REPORT

Wind Power in cold climate

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1 Executive Summary

The Scandinavian countries have high national development goals for wind power, and the spatial potential is big. However, cold climate has shown to cause several problems in regions of the north and at high elevations. The major problems occur when turbine blades are iced-up.

The present report outlines the main aspects and problems of icing, summarized in the table below.

Subject/ Aspect	What is known	Reflections
Research institutes	**Denmark:** Risö DTU, Vestas, Aarhus University **Finland:** Technical Research Centre of Finland (VTT), Finnish Meteorological Institute (FMI, Ilmatieteenlaitos),Tampere University of Technology (TTKK), Labko Oy, Kemijoki Oy, Kone Sampo, Imatran Voima Oy, Neste NAPS Oy, Vaisala Oy, and Kumera Oy among others. **Norway:** Kjeller Vindteknikk AS, Nordkraft Vind, Prof. Per-Arne Sundsbö at University of Narvik **Sweden:** The Swedish Energy Agency, the Swedish Wind Power Association, Vindkraftcentrum i Barentsregionen, Luleå University of Technology, Umeå University, Halmstad University, Gotland University, KTH Royal Institute of Technology, Swedish Polar Research Secretariat, MW Innovation, SMHI, WindREN AB, Dong Energy, Nordisk Vindkraft, o2 Vindkompaniet, Skellefteå Kraft, Svevind, among others. **Canada:** Canadian Wind Energy Association (CanWEA), Wind Energy Strategic Network (WESNet), TechnoCentre éolien, Wind Energy Institute of Canada (WEICan)	The Scandinavian countries participate in in several international R&D programs, including Nordic initiatives. The development of wind farms in Denmark is far ahead compared to the rest of Scandinavia, but due to the early development there is an on-going exchange of the old smaller turbines to the larger models available today. In Finland research has been carried out since the 1980´s but the development of wind farms has been slow. Research in Norway is poor due to their milder climate and limited number of wind farms. Only parts of the knowledge from Canada can be applied to the Scandinavian wind industry due to other weather conditions.
Conditions for icing	• Icing is a complex process dependent on different weather conditions resulting in different types of icing. • Icing appears not only in cold climates, it may occur on sites where temperature reaches just below 0 °C. • Icing depends on height, i.e. the taller turbines the higher is the icing rate.	Knowledge status is relatively good, much information can be found in aviation and military industry. Some of the knowledge is applicable to the wind power industry.

	• An ISO standard is available	
Icing measurements and forecasts	• The key parameters for estimating icing are expected to be the droplet size distribution and the liquid water content of air, combined with temperature and wind speed. This is currently not possible to measure. Instead, measurement of the visibility and estimation of the vertical velocity can be used to approximate droplet size distribution and liquid water content of air. Another strategy to predict icing is measurement of air temperature combined with humidity. • Several ice detection instruments have been developed, none is fully reliable. • Heated anemometers have been developed and are in use. They still need further development. • The occasion when icing starts can be detected quite well with available instruments in use. But icing of sensors is a problem. It gives an overestimation of the period of time with icing. • Due to the fact that the measurements cannot be performed at the exact location of the turbines in a wind farm, there will always be a location error in icing measurements. • Measurements of icing at the highest elevation of the blade are difficult. • Icing prediction models are today in regular use within civil and military aviation services. Models have been developed for wind power. However, models need higher resolutions to capture terrain effects as well as to be verified by measurements.	Suitable ice detectors are needed for direct measurements of icing. No verified and fully reliable ice detectors are available on the market. Ice maps presented for entire nations are not fully reliable. Models need to be developed at several levels; parameter used, terrain resolution, altitude resolution and verifications.
Effects of icing on wind power plants	• **Loads:** Additional vibrations caused by mass and aerodynamic imbalance. Production losses when turbine is stopped due to high loads. May increase the structural loads of a turbine significantly. • **Production losses:** Icing changes aerodynamics of the blade resulting in production losses. • **Difficulties in production forecasts:** icing of anemometers, difficulties both	In order to enable forecasts and investment decisions on prevention systems reliable ice measurements (synoptic measurements) in the planning stage is needed. This applies both on meso-scale and site specific. There are currently no fully reliable measurements. Development of de- and/or anti-icing systems is needed. Preferably

	in resource estimation and in turbine control • **Shortening of component´s lifetime:** vibrations cause higher loads • **Increase of blade generated noise:** changes in blade structure cause higher noise. • **Unfulfilled power curves:** iced up blades makes rotor speed slower. • **Safety risks:** ice thrown off the blade may pose a safety risk even in areas where icing is infrequent. Mitigation measures can effectively be assessed and the risks are very low relative to generally accepted natural hazards. Mitigation methods are available.	to be installed pre-construction.
De-icing and icing prevention	• Effects of iced blades can be prevented by anti-icing methods or removed after the occurrence; anti-or de-icing. • Turbine manufacturers have shown little interest in developing solutions for de- and anti-icing. This is due to a high development cost compared to a low demand from the market. • Most common techniques are heating of the blades by pumping hot air through the blades, electric heating and coatings. • None of the techniques are yet available for medium and sever icing conditions and neither sufficiently tested and developed for commercial use. • Results from on-going projects are expected in the coming years. • Lightning can be a challenge for de- and anti-icing systems.	From energy saving point-of-view it is desirable to apply strategies adapted for the severity of the icing at the specific site. Classification of sites would be a helpful guide in the decision on what method is needed for the specific site.
Economic aspects of icing on wind turbines and measurement instruments	• Very little information available on actual costs. • No specific guidelines for assessing the economic impacts and risks associated with projects in extreme and arctic climates. • De- and anti-icing systems are not economically profitable to install today when looking at production losses. • De- and/or anti-icing may be economically viable when looking at turbine loads and wear during the turbine life time.	Due to the very little information available on economic aspects of icing it is difficult to estimate the additional costs when developing a wind farm in cold climate. In order to draw any conclusions more projects needs to be analysed from scratch. It will always be difficult to tell the specific cost of a project until icing and wind climate measurements has been undertaken for the actual wind

	• Insurance costs are higher for wind farms in cold climates. • Better forecasts on cost may be possible to achieve by further development and verifications of forecast models. • Different strategies for de- or anti-icing due to the severity and the length of time in which icing occurs at a specific site may increase the cost-efficiency.	farm site. In case measures to cope with icing are needed on a wind farm it might be cost-efficient to adapt the strategy for de- or anti-icing to the severity and the length of time in which icing occurs.
Other effects on turbine operation and maintenance in cold climate except from icing	• Operation and maintenance: o Brittle fracture of materials o Insufficient lubrication of bearings and gearbox o Malfunctioning hydraulics o Malfunctioning electronics o Service and monitoring under difficult conditions • Solutions have been developed by the industry and most manufacturers can offer such solutions. • Freezing grounds cause problems when combined with wet grounds. The foundations get instable when the ice melts. • Offshore foundations need to be adapted to ice loads from the sea.	Most manufacturers offer different turbine component solutions.
Actions needed – a priority list	**Step 1:** Find reliable methods to more secure find out how big the actual problem of icing is. **Step 2:** Find out how much the icing actually cost. **Step 3:** A documentation of what methods there are to cope with the problems of icing and what is their cost. **Step 4:** A mapping of what effects there will be if possible measures are to be used, i.e. what will be gained from the decrease in production losses. **Step 5:** A cost-benefit analysis; will the necessary actions reach the intended effects at a reasonable cost? Is it economically feasible to take action? Is there reason enough to avoid development of wind power in areas where severe icing occurs?	

2 Introduction

2.1 Background

Research and development associated with the problems of icing of wind turbines has been undertaken during several years throughout the countries exposed to icing of turbines. To outline what is really known on the matter and what knowledge gaps there is this report has been set up, on behalf of Nordic Energy Research. The report is to be a basis on further research and development needs and initiatives according wind power in cold climates. Hopefully the report will also serve as a helpful tool for the wind power industry and authorities in development of wind power in the Nordic countries.

The project was contracted in June 2011 and an intermediary draft report was delivered to Nordic Energy Research in August 23rd 2011.

The study has been composed by WSP wind power groups in Sweden and Finland and our affiliated company Multiconsult in Norway.

WSP is a global business providing management and consultancy services for the built and natural environment. The Group has over 9 000 staff operating from over 100 offices worldwide bringing together multidisciplinary planning, engineering, corporate services, sustainability, environmental and management skills and is active across the full range of sectors. Renewable energy, especially wind power, is a fast growing business area within the company.

Multiconsult is a Norwegian affiliated company to WSP with wind power competence and track record in market and policy advisory, multi-disciplinary engineering and project management. Together with WSP, the joint project team brings the wind and renewable energy expertise and international perspective necessary to support Nordic Energy Research.

Nordic Energy Research is the funding institution for energy research under the Nordic Council of Ministers. The aim of the institution is to reach knowledge for sustainable, affordable and clean energy solutions. Nordic Energy Research promotes research and innovation in new energy technologies and systems by fostering competitiveness, cooperation and increased knowledge creation in Nordic research initiatives.

2.2 Objectives and scope of work

The overall objective of this report is to summarise the knowledge, research and development that has been undertaken in the field of wind power in cold climate and icing until today. The report is to be based on existing knowledge, i.e. completed studies and reports.

Four main aspects have been pointed out by Nordic Energy Research:

- Conditions for icing to occur
- Effects of icing
- Methods for de-icing and prevention of icing
- Economic aspects of icing and de/anti-icing

For every of the four aspects appointed research results and development in the Nordic countries Denmark, Finland, Norway and Sweden has been collected and analysed. A comparison to development in Canada has been included and the aspects listed above has been analysed in order to identify the knowledge gaps in the field. Unfortunately, a number of the research reports from Canada are only available in French why they are not included in the study.

Based on the results of each aspect, the report holds an analysis of how the cold climate affects the wind power industry in certain regions and what important aspects should be valued in the context. The most possible scenario for the near future is described as well as an analysis and description of a desirable scenario. The development in and reports from other parts of the world are not included in the report.

It has also been shown that available ice maps only represent a coarse tool in wind power planning, why they are not attached to the report. The resolutions of the calculations are too low, why the terrain is not sufficiently reflected. There is a risk that too far-reaching conclusions are drawn in wind power planning. In some cases sites, where there are no risk of icing, might be deselected.

2.3 Methodology

The project team performed a bottom-up research of publicly available information in three approaches:

1. Nation wise (National wind power trade organisations; Denmark, Finland, Norway, Sweden, Canada)
2. Latest trends (conferences and direct engagement with market players)
3. Project research (national wind power research institutes, pilot project owners in Sweden)

The collection of available data was allocated to the WSP and Multiconsult offices in each country of question in order to facilitate the research. WSP Sweden also conducted the research for Danish and Canadian R&D, composed the report and the basis from each country and conducted the analysis.

While most of the knowledge and research on the subject is coherent internationally, the backgrounds on icing conditions and effects of icing are the same irrespective of nation. What separates the nations from each other is the regional and local climate, which can have different effects on icing appearance and icing extent on wind turbines. Thus, the first part of the report holds a chapter with dedicated sections to each country with descriptions of the national wind power development, climate and the research and development (R&D) status.

Thereafter the report follows the structure of the objectives described above. An additional chapter has been added describing icing measurements and forecasts. Measurements in icing conditions, measurements of icing and forecasts of icing do not obviously fall under the four main objectives of the study. They have been devoted a separate chapter while they are aspects important of particular highlighting.

Each chapter contains a section with reflections where conclusions and the state of knowledge on the subject is summarised.

A list of references is presented in the end of the report.

In attached appendix on-going and completed research and development projects noted in the study are reported. It is not a full list of all current and completed projects on the subject.

