cloud at subzero conditions. Cloud height data from airports 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.

## **8.2 Meteorological models**

### **8.2.1 Physical models**

Physical icing and meteorological models are quite detailed and require specific definition of meteorological parameters including the water content of the air, droplet size, wind speeds, and temperature. When modelling the ice accretion on wind turbine blade or power line, one also has to know accurately the shape and size of the object under consideration. Detailed models are computationally demanding and have therefore been improved together with the technological improvements of computers. As a separate category, full physical meteorological models can also be used to predict icing events. For instance meso-scale models (MM5, MC2 and others) have the physical basis to be extended to determine icing events. These models, generally used in regional weather prediction, can be used to predict upcoming icing events or to provide a general prediction of the likelihood of such events for specific projects under consideration.

### 8.2.2 Empirical/statistical models

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

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

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

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

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

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

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

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

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

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

### 8.2.3 Icing rate

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

## 8.3 Ice prevention technologies

### 8.3.1 Materials and coatings

Research in Switzerland has shown that antifreeze coatings are possible. 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.

### 8.3.2 Ice accretion simulation

TURBICE is a numerical model which simulates ice accretion, i.e. 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 newest features have been developed and implemented to TURBICE in 2000.

The model accretes ice on a two-dimensional airfoil section in a potential flow field directed perpendicular to the airfoil axis. The numerical solution for the potential flow follows the commonly used “panel” method. Droplet trajectories are integrated from the steady-state equation of motion, using droplet drag coefficients of Langmuir and Blodgett (1946) and Beard and Pruppacher (1969). The integration begins ten chord lengths upstream of the airfoil section, and is carried out using a fifth-order Runge-

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Kutta scheme with an adaptive step-size control. The impact point is determined by linear interpolation between the 600 coordinate points, which define the airfoil section.

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

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

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

### **LEWICE**

Another software that can be used for ice accretion and heating demand is LEWICE, the newest version is LEWICE 3.0. LEWICE [40] was developed by the icing branch at the NASA Glenn Research Center in Cleveland, Ohio. It is an ice accretion prediction code that applies a time stepping procedure to calculate the shape of an ice accretion. LEWICE does not predict the degradation in aerodynamic performances due to icing rather it evaluates the thermodynamics of the freezing process that occurs when 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.

The particle trajectories and impingement points on the body are calculated from a potential flow solution that is produced by the Douglas Hess-Smith 2-D panel code included in LEWICE. Alternately the potential flow solution can be bypassed and the flow solution can be obtained from a grid generator and grid-based flow solver (Euler or Navier-Stokes) or to read in the solution file from this flow solver. The possibility to get flow solution from these kinds of solvers allows the software to predict ice accretion also for stalled blades.

Notwithstanding the method used, the flow solution determines the distribution of liquid water impinging on the body, which then serves as input to the icing thermodynamic code. The ice growth rate on the surface body is calculated from the icing model that was first developed by Messinger [40, 41]. This is an iterative process by which an ice thickness is added to a body through the ice growth rate. This procedure is repeated for specific time duration.

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.

### **8.3.3 Mechanical ice removal**

It has been proposed that ice can be removed from wind turbine blades by using a crane, hot water and glycol. 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 to remove ice.

## **8.4 Safety**

### **8.4.1 Ice throw**

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

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