3 National conditions and summaries

3.1 Denmark

3.1.1 Introduction

The Danish wind turbine industry has a 27 % share of the global market and employs approximately 27 000 people, making it the world leader in wind power. Furthermore, some 20 % of the domestic electricity production comes from wind energy. The development of wind power in Denmark is characterized by a close collaboration between publicly financed research and industry.[1]

As of May 2010, there were 5 052 wind turbines in Denmark with an installed wind capacity of 3 545 MW, offshore wind power accounting for 505 MW. However since then Horns Rev II has been put in to operation and Rødsand II is also under construction. This means that Denmark in May 2010 had over 720 MW wind capacity placed offshore.[2]

In 2009, wind-power production accounted for 19.3% of domestic electricity supply. In 2009 wind turbines produced 6 721 GWh electricity. In 2010 the Danish turbines produced 7 807 GWh. In the Environmental plan from the government the goal 1996 to be fulfilled 2005 were that 10 % of the power consumption ought to come from wind power and 2030 it should be 50 %. Year 2010 the wind power accounted for 21.9 % of the total power consumption. [3]

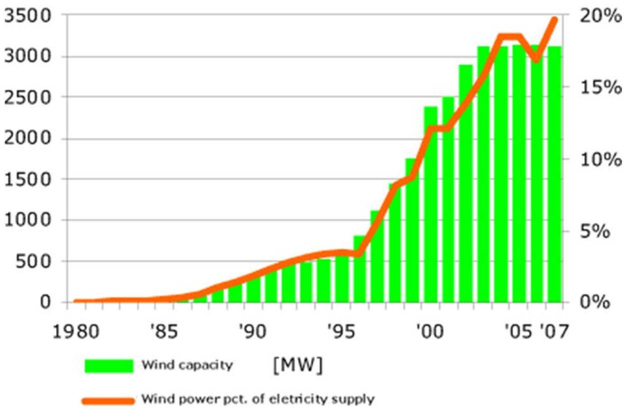

Figure 1: Wind power development in Denmark [4]

[1] Risø DTU National Laboratory for Sustainable Energy, 2011-07-07
[2] Danish Energy Agency, 2011-07-07
[3] Ibid
[4] Ibid

Denmark has got one of the world´s largest wind farms, Nysted Wind Farm. The wind farm itself is owned by a consortium. The 72 wind turbines of which the nearest are placed some ten kilometres offshore, generates enough power to supply 145,000 family homes. [5]

3.1.2 Climate

The climate in Denmark is relatively warm compared with other geographic areas on the same latitude. The mildness is largely conditioned by the surrounding seas and the warm North Atlantic Drift as well as and the closeness to the continent. The weather varies depending on the dominant wind direction and the season. The prevailing wind direction is west which holds about 25 % of all winds, but the winds vary widely from coastal regions to inland. The average annual temperature for the country is 7.7° C. The mean temperature in January and February, the coldest months, is 0° C, but extremes down to -30° C have been measured. The average annual precipitation over land is 712 mm. The precipitation varies greatly from year to year and from place to place. It occurs all year round but the summer and autumn are the wettest seasons. The average duration of snow cover is about thirty days. [6]

3.1.3 Research and development

The Technical University of Denmark, Risø DTU (Danish National Laboratory for Sustainable Energy) contributes to research, development and international exploitation of sustainable energy technologies and strengthens economic development in Denmark. Risø DTU is one of Europe's leading research laboratories in sustainable energy and is a significant player in nuclear technologies. Risø DTU creates pioneering research results and contributes actively to their exploitation, both in close dialogue with the wider society.

There are a significant number of projects and research activities in Denmark on wind power. Due to the climate the most part of the research on wind power in cold climate has been conducted outside of Denmark up till today. One of the main projects is IceWind, described in Appendix.

The iNano-centre at the University in Aarhus is a part of the Nordic Top-level Research Initiative, TopNano. The project addresses nanotechnology coatings for antifreezing for efficiency in power generation and safety of aircrafts and wind turbines. The aim is to develop sustainable and efficient methods based on nanotechnology to reduce problems and costs with ice build-up and runs from 2010-2013. The project is further described in Appendix.

[5] Danish Energy Agency, 2011-07-07
[6] Danmarks Meteorologiske Institut, 2011-08-22

3.2 Finland

3.2.1 Introduction

The wind power capacity in Finland is 197 MW, 130 wind turbines. Wind power production in 2010 was about 292 GWh which is 0.3 % of the Finnish electricity consumption.[7]

By the end of May 2011 there were almost 6 300 MW of wind power projects published in Finland, of which about 3 000 MW is offshore projects.

On onshore projects 36 projects from 132 projects (27 %) are planned to be placed in north Finland (in Raahe or north from Raahe) and on offshore projects 11 projects from 17 (64 %).[8]

An assessment of icing risks for planned projects where made by Holttinen in 2011, who concluded that 6 projects with approximately 400 MW installed capacity is at high risk to be affected by icing. Some inland site projects also have risk of exposure to icing of blades.[9]

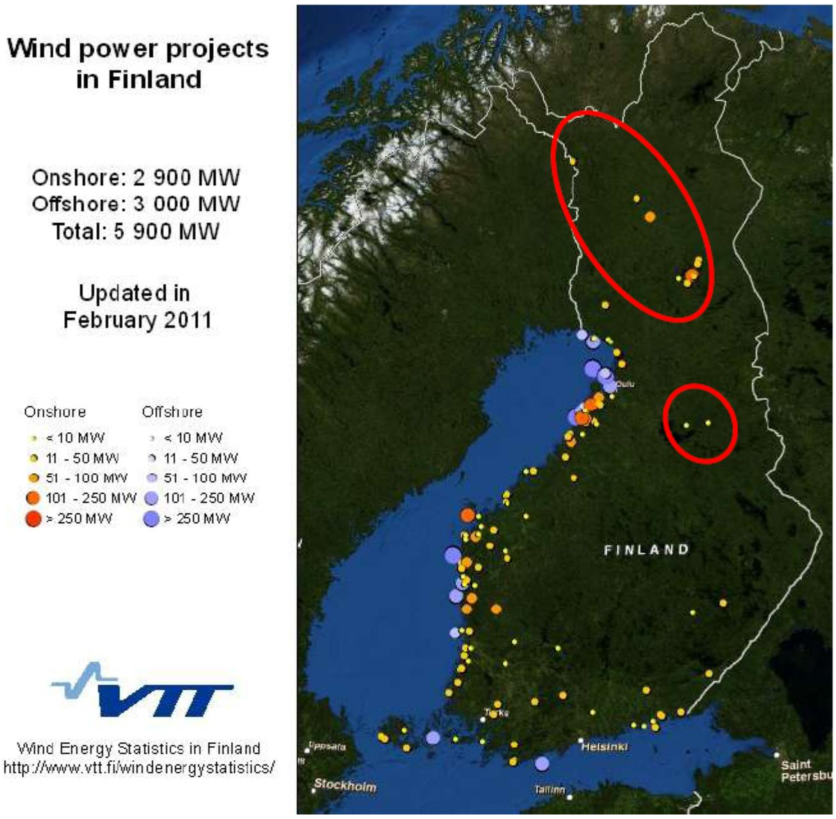

Figure 2: Planned wind power projects with strong risk for icing of blades.[10]

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[7] VTT Technical Research Centre of Finland, 2011-06-20
[8] Ibid
[9] Holttinen, H., 2011
[10] VTT Technical Research Centre of Finland, 2011-06-20

3.2.2 Climate

The main factor influencing Finland's climate is the country's geographical position between the 60th and 70th northern parallels in the Eurasian continent's coastal zone, which shows characteristics of both a maritime and a continental climate, depending on the direction of air flow. The mean temperature in Finland is several degrees (as much as 10°C in winter) higher than that of other areas in these latitudes, e.g. Siberia and south Greenland. The mean annual temperature is about 5.5° C in south-western Finland, decreasing towards the northeast. The 0° C mean limit runs slightly to the south of the Arctic Circle. Temperature differences between regions are great. The temperature is raised by the Baltic Sea, inland waters and, above all, by airflows from the Atlantic, which are warmed by the Gulf Stream. When westerly winds prevail, the weather is warm and clear in most of the country due to the 'föhn' phenomenon caused by the Keel range. Despite the moderating effect of the ocean, the Asian continental climate also extends to Finland at times, manifesting itself as severe cold in winter and extreme heat in summer.[11]

Since Finland is located in the zone of prevailing westerly winds where tropical and polar air masses meet, weather types can change quite rapidly, particularly in winter. The Finnish climate is characterized by irregular rains caused by rapid changes in the weather. The very first snowflakes fall to the ground in late August or early September over the higher peaks in Lapland. The first ground-covering snow and permanent snow cover arrive at different times in different parts of the country. In Lapland the winter is long (approximately seven months) and the permanent snow cover comes significantly earlier than in southern Finland [12] In the Sodankylä district in Finland, rime days occur during eight months of the year, from October to May. Rime days occur most frequently in the beginning of the year and on the tops of higher mountains. Rime formation is an almost daily phenomenon in January and February; up to 20-25 consecutive rime days can be expected, although this is dependent on the observed height. [13]

Humidity is dependent primarily on temperature. The humidity of the air is highest in July and August and lowest in February. Like temperature, humidity decreases towards the north. The figures do not vary very much within any region in any season.[14]

Fog is most common in autumn, in southern and south-western Finland, usually at night and early in the morning. In winter, though, fog can occur in daytime. Early winter is often quite foggy in the 'fog corridor', about 40 to 80 km from the coast.[15]

The Gulf of Bothnia gets covered by ice for 5-7 months every year, from November to May. The maximum ice thickness varies from 50 to 120 cm. At the beginning of the winter narrow fast ice zones occurs close to the coasts. When the ice gets thicker the fast ice zone moves further away from the coasts. Only in very cold winters

[11] Finnish Meteorological Institute, 2011-06-20
[12] Ibid
[13] NEMO-REPORT 31, 1998
[14] Finnish Meteorological Institute, 2011-06-20
[15] Ibid

when the ice thickness is more than 50 cm in whole Gulf of Bothnia ice can be immobile.[16]

3.2.3 Research and development

In Finland research and development work concerning wind energy in cold climate started in late 80's. Since then a significant number or research work and projects has been followed through. Finland was the pioneer nation in the world in arctic wind turbine development in the 1990s, and is still the leading nation according to Walsh.[17] Most of the studies have been carried out by the Technical Research Centre of Finland (VTT), Finnish Meteorological Institute (FMI, Ilma-tieteenlaitos) and Tampere University of Technology (TTKK) together with wind power companies and ice detector and blade manufacturers. The main research projects in Finland have been NEMO, NEMO2 and NewIcetools. VTT and FMI have also participated in international, European and Scandinavian projects.

Several companies have been involved in the R&D during the years; Labko Oy, Kemijoki Oy, Kone Sampo, Imatran Voima Oy, Neste NAPS Oy, Vaisala Oy, and Kumera Oy.

Kemijoki Arctic Technology Oy developed an ice prevention system that has been installed in such an extent that more than 110 heating seasons using the same solution has been undertaken. Kemijoki Oy is now out of wind business.

Since the beginning of the 2000´s research has mainly been part of international projects such as WECO, EU-project NewIcetools, IEA Task 19, TopNANO and COST 727 (described in Appendix). Ice-repellent coatings were the subject of study of VTT 2007-2009.

Today new research is on-going; VTT and FMI is currently setting up an IceAtlas for Finland and measurements in icing conditions are carried out by LIDAR-technology. Carbonel Oy is working with heating system development for other applications and Labkotec Oy develops ice detectors mainly for safety.

[16] Leppäranta, M., 2011
[17] Walsh, M. ,2010

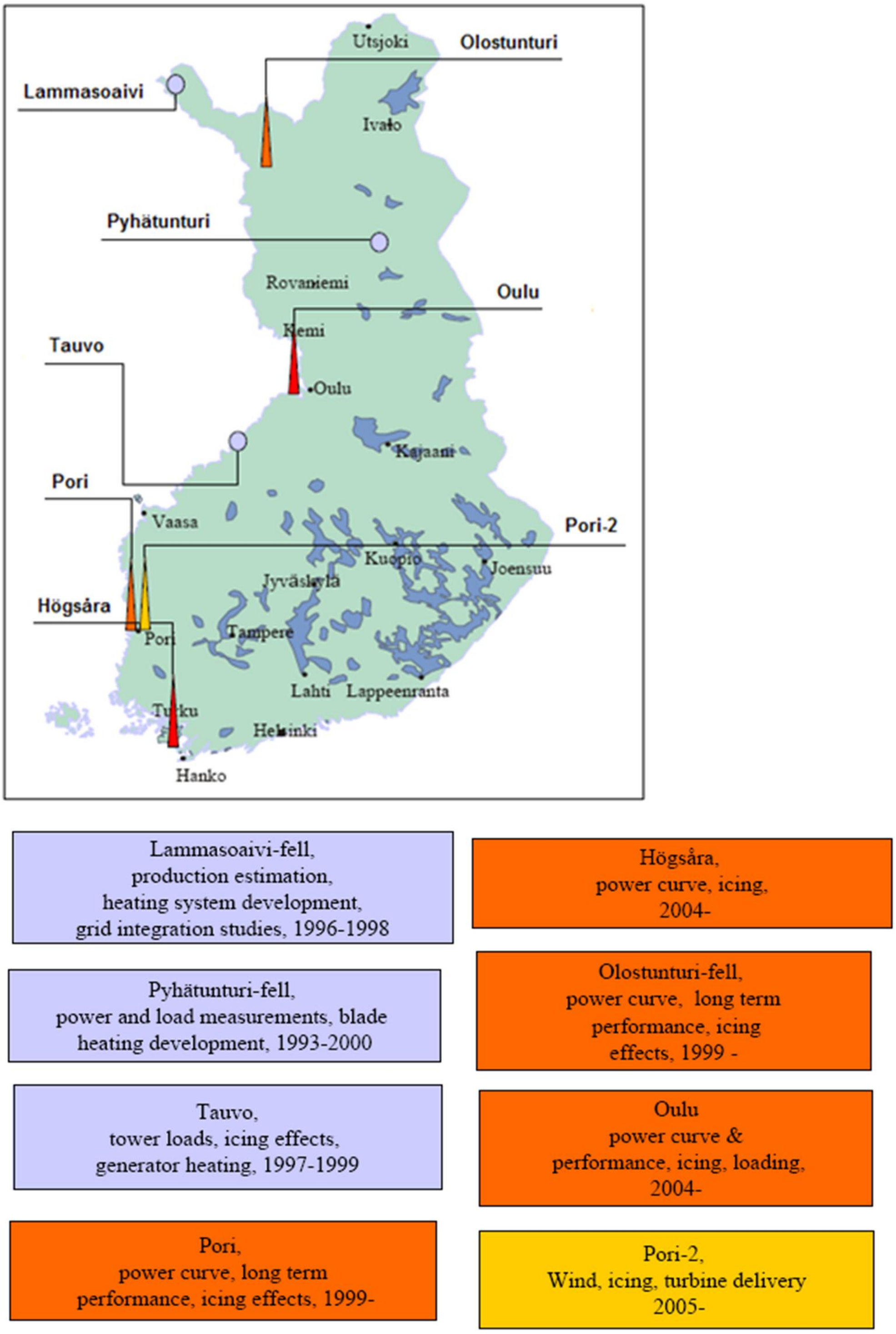

Figure 3: Activities & experiences in Finland concerning icing of towers/masts/wind turbines.[18]

[18] Laakso, T., 2005

3.3 Norway

3.3.1 Introduction

The knowledge base on icing conditions and icing effects in Norway is quite poor. This is mainly based on the relatively low amount of wind farms in operation (435 MW installed at the end of 2010), and that nearly all the wind farms are situated at an altitude below the limit where icing starts to be a problem. The limit varies with latitude, distance from the shore line and the local topography.[19]

3.3.2 Climate

Norway has a long shoreline facing the warm waters of the eastern part of the North Atlantic Ocean. Low pressure systems forming in the polar jet stream areas over the warm Atlantic waters move eastward and ensure high wind speeds and a mild climate along the Norwegian coast. Well exposed islands and ridges along the coast are well suited for wind energy. Compared to other areas in the world at the same latitude, the temperatures in wintertime are relatively high. At North Cape (71º), -4ºC is the lowest monthly average temperature at sea level. 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. [20]

3.3.3 Research and development

On behalf of Norwegian Water Resources and Energy Directorate (NVE), Kjeller Vindteknikk has mapped Norway´s wind resources.[21] The wind resource mapping is based on meso-scale modelling WRF (Weather, Research and Forecasting). The meso-scale model also models moisture fields and temperature, and this has been utilized to calculate icing and produce a map of icing conditions. Further information is available in Appendix.[22]

Kjeller Vindteknikk is involved in a R&D project called IceWind financed by Nordic Energy Research among others, further described in Appendix. The main objectives are to generate icing maps for Sweden, Finland and Iceland, and develop a better model for production losses due to icing[23].

Norway does not have a centralized system for collection of operational experience from wind farms. Data for downtime and production losses due to icing or low temperature is therefore generally not available. Only a few wind farms are located in areas where icing seems to occur more frequent; Nygårdsfjellet and Mehuken. Research is on-going at the farms on icing and production losses. Nordkraft Vind cooperates with Professor Per Arne Sundsbö at the University of Narvik on the Ny-

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[19] VTT Technical Research Centre of Finland, 2010

[20] Ibid

[21] Kjeller Vindteknikk AS is the leading company in wind measurements and analysis in Norway. Their services include creating wind resource maps, finding locations, wind measurements, analysing data and energy production calculations. Kjeller Vindtekknik also makes Wind- and icing maps for Sweden which can be ordered from them.

[22] Byrkjedal, Ø., 2008

[23] Byrkjedal, Ø., personal contact, July 2011

gårdsfjellet wind farm to rate the snow collection. Surveys will be used as a basis to build a draft screen and for other possible actions to minimize problems with snow in the operational phase from 2012.

3.4 Sweden

3.4.1 Introduction

Wind power is one of the fastest growing industries in Sweden, and in the world, of today. Wind power is seen as a clean generation of electrical power and new taxes on greenhouse gas emissions will make it a competitive source of energy. Large wind power farms are planned in Sweden to meet the ambitious plans. Especially the northern mountain regions, the coastal sea areas and the inner high plateau landscapes and surroundings have generated great interests for investors. In general, all areas of Sweden will experience times where icing may occur during the winter.[24] The number of turbines increased by 304 in Sweden to a total of 1 723 in the end of 2010. The total production during 2010 was approximatly3 497 GWh. During 2010 the total installed capacity in Sweden increased by 38% to 2 163 MW.[25]

3.4.2 Climate

Sweden has got a cold climate, characterized by dark and long winters with minimum temperatures of -15°C/-20°C; in the north part of Sweden the ice persist from October to May and obstruct navigation in the Gulf of Bothnia. Summer is short, with temperatures ranging between 15°C and 20°C.

In central and southern Sweden the winters are short and quite cold, and summer temperatures are mild. In the north winters are severe with snow lying the year-round on elevated areas. The summers are short and changeable.

3.4.3 Research and development

The Swedish Energy Agency has been appointed by the Government to promote the development of wind power in Sweden and therefore hold a fund for the mission. The Agency has started several so called knowledge programs in R&D for wind power; Vindval, Vindforsk and Nätverket för vindbruk. The Agency also has been appointed a research funding to be distributed to wind pilot studies, where several wind farms under development and in operation have received funding’s. Approximately half of the funding of pilot projects is attributed to wind power projects in cold climates in northern Sweden (described in Appendix). The support program´s first stage lasted 2003-2007 with a total fund of 350 MSEK. For the period 2008-2012, the government has granted the program an additional 350 MSEK.[26]

Göran Ronsten at WindREN AB has during several years performed state of the art reports on wind power in cold climate for the Vindforsk-program and participated in international research meetings and conferences etc.

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[24] Vindforsk, 2008
[25] Svensk Vindenergi, 2011
[26] Vindforsk Nyhetsbrev, 2010 & Energimyndigheten, 2011-08-23

For the last years an annual conference on wind power in cold climate has been arranged in the north of Sweden by the Swedish Wind Power Association and The Swedish Energy Agency.

Several Swedish universities, institutes, companies etc. are involved in international and European research programs such as IceWind, WECO, Cost 727, TopNANO and HIRLAM.

Institutions involved in related research

- The Wind Power Centre of the Barents Region
- Luleå University of Technology
- Umeå University
- Halmstad University
- Gotland University
- Kungliga Tekniska Högskolan, KTH
- Swedish Polar Research Secretariat
- MW Innovation
- Swedish Meteorological and Hydrological Institute (SMHI)
- Svensk Vindkraftförening
- Swedish Energy Agency
- Elforsk
- Vindforsk

3.5 Canada

3.5.1 Introduction

In Canada, renewable energy has a high priority, particular wind energy, both on federal and provincial government levels. Hence, targets, incentives and subsidizes have been established. At the federal level, the Wind Power Production Incentive (WPPI) 2 subsidizes a portion of the cost of establishing a wind farm for the first ten years. Several targets have been set for renewable energy at provincial levels, which provincial utility companies are encouraged to meet. A compilation list of provincial initiatives is available from Canadian Wind Energy Association (CanWEA), updated in June 2011.[27] Together the provinces targets reach 9000 MW installed capacity by 2015.[28]

CanWEA believes the potential of the Canadian wind energy industry to be high in terms of increased output, investments and job growth. The wind industry in Canada currently consist of hundreds of companies and firms, including manufacturers of components, project developers, consultants on necessary assessments for project approvals and local construction teams.[29]

[27] Canadian Wind Energy Association, September 2007
[28] Lacroix, A., 2011
[29] Canadian Wind Energy Association, 2011-07-06

Canada´s currently installed capacity is 4 611 MW[30] and 2011 is projected to be a record year with more than 1 000 MW likely to be installed. In 2010, 690 MW of new capacity was installed.[31]

Figure 4: Wind power installations in Canada 2011[32]

3.5.2 Climate and geography

Canada´s vast landscape, three windy coastlines, plains and mountains contributes to a huge wind resource and creates a massive wind energy potential.[33] Low air temperatures occur in the heartland and in the arctic regions. Atmospheric icing is present along the coasts, on high elevations and in the south central parts of the nation.[34]

Cold air temperature affects a majority of Canada and the best wind resources are often located in ice prone areas. There are 310 remote communities in Canada, not connected to the grid. These communities are entirely powered by diesel generators. Authorities, governments and companies are currently working for a development of wind power integrated systems in such areas, so called wind-diesel projects. Unfortunately, icing is common on these sites. There are a potential of 347 MW of wind power on these sites, although progress is slow. It is believed that if the low temperatures and the effects of the rime icing could be overcome wind power could be cheaper than diesel generation. Hence solutions for wind turbines in cold climate are important.[35]

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[30] Canadian Wind Energy Association, 2011-07-06
[31] Canadian Wind Energy Association, June 2011
[32] Canadian Wind Energy Association, 2011-07-06
[33] Ibid
[34] Lacroix, A., 2011
[35] Maissan, J.F., 2001 & Lacroix, A., 2011

The climate in northern parts of Canada is sub-arctic with a mean daily temperature of -25 °C in January, with lowest temperatures around -40°C. In Yukon rime icing is most severe in the early winter around mid-October to the end of December.[36]

A big part of Canada´s wind power development takes part in the province of Ontario, which in 2007 was the province with highest installed capacity and highest amount of planned capacity in Canada.[37] Ontario is situated in south-eastern parts of the country bounded on the north by Hudson Bay and James Bay and the American border which is mostly made up of water by the Great Lakes. Here the local climate, and conditions for icing, is strongly affected by the proximity to large bodies of water of the Great Lakes, which has a tremendous impact on the climate and weather variations. Due to the vast size of the province the weather also varies from region to region and within the regions themselves.[38]

3.5.3 Research and development

Research and development concerning wind power in cold climate and especially icing of wind turbines, have been present for several years in Canada. There are institutes and government based organizations carrying out research and development on wind power in Canada, listed below.

Canadian Wind Energy Association (CanWEA) is a non-profit trade association that promotes the appropriate development and application of all aspects of wind energy in Canada. The association has over 230 members. CanWEA annually holds an international wind power conference and exhibition, this year will be the 27th edition.[39]

Wind Energy Strategic Network (WESNet), who is a wide, multi-institutional and multi-disciplinary research network funded by industry and the Natural Sciences and Engineering Research Council of Canada (NSERC). WESNet can be compared to the Swedish Vindforsk-program, who collects and coordinates the research of 39 researchers at Universities across Canada. One of the objectives of WESNet is to develop innovative solutions to key technical issues facing the wind industry, particularly cold climate issues.[40]

WESNet has several on-going projects on wind power in cold climates where TechnoCentre éolien also is a part. Four major research themes have been listed; Theme 1 – Wind resource assessment, Theme 2 – wind energy extraction, Theme 3 – wind power engineering and Theme 4 – techno-economic modelling and optimization of wind energy systems. Especially cold climate research is found in Theme 1 and 2.[41] On-going projects are listed in Appendix.

TechnoCentre éolien is a Quebec-based not-for-profit organization founded in 2000. The priority of the centre is to support the development of Quebec know-how

[36] Maissan J.F., 2001
[37] Canadian Wind Energy Association, September 2007
[38] GE Energy, October 2006
[39] Canadian Wind Energy Association, 2011-07-06
[40] Wind Energy Strategic Network (WESNet), 2011-06-20
[41] Ibid

on wind energy.[42] The centre is a partner of WESNet in the Canadian R&D efforts on cold climates and is also involved in the research projects listed in Appendix. Research development and technology transfer projects on northern climates and complex terrain is one focus.[43]

In 2007 the TechnoCentre éolien initiated a research centre as a division of the TechnoCentre – **Centre CORUS**. The centre is a research, development and technology transfer centre that studies the impact of Nordic conditions on wind energy production.

Wind Energy Institute of Canada (WEICan) was established in 1981 with the mission to advance the development of wind energy across Canada through research, testing, training, and collaboration. The institute is funded by Natural Resources Canada (NRCan), acting on the regulations of the Minister of Natural Resources, and provincially through the PEI (Prince Edward Island) Energy Corporation.[44] The PEI Energy Corporation is a part of the Department of Environment, Energy and Forestry in the provincial government of Prince Edward Island.[45]

3.6 Reflections

The Scandinavian countries participate in several international R&D programs, including Nordic initiatives. Research in Norway is poor due to their milder climate and limited number of wind farms. In Finland research has been carried out since the 1980´s but the development of wind farms has been slow. The development of wind farms in Denmark is far ahead compared to the rest of Scandinavia, and due to the early development there is an on-going exchange of the old smaller turbines to the larger models available today. Research in Denmark is not as extensive as in Finland, Sweden and Canada.

The international research can be used as a basis independent on the development in each nation since the facts on icing conditions and effects of icing are the same irrespective of nation. What separates the nations from each other is the regional and local climate, which can have different effects on icing of wind turbines. Only parts of the knowledge from Canada can be applied to the Scandinavian wind industry due to the different weather conditions.

4 Conditions for icing

Ice build-up is not unique to wind turbines; in moist winter climate ice build-up is present on all types of buildings[46]. Any solid object accumulates ice which grows into the wind[47]. Icing on turbine blades and other structures can occur in different forms and due to various conditions. There is an ISO-standard that describes differ-

[42] TechnoCentre éolien, 2011-07-06
[43] Côté, R.F., 2011
[44] Wind Energy Institute of Canada (WEICan), 2011-07-06,
[45] Department of Environment, Energy and Forestry, 2011-07-06
[46] Elforsk, 2004
[47] Maissan J.F., 2001

ent kind of icing, ISO 12494:2001 ”Atmospheric icing of structures”. The International standard describes the general principles of determining ice load on structures of different types of ice.

4.1 Weather conditions and different types of icing

Ice occurs in several states with difference in appearance, density, solidity, colours and shapes. What type of ice that occurs in a specific location at a given time depends on a number of weather parameters. These parameters also affect the amount of accumulated ice on a turbine.

Atmospheric icing is the cause of icing of wind turbines. Atmospheric icing occurs from three different formation processes; precipitation icing, in-cloud icing and hoar frost. The main types that are of interest for wind turbine applications are precipitation icing and in-cloud icing. The main part of the atmospheric icing in Sweden is due to in-cloud icing. The density and persistency of hoar frost is too low to affect the power production of a wind turbine.[48]

According to later experiences, icing on wind turbines mainly occurs in the presence of water in liquid phase at temperatures below 0^{o}C. Clouds and reduced visibility are often due to free-floating water drops, but could also be caused by sublimation when ice crystals precipitate from water vapour (hoar frost). [49] When a wind turbine, at temperatures around 0 ° C and below, is rotating in clouds, fog or chilled precipitation there is a risk that ice forms on the blade front edges. On stationary units sleet may also freeze on the blades and other exposed parts.[50]

Formation of ice on wind turbine wings is not limited to the far north, but may occur on such southern sites where temperatures may reach just below 0 ^{0}C.When warm air lifts from the coastal seas onto the higher inland areas, it brings substantial amounts of water vapour. The water vapour then condenses to liquid water drop-lets when the air is cooled at higher altitudes. Such droplets can in sub-zero temperatures either freeze to snow or hail, or stay liquid as super-cooled droplets.[51]

4.1.1 Precipitation icing

Precipitation icing is ice that forms due to precipitation in form of wet snow or freezing rain[52]. The accumulation rate of precipitation icing can be higher than icing caused by in-cloud conditions. Precipitation icing also causes more significant damages than in-cloud icing. Icing due to freezing rain occurs when rain falls on a surface whose temperature is below 0 °C. Freezing rain often occurs during inversion. The ice density and adhesion of freezing rain are high.[53]

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[48] Carlsson, V., 2010
[49] Elforsk, 2009:61
[50] Elforsk, 2004
[51] Vindforsk, 2008,
[52] Carlsson, V., 2010
[53] Gedda, H., 2011

Wet snow occurs when the air temperature is between 0 and -3°C. The wet snow can be easy to remove if it does not freeze on to the surface. [54]

In 2008 there was no standardized way to measure icing caused by wet snow. Wet snow has been the cause of great problems for masts, towers and power lines. Problems for wind turbines occur when not in operation.[55]

4.1.2 In-cloud icing

In-cloud icing will occur when the weather condition is foggy, the liquid water content of air is high and the temperature is below 0°C[56]. In-cloud icing describes the process where super cooled liquid droplets (SLD), typically cloud droplets, collide with structures and freezes to the structure[57]. Super cooled cloud droplets tend to dry out when they are transported over a hill or a ridge. [58]

In-cloud icing is known to accumulate thick layers of ice[59]. This is e.g. a significant problem for aircrafts while passing through clouds.

Two types of ice occur due to in-cloud conditions, rime- and glaze ice. Rime ice is the most common type of in-cloud icing. The intensity and firmness of the rime accretion is dependent on local variations in cloudiness, height of cloud base, rate and size of super cooled water droplets, air temperature and wind speed.[60] The probability and frequency of rime accretion on a given location are also dependent on geographical location and its elevation. The number of days on which rime accretion takes place can be inferred using wind speeds and air temperatures observed.[61] The rime ice can be either soft or hard. The hard rime is more difficult to remove from wind turbines.

When the droplets do not freeze momentarily when hitting the blade, the droplets can run alongside the blade until it freezes at a later point. When the droplets freeze glaze ice is formed. Glaze has a strong adhesion and high density, and is therefore hard to remove.[62]

In-cloud icing is most likely to cause the most significant problems for wind farms in Sweden according to Ronsten.[63] As of 2008 the analysis of rime icing at interesting wind farm sites in Sweden had not yet started.[64] Although, the methods for analysing the occurrence of SLD has, according to Ronsten, improved.[65]

[54] Gedda, H., 2011
[55] Elforsk, 2008
[56] Elforsk, 2008 & Byrkjedal, Ø., 2008
[57] Byrkjedal, Ø. et al., 2008 & Vindforsk, 2008
[58] VTT Technical Research Centre of Finland, 2010
[59] Byrkjedal, Ø. et al., 2008
[60] NEMO-REPORT 31, 1998 & Gedda, H., 2011
[61] NEMO-REPORT 31, 1998
[62] Gedda, H., 2011
[63] Elforsk, 2008
[64] Elforsk, 2008
[65] Ibid

According to Canmet energy technology centre in Canada a lot remains to be known about rime icing, and they state that glaze ice will be an issue for offshore projects.[66]

4.1.3 Hoar frost

Hoar frost is formed when water vapour in the air sublimates into ice. The density and persistency of hoar frost is too low to affect the power production of a wind turbine. Normally it does not result in significant loads on structures.[67]

4.2 Geographical impact

Based on information from measurements, the rate of icing is relatively location independent; instead it is dependent on the height. This has been the results of studies and measurements in Finland, Swedish wind pilot projects and in Germany. Hence, the taller turbine the higher is the icing rate.[68] The trend of building larger and higher wind plants therefore further increases the icing risk.[69] This is also a condition recognized in coastal areas when the large turbines available today are built; the blade tips can undergo in-cloud icing.[70] According to a two winter's measurements at Pori in Finland, in-cloud icing was seven times as frequent at the 84 m level as compared to the 62 m level. This strongly suggests that icing becomes a more important issue also on coastal wind farms at sites like Pori when the dimensions of the wind turbines increase. [71]

According to prevalent opinions, there is an obvious risk of icing on masts, and therefore also on wind turbines in Sweden in places north of a line Karlstad-Gävle. This represents 70 % of the land area in Sweden. The latest available mapping of icing risks, a result from the EU project New Icetools, further confirms the referred opinion. The selection criteria are temperature below the freezing point, and cloud altitude below 200 meters or visibility less than 300 meters. However, icing occurs on the South Swedish Highland, which makes the deviation between calculated and observed data relatively large.[72]

4.3 Ice build-up and appearance on wind turbines

Research has shown that the ice accretes in different formations on blade profiles due to temperature, droplet size, speed etc.[73] If there are water drops running along the blade ice can freeze on local spots along the blade. In such a case the ice growth can be assumed to be linearly increasing towards the tip of the blade. If ice grows at lower temperatures where running water does not occur the growth will be linearly along the total blade.[74]

[66] Lacroix, A., 2011
[67] Fikke, S. et al., 2006
[68] Elforsk, 2004 & O2 Vindkompaniet, 2010
[69] Elforsk, 2009:61
[70] Marjaniemi M. et al. 2001
[71] Ibid
[72] Elforsk, 2009:61
[73] Elforsk, 2004
[74] Ibid

4.4 Reflections

What we know is that the main types of icing that are of interest for wind turbine applications are precipitation icing and in-cloud icing. In-cloud icing occurs in bad visibility conditions when the liquid water content of air is high at temperatures below $0^{o}C$. Therefore, the icing of wind turbines is not limited to the far north, but may occur on such southern sites where temperatures may reach just below 0 ^{0}C.[75]

We also know that the ice occurs in several states due to the very different conditions depending on the specific site and time and a number of weather parameters. However, the rate of icing is relatively location independent, but is dependent on the height above ground. The taller turbines the higher is the icing rate. The trend of building larger and higher wind turbines therefore increases the icing risk.

Though, the methods developed for measurement and calculation of icing is inadequate and further studies are needed in order to improve the possibilities to make correct forecasts of icing occurrence. The problem of measuring super cooled ice droplets is a main aspect.

As the climate is changing, Ronsten indicates that the consequences of icing for wind turbines located in the area of the Baltic Sea needs to be investigated due to a possible increase in liquid water content. This could be the consequence of a Baltic Sea that is not covered by sea ice to the same extent that we´ve seen so far.[76]

Finally, it can be stated that much is known about different types of ice as well as why and when it occurs.

5 Effects of icing

In this chapter a summary of identified effects of glaciation will be given and the state of knowledge in the area will be shown.

5.1 Production losses

Iced-up turbine blades and wind sensors can cause low production or no energy production during extended periods of time.[77] The icing cause production losses both from turn downs due to increased vibrations (higher loads) and too low temperatures as well as while the turbine is still in operation.

When the blades are lightly iced up, this will cause production losses while the turbine is still operating. The ice changes the airflow across the air foil to be more turbulent resulting in lower rotation, caused by a loss in aerodynamic lift and increase in drag. Studies have shown that there are cases where the production has been lowered to less than one fifth of the nominal output due to iced-up blades.[78]

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[75] Vindforsk, 2008
[76] Elforsk, 2008
[77] Ibid
[78] Ibid

In situations with small amounts of accreted ice, it is ice accretion on the tip of the rotor blade that causes the biggest losses of production. The effect on power production will be approximately the same if the outermost 5 % of the rotor blade is iced up as when about 75-95 % of the rotor blade in total is iced up. This shows the importance of keeping the outermost part of the blade free from ice at sites where weather situations with light to medium icing conditions occur. At sites where the icing of the blades reaches medium or severe stages the de- or anti-icing systems must be adapted to the full blade length or the turbine will eventually stop operating as the rotational speed is reduced and/or vibration alarms are set of due to an asymmetrical loading.[79]

According to Ronsten (Sweden) the performance of a severe iced-up wind turbine with a fixed rotor speed often decrease with more than 100%, i.e. it often requires additional energy from the grid to make the turbine running. A turbine with a flexible rotor speed probably could have a higher performance.[80]

According to Canadian experience icing can lower the performance up to 20 %.[81]

In Sweden, standard wind turbines without an anti-icing system have been observed to stand still for up to two months per year.[82]

Stenberg has in his Master's thesis, *Analysis of wind turbine statistics in Finland*, analysed failure statistics between the years 1996 and 2008. The thesis presents disturbance time of different components as a function of the lifetime of turbines. The result is an estimate for the downtime of each component. Data from 72 wind turbines are included in the analysis. The study shows that the main causes of downtime are failures in the gear and the hydraulic system. The largest number of failures arises in the hydraulic system. The report concludes that icing is not the main problem concerning downtimes (Table 1, Figure 5). [83]

[79] Carlsson, V., 2010 & Barber, S. et. al., 2009 (see Elforsk, 2004)
[80] Elforsk, 2004
[81] Lacroix, A., 2003 (see Elforsk, 2004)
[82] Elforsk, 2008
[83] Stenberg, A., 2010

Type of problem	Total down-time under 1996 – 2008 (h)	Average downtime per turbine (h)	Average down-time per tur-bine at one year (h)	Downtime portion of total time (%)
Network	5 504	76,4	5,9	0,07
Service	10 699	148,6	11,4	0,13
Disturbance	72 824	1 011,4	77,8	0,89
Icing	11 120	154,4	11,9	0,14
Other	1 214	16,9	1,3	0,01
Technical error*	152 428	2 117,1	162,9	1,86
Total	**253 789**	**3 524,8**	**271,1**	**3,03**

*technical errors can be troubles with gear, generator, breaks, hydraulics, rotor, heating etc.

Table 1: Downtimes according to type of problem.[84]

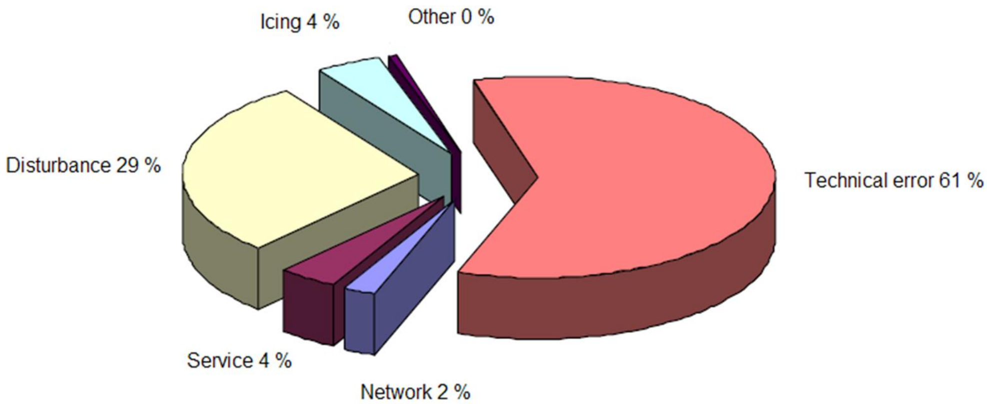

Figure 5: Percentage portions of total downtime.[85]

Currently in Finland wind turbines stops to operate when temperature reaches -15°C to -30°C. The limits for new turbines are between -25°C to -30°C.[86]

Statistics from Finland says that low air temperature has lowered turbine availability annually between 0.2% and 2.8% since 1997. Depending on the year, 5 to 18 tur-bines have been forced to be shut down due to low air temperature per year. The

[84] Stenberg, A., 2010
[85] Ibid
[86] Ibid

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.[87]

Field observations in Finland shows that 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 number is an average number 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. [88]

The Finnish wind farms Lammasoaivi and Olos are both located in areas where low temperature might prevent production. In 450 kW turbines, operation is limited to -25 ºC and in 600 kW turbines lowest operation temperature is -20 ºC. Although the temperature at the bottom of the mountains can get lower than turbine operating limits, it rarely fells under -20 ºC at the top of the mountain. At the end of January 1999, the temperature in whole Northern Finland reached -30 to -40 ºC in several days. During that period wind turbines were stopped because of low temperature.[89]

Despite low temperatures, wind speed at the mountains was still high enough for producing energy. Estimated energy loss in Lammasoaivi and Olos together was approximately 50 MWh, less than 1 % of the annual production. By the experience from Lammasoaivi and Olos, -25 ºC is well adequate operating temperature limit for wind turbines. [90]

In Finnish examinations icing´s share of total downtime varies from 4 - 28 %. The main cause of downtimes seems to be failures in gear and hydraulic systems.[91]

5.1.1 Results from case studies

Different projects are set up for measuring the production losses given with the impact of icing. Results for a number of projects are presented below.

In the Vindforsk project V-151 an analysis of production data from a Vestas V90-2 MW turbine in Svegström (Brickan) in Härjedalen municipality caused an energy production loss of approximately 5 % or approximately 150 MWh from a total production of 2.8 GWh. [92]

For the single installations at Hunnflen, Äppelbo, in Dalarna and Aapua in the County of Norrbotten, there is information on months of standstill due to icing. For the turbines included in the investigation, the production losses were estimated to be between 4 and 10 % of the annual production. It was pointed out that these figures were rough estimates, not based on measurements.[93]

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[87] VTT Technical Research Centre of Finland, 2010
[88] Ibid
[89] Aarnio, E. et al., 2000
[90] Ibid
[91] Peltola,E., 2008
[92] Elforsk, 2009:24
[93] Elforsk, 2009:61

On a forested hill ridge, 3.5 kilometres northeast of Änge community in Krokom Municipality the turbines have been considerably exposed to icing and the production losses were estimated to 5-10 %.[94]

In 2009 the production loss due to icing of a 600 kW Vestas turbine in Härnösand, Sweden, was measured with two HoloOptics Clear Ice Indicators. The result showed an energy output loss of approximately 15 % during January to March 2009. The measuring included times when the plant was shut down due to risk for ice throw. More than a 0,5 mm layer of ice was noted in approximately 505 hours out of a total of 2 200 hours. Any icing during the rest of the year was very light and had no impact on the plant. The loss of energy production over one year was estimated to approximately 5 %, of which approximately 35 % were due to closing down of the turbine due to the risk of ice throw. A calculation of the value of the loss was made, which showed that over a 15 year period with 5 % of interest the loss would correspond to approximately 3-5 % of the total installation cost of the turbine.[95]

In the wind pilot project Storrun operated by Dong Energy, production losses was estimated to approximately 5-10 % in the first year of investigation.[96]

The pilot project of Havsnäs includes studies of production losses due to icing. Measurements of icing are carried out in met masts and on the turbines. Losses will be measured and documented.[97]

In a Vindforsk project the influence of icing on the power performance was measured on the seven NM82 – 1,5MW wind turbines in Aapua. To measure when the power output was affected by icing a comparison was made of the actual power for both summers and winters with the nominal power in each wind speed bin. The average energy production losses were more than four times higher in the wintertime compared to those in the summertime. The average energy production loss was 27.9% in the wintertime and 6.6% in the summertime.[98]

According to a report by VTT Technical Research centre of Finland, the owner of Nygårdsfjellet wind farm has installed ice detectors and two web cameras inside one of the turbines. Experience of the turbines so far shows that the production losses are small, approximately 3% on an annual basis. For wind farm Mehuken, Finland, 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 been shed from the blades.[99]

5.2 Turbine loads

When ice is being build up on the blades the loads on the turbines are increased. The ice causes mass and aerodynamic imbalances and leads to additional vibrations. All commercial turbines include vibration monitors, which will shut the turbine down

[94] Elforsk, 2009:61
[95] HoloOptics, 2011
[96] Dong Energy, 2010
[97] Nordisk Vindkraft, 2010
[98] Elforsk 2009:59
[99] VTT Technical Research Centre of Finland, 2010

when vibrations exceed a pre-set level.[100] In turn, this causes a decrease in energy production.

The wind industry is now trying to find the breaking point of when to turn the turbine off due to high loads and optimization of the energy production. In the early years of iced-up wind turbines it was assumed that the best practice was to let the control system turn the turbine off in situations with high loads due to icing. When turbines with flexible blades came into operation and the development of de-icing systems started, several manufacturers and developers wanted to keep the blades rotating. This could allow an extended use of the de-icing system and reduce the production loss.[101]

Yaw system failure is a known problem caused by icing, which causes downtime and production losses. The most common solution to solve the problem is replacement of the yaw motor, which may have long delivery times. In most cases the downtime is below 20 hours but cases of up to 45 hours exists.[102]

Though, it is not clear that icing always will cause increased loads. At the trial of a case with measured glaciation in Denmark, the output became more stable compared with the ice-free case, and no increased loads could be detected.[103]

Long-time operation with iced-up blades is currently not covered as a design load case in the specifications of presently developed wind turbines.[104] In the EU-project NEW ICETOOLS it was proposed that icing can be simulated by individual, blade faulty pitch angle setting in the order of 5-7 degrees. Such settings are far larger than those included in current design load cases. [105]

5.2.1 On-going tests and measures

At Storrun wind farm loads on blades is measured by detecting icing through a monitoring system used on the blades by the operator Dong Energy.[106] Further studies and analysis will include further evaluation of loads during icing.

5.3 Influence on expected lifetime of components

Extra loads decrease the lifetime of components and structures. The ice cause increased loads to the blades and the rotor, and the turbine will eventually stop operating when the icing gets more severe. The tower also suffers from extra bending loads when blades are iced up.[107]

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[100] Garrad Hassan, 2007 & Canadian Wind Energy Association, September 2007
[101] Elforsk, 2004
[102] Elforsk, 2010:68
[103] Risø National Laboratory, 1997
[104] Elforsk, 2009:24
[105] Ibid
[106] Vindforsk Nyhetsbrev, nr 1. 2010 & Dong Energy, 2010
[107] Frohboese ,P. et al., 2007

5.4 Uncertainties in production forecasts

In order to minimize the impact of icing on wind turbines we need to know the local conditions of icing on a specific site. There are several parameters important to know, for example active icing, intensity of icing, passive icing, type of ice (rime ice, glace ice or wet snow) and maximum ice load. When these parameters are known, one can choose the appropriate measures for the turbines to be built on the site and evaluate the economic terms of the wind farm.

In order to facilitate the planning process before measurements may take part, a development of forecast models and icing maps are undertaken. Though, to verify a weather model´s prediction of icing, synoptic measurements of icing is needed.[108]

In order to measure the different icing parameters instruments has been developed. Measurements to verify the wind climate at the site in order to make forecasts on energy production are also needed. But, if the site is exposed to icing conditions the measurement instruments will be iced up. The ice on the measurement instrument prevents a correct reading of the present wind conditions and causes insufficiencies in the collected data. To overcome the problems of iced up instruments different methods and instruments are being tested. Another problem with measurements in climates where icing occurs is that masts supported by guy wires could be cracked at sites affected by medium to sever icing and strong winds.[109] Problems of climate- and wind measurements in icing conditions and methods for forecasts of icing are outlined in Chapter 6.

5.5 Power curves do not match

According to current IEC standard measurements of power curves may only be carried out in conditions free of ice. This is a limitation for wind farms in cold climates when iced up blades causes lower energy output with a certain wind speed. Power curves are a part of the warranty commitment for a wind farm. Power curves in cold climates is studied and measured at the pilot studies in Havsnäs in order to provide a standard for measurements in cold climates.[110]

5.6 Increase of blade generated noise

The accretion of ice on the turbine blades causes an increase in generated noise from the blades when cutting through the air. If the noise levels become too high according to what is allowed in the environmental permit this might stop the turbines from being able to operate. This also causes production losses and thus economic losses.[111]

5.7 Safety threats due to ice throw

Ice throw is a public health risk associated with wind power in cold climate. In some countries the subject is due to regulations. In populated areas some warning signs

[108] Elforsk, 2008
[109] Ibid
[110] Nordisk Vindkraft, 2010
[111] Elforsk, 2008

may be sufficient.[112] Warning light and warning sound are often given prior to start up after an icing event.[113] In some countries operation of wind turbines with a certain level of deviation between the actual power produced and the nominal power were prohibited in order to avoid ice throwing from iced-up turbines. This was shown to be devastating for the operation of the turbines due to the fact that when the rotor was stopped, the ice will accrete on the rotor blades making it more difficult or impossible to restart the turbine. Today turbines are allowed to operate as long as they can rotate.[114]

What is known about ice shedding from wind turbines is that two types of risks occur when ice is being accumulated on turbine blade, nacelle and tower. Either ice fragments dislodge and are shed from the rotor of the operating turbine due to aerodynamic and centrifugal forces or they dislodge from the structure and fall to the ground when the turbine is out of operation. [115]

The majority of recorded fragments of ice shed from wind turbines shows that they have landed less than 100 m from the turbine.[116] Observations in several studies also show that ice fragments breaks up into smaller fragments after detaching from the blade. There are several parameters affecting the throwing distance of an ice fragment from a wind turbine; geometry and mass of the ice fragment, rotor azimuth, local radius, rotor speed and wind speed. The wind direction is an important parameter for the assessment of possible risk in both cases. In order to assess the risk for a person or an object staying nearby a wind turbine input data are needed on the wind direction, wind speed frequency distribution in combination with information of icing events or in combination with the air temperature as well as the number of persons passing the risk area per year and number of icing events per year.[117]

Ice throw (shedding) has in Canada been a question of public safety in the regulatory process of wind farms. Thus, measures have been taken in order to enable wind power development. In 2007 CanWEA suggested a minimum distance of blade length plus 10 meters from public roads, non-participating property lines and other developments to ensure public safety in the event of ice shedding. Studies on the matter of ice shedding conclude that risks to objects or individuals directly drop off significantly with increasing distance from the turbine.[118]

5.7.1 Risk assessment of ice throw

Risk analysis's was first established in the beginning of the 2000s. In 2007 Garrad Hassan presented an assessment methodology and guidelines for risk analysis were presented. The assessment methodology includes several steps and is applicable to wind farm projects when considering the proposed turbine type, the terrain of the site and surrounding area, and assumptions for human presence in the surrounding area. Several scenarios where calculated for. Overall, the results from calculated

[112] HoloOptics, 2011
[113] Elforsk, 2008
[114] Ibid
[115] Canadian Wind Energy Association, September 2007
[116] Garrad Hassan, 2007
[117] Seifert H. et al., 2003
[118] Canadian Wind Energy Association, September 2007

risks were low. The report also includes a suggestion of control mitigation strategy for situations where a significant risk to the public or operational staff due to ice throw is believed to exist. Reliable detection of icing conditions in order to allow automated turbine curtailment and/or activation of blade heating systems during unattended operation would lower risks of ice throw. [119]

The extent of the risk depends of the regional weather and wind conditions, instrumentation of the turbine´s control system, and the operational and mitigation procedures in place in every situation. CanWEA has suggested operational procedures and mitigation strategies to be undertaken in order to reduce risks of ice throw. CanWEA also concludes that with mitigation measures, the risk associated with ice shedding can effectively be assessed and that the risks are very low relative to generally accepted natural hazards. This is particularly true to the area outside of the area immediately under the turbine (outside the radius of the turbine blades). The safety distance of ice throw most often does not need to be considered when it comes to safety distances to residences while the sound criteria often demands much longer distances between the turbine and the residence.[120]

In Finland two risk analysis´ of ice throws has been carried out the last years by Ramboll. The assessments were carried out in the planning process of the wind farms Alahärmän tuulivoimapuiston jäävaaraselitys and Koillinen teollisuusalue, Rauma jäävaaraselvitys, because of close residences. The sites are located in the south and middle of Finland.

In Rauma the conclusion of the work was that 70 % of the ice pieces will be thrown 270 meters from turbines at the most (Figure 6).

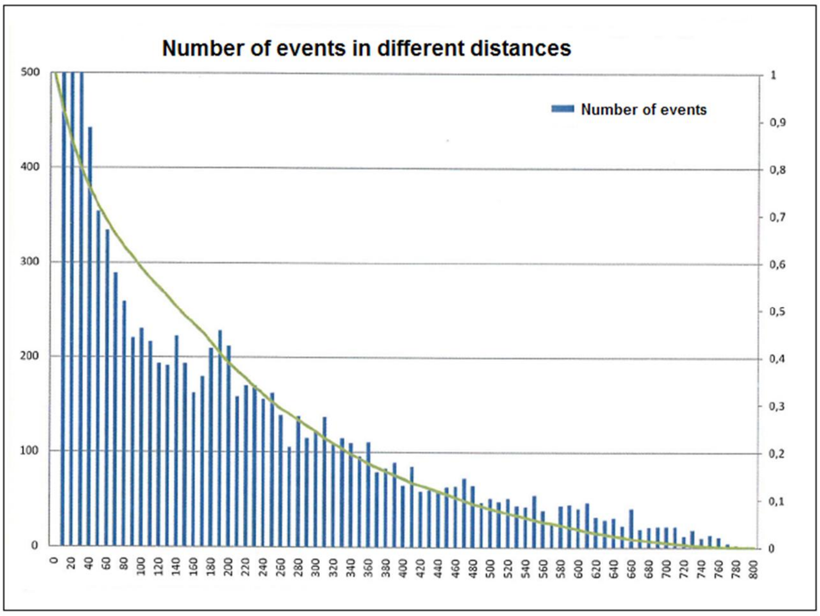

Figure 6: Number of events in different distances.[121]

[119] Garrad Hassan, 2007
[120] Canadian Wind Energy Association, September 2007
[121] Ramboll, 2010

5.8 Reflections

Icing leads to production losses, both from lower energy output due to iced up blades and due to down time when turbine is turned off because of high loads or risk for ice throws. Ice built up on the turbine blades will lead to additional vibration caused by both mass and aerodynamic imbalance. All commercial machines include vibration monitors, which will shut down the machine when vibrations exceed a pre-set level. When reaching smaller amounts of icing, the production is decreased by a lowered lift capacity on the blades and thus a smaller energy output from a certain wind speed is given. Icing of blades also shortens the lifetime of components.

Though, icing is not the main problem concerning downtimes up till today. But in the future it may become a significant problem when more turbines are being built in regions where icing is present. Installation of de- or anti-icing systems will be economically viable due to the amount of ice, hours of icing per year and installation cost.

In order to enable forecasts and investment decisions on prevention systems there is a need for more measurement stations and icing measurements in planning stage to get reliable statistics of icing occurrence. This applies both to meso-scale and site specific wind power planning. Non-reliable measurement equipment makes statistics and forecasts of today unreliable.

The conclusion is that it is of significance for the wind industry with available and reliable ice detectors and wind measurement instruments for measurements in cold climate, as well as masts that are designed to operate in cold climates. There is also a need for prediction of icing at a larger scale. Methods are under development but are not fully useable today. In order to verify the models, measurements are needed.

Icing may also cause ice being thrown of the blades while in operation or fall from the turbine at stand-still. This will cause a safety risk in the direct proximity to the turbine. The extent of the risk depends of the regional weather and wind conditions, instrumentation of the turbine´s control system, and the operational and mitigation procedures in place in every situation. With mitigation measures, the risk associated with ice shedding can effectively be assessed and the risks are very low relative to generally accepted natural hazards.

The fact that long-time operation with iced up blades is not covered as a design load case in the specifications of presently developed wind turbines can be a problem both in terms of lifetime of the turbine, insurance and warranty levels.

6 Measurements and prediction of ice accretion

Based on the conclusion from previous chapter it is of importance for the wind industry that reliable ice detectors, climate measurement instruments for cold climate sites and forecast methods is available. In this chapter parameters needed to estimate icing occurrence and rate as well as different methods for climate measurements and available instruments for ice accretion measurements is described. Forecast methods and models are also included.

6.1 Measurement of icing parameters

Measurements have been carried out in different national, international and European research programs (COST 727, Wind pilot programs, Vindforsk among others).

Measurements have resulted in identification of improvements needed on different ice detector systems as well as an increased knowledge of icing parameters and what can be measured by today's technology. The key parameters for estimating icing are expected to be the droplet size distribution and the liquid water content of air, combined with temperature and wind speed. The two cloud parameters liquid water content of air and droplet size distribution are currently not possible to measure in the field at reasonable cost. Measuring the visibility and estimating the vertical velocity may instead be used to approximate these parameters. For the latter, ice accretion on an object can be calculated using Makkonen´s formula. To measure correction factors one of few possibilities is to carry out tests in icing wind tunnels.[122]

Relative humidity has often been believed to be a key parameter for icing, and it can be used to indicate a risk for icing, but it cannot be used to calculate the rate of icing on a particular object.[123] Air temperature also can be used as an indicator of icing risks.[124]

Testing of different ice detectors show that the occasion when icing occurs can be detected quite well with available instruments. But when instruments are iced up, they will give an overestimation of the duration of the icing period, especially when humidity sensors are iced up.[125] The normally used climate and wind measurement instruments are also being iced-up, why there is a need of development of such instruments as well. There are available instruments, but like the icing measurement instruments, the instruments are not as well-developed as needed.

Testing of HoloOptic icing sensor resulted in the conclusion that location and surface of the measurements differs from the actual status of the turbine blades, due to the fact that the measurements are carried out either in a mast in the surroundings or at the top of the nacelle. This gives a location error or measurement surface error. The amount of ice will vary both radial and across the blade. Thus, an absolute result for ice rate deposition or for the thickness of the ice cannot be given. The results from the measurements can be used, in support of experience, to decide on appropriate de- or anti-icing measures for the wind turbine.[126]

As the icing frequencies increase with increasing altitude, the wind measurements should be carried out up to the highest blade passage altitude, or, at least up to hub height. This is seldom the case, since ice covered measurement masts and guy-wires tend to be very wind susceptible. To avoid structural collapse of measurement towers they can either be correctly dimensioned for the site specific icing conditions or

[122] Elforsk, 2008
[123] Ibid
[124] Elforsk, 2009:24
[125] Carlsson, V., 2010
[126] Elforsk 2010:05

additional energy can be applied for de-icing of the mast, wires and boom supporting structures.[127]

Icing measurements being carried out on turbines in operation mostly are overestimating the icing risk and ice occurrence. But, due to the fact that the indicators show when ice is not an issue they still can be used. They can tell when it is not a risk for ice being thrown from rotating blades and thus minimize the safety risks.[128]

6.2 Ice detection methods and instruments

There are several ways to detect and measure icing on wind turbines. There are currently no widely available, sufficiently reliable ice detection systems suitable for wind turbines.[129] Measurements and testings' show that none of the available sensors works satisfactory. Instead, the recommendation is to use at least two types of sensors when measuring ice occurrence and amount of accreted ice.

A review of ice sensor technology and the challenges for icing detection for wind turbines was performed in a study by Matthew C. Homola et.al, Narvik University College. A total of 29 different methods for detection of icing were found. The methods and instruments were compared to a list of basic requirements for an icing sensor for wind turbine applications. No ice sensors performing satisfactory were found. Techniques that were believed to be best suited for wind turbine icing detection was sensing methods using infrared spectroscopy through fiber optic cables, a flexible resonating diaphragm, ultrasound from inside the blade or a capacitance and/or inductance or impedance based sensors.[130]

Different possible methods for detection of icing and estimation of icing identified by Elforsk are listed in the table below:

- Measurements of liquid water content and droplet size distribution
- Changes of a vibrating frequency
- Changes in load of ice
- Spectral analysis of scattered light
- Retro reflective surface
- Obstruction of a light beam
- The formation of an ice film as analysed by an IR-camera
- Detection of the attenuation of an ultrasonic signal
- Detection of changes in the electrical impedance on the probe's surface
- Analysing the output from a heated and an unheated anemometer
- Detecting a frozen wind vane
- Change in sound spectrum
- Change in power[131]

[127] Vindforsk, 2010
[128] Elforsk 2009:06
[129] Walsh, M., 2010
[130] Homola M.C. et al., 2006
[131] Elforsk, 2008

Since there are no fully reliable climate- and icing measurement instruments, other methods are used. One method is to set the turbine's energy output in relation to the wind speed. If this relationship deviates from the normal, and the temperature is within the risk for icing, the de-icing system can be started. Another method is based on the fact that the ice rarely arises equally on the three blades. Therefore ice can be detected by variations in the electrical power output or in increased loads on turbine components. The simplest indication will be to observe the variations of the electricity output.[132]

Other possible sources of information are those error logs that are accessible to owners and manufactures. If a plant stops due to vibrations or low energy production in relation to the measured wind speed, this might indicate icing.[133]

6.2.1 On-going tests

At Storrun wind farm tests are being carried out in order to model the blade loads at times of icing with a monitoring system used on the blades. Further studies and analysis will include evaluation to better understand the conditions under which icing occurs and how the loads are affected during icing. The results will be used for implementation of the ice detection system with the WTG controller.[134]

Wind pilot project carried out by O2 Vindkompaniet includes measurements of icing in order to verify general measurement- and calculation methods for icing and wind speed. The objective is to enable better calculations on investment for equipment specialized for icing conditions on specific sites. Measurements will take place in 8 project sites (Bliekevare, Glötesvålen, Aapua, Tåsjö and Dundret amongst others). [135] So far O2 Vindkompaniet has been able to state that the ice load increases significant with elevation.[136]

Icing measurements have also been carried out in Bliekevare and Sveg. In April 2009, a new icing measurement station was installed on turbine #13 in Bliekevare. This turbine was equipped with an anti-icing system from MW-Innovation/Kelly Aerospace Thermawing. The data shown is from 2009-04-07 to 2009-04-10 when HoloOptics T23 ice detector indicated icing at an early stage as the temperature was falling. The signal from the ice load sensor; Saab Security's "IceMonitor", was initially unstable and didn't indicate a significant ice load until 18 hours after the first ice detection. It is assumed that this was a wet snow icing event. On such occasions, the vertical ice load sensor can't be expected to measure icing unless the wind speed is high. The temperature measured is likely to be a few degrees too high, an assumption which has been verified by Saab Security. Another issue with the thermometer used in Bliekevare is, due to the heated sensor, its inability to correctly measure the temperature at wind speeds below 4 m/s. In 2009 the icing measurements in Sveg were unique as icing has been measured versus height at several levels. The amount of ice measured at 15 m is significantly lower than the ice measured higher up. Con-

[132] Elforsk, 2009:61
[133] Vindforsk, 2010
[134] Dong Energy, 2010
[135] Dong Energy, 2010 & O2 Vindkompaniet, 2010
[136] O2 Vindkompaniet, 2010

sequently, the ice load measured on the nacelle will not always be representative for the icing conditions encountered by the wind turbine blades.[137]

6.3 Heated anemometers

In locations where icing is present wind measurement instruments are facing problems when being iced-up, and thus cannot deliver correct measurement data. There is a need to develop a simple, robust and reliable measuring instrument capable of optimum operation in cold climates. Therefore there is on-going development on heated anemometers in order to overcome this problem. In 2009 there were three heated anemometers available on the market, Vaisala´s WAA252, NRG´s IceFree3 and Hydrotech´s WS3.[138]

Development of a heated anti-icing anemometer is being carried out by Canadian researchers in TechnoCentre éolien program. Tests and measurements are simulated in a refrigerated wind tunnel; research on calibration, distance constant, start-up threshold, angular response, torque measurement, effects of temperature and defrosting tests are carried out. First generation of anemometers were not heated, the research group has developed a second generation of anemometers that are heated that are currently being tested. Next on the agenda is to study the angular response to optimize the aerodynamic performances, make de-icing and anti-frost test, develop a third generation anemometer with thermal and aerodynamic improvements, integration of the smart control algorithm based on a digital vision system and finally make tests on an actual operating site [139]

Evaluation of measurements is a goal for several R&D projects.

6.4 Ice mapping and other methods for forecasts of icing

Icing analyse models and forecasts are today in regular use within civil and military aviation services. Attempts have been made to develop and present icing maps which can describe the assumed losses at an intended wind farm site.

To determine changes in the climate, meteorologists often use 30-year data sets. Long data series of observed icing events can be used for rough verification of icing. However, long-time icing measurements are scarce in the Nordic countries and those available seldom provide information required for wind turbine applications. Often information on number of active and passive icing hours, intensity and type of icing is lacking and are not carried out at relevant heights. Although, probabilistic methods to estimate extreme icing events based on historical data have been developed.[140]

In Canada there are available long term data from 20 years of icing measurements for grid operators carried out by Hydro Quebec. In Germany measurements have been carried out by the Deutscher Wetterdienst (DWD) in a mast in Falkenberg outside of Munich. The German icing measurements were carried out at 5, 50 and 90 m

[137] Elforsk 2009:59
[138] Bégin-Drolet et al., 2009
[139] Bégin-Drolet et al., 2009
[140] Elforsk, 2008

elevation respectively. There were no long time trends found in the measured data.[141]

The point to point study developed by Corneau in Canada for prediction of icing is not directly applicable for mapping of icing in Sweden and Scandinavia. This is due to the fact that clear icing is of great concern in Canada, while it is rime icing, or in-cloud icing, that is likely to cause the greatest production losses in Scandinavia.[142]

Both numerical and simple models have been developed. The numerical models are meteorological boundary-layer models and incorporate the basic equation for ice accretion on a standard cylinder. The Norwegian model WRF is a numerical model that was tested in the COST Action research program. The simulations were performed for periods of winter 2007/2008 and shows extremely positive results, modelled data and measurements agree with each other. [143]

Simple models are based on simple correlations between available meteorological data during the icing process and the ice load. [144]

Verifications of analyses and forecast tools, for example from temperature and icing measurements in high masts are needed to enhance the reliability of existing models. Only after verification is made possible, it is meaningful to develop reliable icing maps, which can describe the assumed losses at an intended wind farm site. In combination with the wind energy resource it is possible to estimate the losses in energy production that is caused by icing. After doing this, a wind energy developer, or owner, will be able to judge which type of de-icing equipment is most economical to order, if any. [145] According to Ronsten, there are three missing links between these icing measurements and modelling; a) liquid water content of air, b) droplet size distribution and c) ice accretion on an object under known weather conditions.[146]

In 2008 a questionnaire was sent to meteorological institutes and companies in Norway, Sweden and Finland in order to find the state-of-the art in modelling of icing for wind energy applications in the research of Vindforsk in Sweden. The answers showed a consensus over the fact that synoptic icing measurements are needed to verify the results of modelling and to improve weather models. Sensors for measuring liquid water content in the air (LWC) and droplet size distribution (DSD) would be very valuable for the verification process. As mentioned, both are difficult to measure directly and are therefore approximated by visibility and vertical velocity respectively. [147]

Another problem of mapping and modelling of icing is that high resolution is required for the model to capture terrain effects, both horizontally and vertical, which is crucial if the map/model is to be used for wind power planning.[148] This has been a big problem up till today, available models has been to rough. All the respondents to

[141] Elforsk, 2008
[142] Ibid
[143] Ibid
[144] Ibid
[145] Vindforsk, 2010
[146] Elforsk, 2008
[147] Ibid
[148] Ibid

the above mentioned questionnaire stated that their model terrain resolution was increasing, which will improve local modelling of icing. [149] In the last five years great progress have been made due to evolvement of weather prediction models, which have been extended with more advanced cloud schemes and reached resolutions not previously believed possible. The reason for the latter is not only due to model development but also to the ever-increasing computer capacity made available to meteorologists. [150]

The Elforsk report 08:40 *Mapping of icing for wind turbine applications – A feasibility study* gives a good picture on the available models in Scandinavia which also shows icing maps.

6.5 Classification of sites, measurement instruments and icing prevention systems

How severe and in what state icing appears have great effect on the demands on a turbine that is going to be built on a specific site. To standardize icing conditions and development of techniques on the area, the techniques of anti- and de-icing, sites and wind turbines can be divided into categories and classes. This would facilitate the wind power planning.

Ronsten has identified three classes for de-icing and anti-icing systems respectively divided into light icing, moderate icing and severe icing.[151]

In the COST 727-project five site and instrument classes was proposed according to the severity of icing and the site climatic environment.[152] According to Ronsten the instrument class index proposed by COST 727 can be matched to the appropriate site icing index in order to achieve the desired availability. The classification of sites and instruments are tools needed to take the next step in research on icing according to Ronsten.[153]

The proposed classification standards were not yet adopted by the World Meteorological Organisation (WMO) in 2008.[154, 155]

6.6 Reflections

The key parameters for estimating icing are expected to be the droplet size distribution and the liquid water content of air combined with temperature and wind speed, these parameters are currently not possible to measure in the field at reasonable cost. Measuring the visibility and estimating the vertical velocity can be used to approxi-

[149] Ibid
[150] Ibid
[151] Elforsk, 2008
[152] Fikke, S. et al, 2006 (see Elforsk, 2008)
[153] Elforsk, 2008
[154] Ibid
[155] No information on the fact that any standard has been adopted has been found during the study.

mate these parameters. Air temperature and humidity may also be used as indicators of icing risks.[156]

There are a number of measurement instruments under development, measuring different parameters for the estimation of icing. None of them is fully reliable today. The recommendation is therefore to use at least two separate measurement systems on the same site. The occasion when icing occurs can be detected quite well with available instruments, but when instruments are iced up, they will give an overestimation of the duration of the icing period.

Independent on how the technique develops there will be a location error of the collected data, due to the rotation of the rotor and therefore difference in height of the blades at different points.

The development of wind farms in Scandinavia also would be facilitated by development of standardised classifications for cold and icing climates on wind turbines, measurement instruments and sites.

7 Methods for de-icing and icing prevention

De-icing features need to be incorporated on turbine blades located in cold and humid weather zones to avoid risk of shut down for months during winter time with high economic losses as result. The problem is accentuated by the steadily larger and higher wind turbines, since the blade tips for much of the year can pass in the low clouds that can cause icing when temperatures fall below zero.

A distinction is made between “anti-icing” systems and “de-icing” systems. The anti-icing systems prevent ice from being built up while the latter removes ice.[157] Different techniques for de- and anti-icing of wind turbine blades have been under development since the early 1990´s. The most frequently tested technique of the two is de-icing because of the fact that anti-icing have a higher power demand while it has to be in operation for longer periods of time to prevent icing. A de-icing system is only turned on after icing has been detected and runs till the blades are de-iced. The power available for de-icing is normally less than 5% of the rated power of the turbine, while the anti-icing requires much higher amounts of the rated power.[158] For both techniques dimensioning and effect requirements are affected by the demands of the specific system.[159]

A study of power consumption of the Pori ice prevention system was measured to be 1% of the turbines annual production. Maximum heating power of the turbines was 6% of the nominal power of the turbines. The costs of the ice prevention system in systems such as in this study are between 5 - 10 % of the factory price of the turbines.[160]

[156] We don´t have any information on what parameters are studied with the measurement instruments under development
[157] Seifert, H., 2003
[158] Elforsk, 2008
[159] Elforsk, 2009:61
[160] Marjaniemi M. et al. 2001

The current anti-icing technology calls for power requirements at 6%-12% of the capacity for turbines ranging from 220 to 1000 kW while the anti-icing technology is in operation.[161]

There are several systems under development in different R&D projects throughout Scandinavia and Canada. For most of them there are no fully reports on the results since they are still on-going. What is known about different techniques and results public available from R&D-projects is presented in the applicable section below.

7.1 Blade heating

Heating systems inside the blades is an anti-icing technique based on electric heating elements. Blade heating may be necessary at sites that experience severe or long periods of icing. For sites with light icing and temperatures frequently rising above 0^{o}C after the icing event, less power demanding techniques may be sufficient to melt the ice, for example black coated blades.[162]

Different types of blade heating systems are required due to the site´s icing climate and the expected severity of the icing events. There are two types of active blade heating systems; electrical heating and blowing warm air through the blades. The heating energy required and the area to be heated depends on different factors such as turbine blade geometry (blade thickness, chord length, torsion, pitch angle), rotational speed of wind speed, meteorological wind speed, outdoor temperature, cloud droplet size and liquid water content of air.

The method where warm air is blown through pipes in the blade has the advantage that it doesn´t influence the aerodynamics of the blade but on the other hand , the glass fibre reinforced plastic blades are fairly poor heat conductors which calls for high heating power to de-ice the blades. If this heating system is activated at standstill, the power has to be taken from the grid and paid for by the operator. [163]

The power requirements for blade heating have been possible to reduce during the development since 1991, though it is still high.

An example of electrically heated blades is the Finnish blade heating system that uses carbon fibre elements, mounted on the blades near the surface of the leading edge.[164] Nowadays e.g. Finnish manufacturer WinWinD sells wind turbines with blade heating system (WinIce).[165]

In the Dragaliden wind pilot project, owned by Svevind (Appendix), Enercon´s de-icing system has been tested. The system is a hot air system where air circulates inside the blades. The system is cheap but has high energy consumption.[166] In the study comparison and testing gave the result that the turbines produce 54 % more energy with the de-icing system than operating without. The study also showed that ice that builds up on the rotor blades changes the aerodynamic profile of the turbine,

[161] VTT Technical Research Centre of Finland, 2009
[162] Laakso, T. et al., 2003
[163] Seifert, H., 2003
[164] Laakso, T. et al., 2003
[165] WindWinD, 2011-07-07
[166] Gedda, H., 2011

meaning that with the extra weight on the rotor blades power output drops and the curve no longer corresponds to the optimized profile for maximum yield. The de-icing system is controlled and started when the turbine monitoring system (SCADA) registers a power curve below the normal curve. Then the rotor blade heating system is activated and warms the blades to temperatures over 4 degrees Celsius.[167]

Enercon de-icing system handles light icing and de-ices the turbines while not in operation, and thus the turbines cannot produce electricity to its own de-icing.[168] According to Enercon the system can reduce the downtime by 60-90 % depending on the local climate and has an investment cost of 200 000 SEK per turbine.[169]

Other available electro thermal systems are EcoTEMP and VTT. [170]

7.2 Ice-repellent coating

Another way to prevent ice to accumulate on the blades is to cover the blade or parts of the blade with special coatings. Different coatings are under development, both de- and anti-icing techniques are used. The foil is installed on the outside of the blade, which is an advantage while there is no need to change the construction of the blade. One of the questions being investigated is whether the system affects the aerodynamics or not.

Advantages of the coatings technique is that it also reduces sensitivity to dirt and bugs which also makes the maintenance of the blade easy, the cost is low, no special lightning protection is needed and it is easy to apply. There are still some issues to be solved while several materials have been tested but no good solution has been found. Icing still occurs on the blades and materials degrade which makes the coating porous. A clean and smooth surface is preferable.[171]

As a part of Nordic Top-level Research Initiative, TopNANO is developing nanotechnology coatings for anti-icing in the aviation and wind power industry. The aim is to develop a surface of the blades from nanotechnology where the ice does not stick. TopNANO will run from 2010-2013.[172]

Prototypes of surface finish are tested on the blades for minimization of ice build-up in the Storrun Wind pilot project. Every turbine is equipped with a passive system to reduce icing on turbine blades through an “anti-ice coating”. This method has according to Dong Energy reduced the production losses due to icing to about 5-10 %. Though, Dong Energy does not consider this system as enough for anti-icing.[173] Preliminary results were shown on WinterWind 2011 Conference.[174]

In wind pilot projects of O2 Vindkompaniet two different de-icing systems will be tested at a couple of project sites during two winters. The ultimate objective is for the developed de-icing system to be installed on a large scale at Sjisjka or Glö-

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[167] Svevind, 2011 and Gedda, H., 2011
[168] O2 Vindkompaniet, 2010 & NyTeknik, January 26 2009 & Elforsk, 2008
[169] NyTeknik, January 26 2009
[170] Gedda, H., 2011
[171] Gedda, H., 2011
[172] Nordic innovation, 2011-08-18
[173] Vindforsk Nyhetsbrev, nr 1. 2010
[174] Dong Energy, 2010

tesvålen where icing is severe.[175] The American de-icing/anti-icing system Thermawing developed by Kelly Aerospace, produced and used for aviation de-icing in cooperation with Nasa, was installed in one wind turbine at Bliekevare and Aapua respectively in 2009. The technique is a mix of electrical heating and blade coating, based on a foil of expanding graphite that reacts very fast when electricity is added. The fast response makes it possible to heat the blade in sequences. The foil can, according to Kelly Aerospace, de-ice the blades in 7-14 minutes with an effect of 25 kW. If the effect is increased to 100 kW the system will prevent icing. One of the questions being investigated is whether the system affects the aerodynamics or not. Another aspect is the high cost of the system; in 2009 the price of the system was approximately 2 MSEK for a 2 MW turbine, which is 5-10 % of the total investment cost. o2 Vindkompaniet believes that series produced will lower the cost which will end up in an additional cost of approx. 1MSEK.[176] The system can be installed both on field and in factory.[177]

o2 Vindkompaniet shared some experiences from one of their project at Winterwind 2010 conference where they do not recommend installation of a prototype system on a certified product without participation of the manufacturer, installation of a de-icing system in a tent, installation of a de-icing system from a crane basket in storm, fog or cold weather. They also conclude that none of the prototypes nowadays works with satisfaction so far, but the principle of foil on the blades is the right track. The challenges are connected to installation, system integration and power supply. Through cooperation with the manufacturer o2 Vindkompaniet now believes that they have a financial and technical mature system within reach.[178]

In the Uljabuouda Wind pilot project owned by Skellefteå Kraft (Appendix) the turbine blades are equipped with an ice-prevention system with electrical heating of a built in foil on the front edge of the turbine blades developed by MW Innovation. Measurements and evaluations of the ice-prevention system are carried out by Skellefteå Kraft.[179]

In the wind pilot project Storrun operated by Dong Energy, every turbine is equipped with a passive system to reduce icing on turbine blades through an “anti-ice coating”. In the first year of investigation the production loss was a total of minimum 5-10 %.[180] Dong Energy does not consider the anti-ice coating system as enough for anti-icing.[181]

7.3 Black paint

Black paint has been tested as a de-icing technique and is about putting black paint on the turbine blades in order to make solar radiation melt the ice. At tests in Yukon, Canada, the method showed an immediate and noticeable improvement in turbine

175 Swedish Energy Agency, 2011-06-22 & O2 Vindkompaniet, 2010
176 NyTeknik, January 26 2009
177 Gedda, H., 2011
178 O2 Vindkompaniet, 2010
179 Vindforsk Nyhetsbrev, nr 1. 2010 & Skellefteå Kraft, 2011 & MW Innovation, 2011-07-05
180 Dong Energy, 2010
181 Vindforsk Nyhetsbrev, nr 1. 2010

performance. However, the technique does not particularly well at Scandinavian sites during winter because of the long dark hours. It would neither work on sites where icing is severe and frequent. Icing periods need to be followed by temperatures above 0° C or the site has to have a high winter solar intensity.[182]

7.4 Chemicals

The use of chemicals as a de-icing method springs from aviation where chemicals are applied on aircraft wings before take-off. Chemicals lower the freezing point. Chemicals have one big disadvantage; they are poisonous to the environment, and they do not stick on the surface for a long time.

7.5 Flexible blade/active pitching

To flex the blades is a technique to get the ice to crack and come loose. Information on the technique is sparse. The method is not scientifically verified and it may probably damage the turbine.[183]

7.6 Mechanical

There are cases where de-icing has been carried out by crane, for example when using chemicals for de-icing.[184]

7.7 Microwaves

Halmstad University conducts a pre-study on how to prevent icing by choosing the right blade structure and other characteristics and by using microwaves. The results show that the form of the wing, especially the contact area, may be crucial to the icing problem. The nano-metric structure of the wing surface can probably be designed so that the water droplets have a minimized contact area to the wing.

A problem of using microwaves is that pure water and ice absorbs microwaves poorly, the microwaves are too inefficient to heat water or melt ice. Direct microwave devices should therefore not be developed. Indirect heating with microwaves is possible by using microwaves to heat the blade surface which conducts heat to the water/ice. This is thought to be a very efficient and robust method.

Another solution tested was to increase the frequency to millimetre waves. This was show not be sufficiently efficient, but the generation is most probably too inefficient to be of any practical use.

Further, the pilot investigation suggests that infrared waves are very efficient to heat water and melt ice and should be investigated and that heat conduction is also efficient and should be pursued.

The project is a pre-study and further research is required. The authors strongly suggest investigation of the water droplet flow over the wing.[185]

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[182] Gedda, H., 2011
[183] Ibid
[184] Ibid

7.8 Reflections

The development of de-icing and icing prevention methods has occurred on a small scale at the initiative of wind power developers, small businesses and enthusiasts. Hence, it takes time to develop good solutions. Large wind turbine manufacturers have so far showed little interest. There are manufacturers developing techniques such as Enercon, Siemens, and WinWind. However, since most of the world's wind turbines are not at risk of icing, it is difficult to get the manufacturers to tackle the problem. In the market today there are a number of systems for de-icing but the systems have not attracted wind power owners since the technology and the costs are not satisfying the need[186].

The most common methods amongst the tested techniques through the years are heating of the blades through hot air being pumped through channels in the blades, electric heating and coatings. There is no available technique for medium and sever icing conditions that is sufficiently tested and developed for commercial use. Several tests are carried out in the wind pilot programs. Results will be presented during the coming years.

If the electrical power needed for anti-icing systems were to be lowered, this would be a good alternative technique to use while it allows the turbine to always be in operation.

From an energy saving point-of-view it is desirable to apply strategies adapted for the severity of the icing at the specific site. Classification of sites would be a helpful guide in the decision on what method is needed for the specific site.

Chemicals are not an alternative for de-icing due to the environmental impacts they cause.

Lightning can be a challenge for de- and anti-icing systems.

8 Economic aspects of icing

There is very little publicly available information on the economic aspects of icing. Instead, this chapter is to some extent based on conclusions drawn from the study results.

There are no specific guidelines for assessing the economic impacts and risks associated with projects in extreme and arctic climates[187]; however, the knowledge will increase as more wind farms are developed.

8.1 Increased loads

There is no available research or studies on breakpoints of loads and decrease of component life time due to icing. No turbines have been operating in icing climates

[185] Elforsk, 2009:61 & and Vindforsk, 2008
[186] MW Innovation, 2011-07-05
[187] VTT Technical Research Centre of Finland, 2009

for such a long time so that the economic value of operation with severe icing on the blades can be compared to the decreased lifetime of the turbine.

8.2 Insurance

According to several Insurance companies the insurance fee is higher for insurances of wind farms in arctic areas, where the risk for icing is higher than in normal climates.[188]

8.3 Production losses and costs

According to statistics from a turbine in Äppelbo, Dalarna Sweden, the production stand still lasted for almost seven weeks due to icing in one year. The value of the production loss at this occasion was according to the developer 75 kSEK and according to the owner 100-125 kSEK.[189]

In the summary of BOREAS IV in 1998 the estimated energy production loss of severe and very severe icing was calculated to 20-50% on a yearly basis. In such cases, a de-icing system of some type is necessary. [190]

In year 2004 there were only one system of de-icing for stationary power supplies to purchase. The system could be purchased as an option for Enercon E-40 (600 kW) and E-66 (1800 kW) for € 9,200 and € 12,800. If the wind turbine price is 7 000 €/kW the cost for the de-icing system means an additional charge of 2% for the E-40 and 1% for the E-66. The payback time for a blade heating system for a group of turbines of 4*500 kW was calculated to 4.5 years for a wind farm site with 30 days of icing. For a wind farm site with 10 days of icing per year the payback time was calculated to 13.4 years.[191]

From measuring a plant in Härnösand, Sweden, the loss of energy output due to icing was approximately 15 % during January to March 2009. The plant was a Vestas 600 kW installed 1997. The loss of electric energy output over one year was estimated to approx. 5 %, out of which approximately 35 % was due to down time due to the risk of ice throw. The electricity energy output was approximately 1 200 MWh per year. In 2010 its value was 45 000 € per year. The losses due to icing is 2 200 €. Over a 15 year period with 5 % interest that is 25 000 €. This is 3-5 % of the total installation cost. With 500 hours of icing per year the test showed that de-icing is economical viable if the cost of installation is less than 40 000 € per MW rated power calculated over 15 years and 35 € per MWh. If icing is more common or if the value of the electric energy output is higher, then a higher installation cost due to the installation of de-icing equipment may be accepted. Other conclusions from the project were that the most important factor in the calculation of production losses due to icing was how many hours per year the ice thickness was more than 1 mm, or 2-3 mm if the plant was large. It was also believed that a larger plant (larger rotors) is less sensitive to icing. This is not confirmed by the test. The type of ice and the

[188] Elforsk, 2004
[189] Ibid
[190] Ibid
[191] Ibid

wind speed during the icing periods is also of importance. Icing during longer periods or higher value of the electric energy output makes de-icing more interesting. [192]

8.4 Maintenance

Several researches points out that maintenance of turbines in cold climate is harder than in "normal" conditions. There will be losses in time periods over the year that is possible to use for maintenance, such as chilly occasions and icing periods.

8.5 Financial losses

Financial losses result from an assumed increased risk in cold climates with lost energy production, low temperatures and the costs of more demanding maintenance. The effect on the duration of stoppages caused by the site location and access should be determined during the project planning phase. The economic uncertainty associated with cold climate projects is higher than at conventional sites. The increased uncertainty lowers the production probability of the wind project.[193]

8.6 Safety regulations

Regulations on wind turbines operating in icing conditions taken on governmental or authorisation level could make wind power projects unprofitable. Authorisation conditions for operation in certain weather conditions, e.g. at certain temperature intervals and humidity levels, and at specific turbine loads have been used in central European countries (although has been removed). The regulations were justified on security arguments, i.e. ice shedding. In such cases the alternative to install de-icing will be to stop the turbine from operation when icing occurs. As described in chapter 5.7, stopping the turbine at icing may cause a longer duration of the down time. Flexible blades can be used as self-de-icing equipment when rotating, with smaller risks of ice throw as a result. This opportunity would be lost if safety regulations were to be used on the above terms. It has also been showed that the safety distance of ice shedding most often is reached due to the higher distance demands of noise spread.[194]

8.7 Mapping of ice

Mapping and modelling of icing is a time consuming and costly task. As have been showed, a high resolution is required for the model to capture terrain effects, both horizontally and vertical. This is crucial if the map is to be used for wind power planning. The computational time, increases linearly by increased spatial resolution, and hence also the costs.

Ronsten and Nygaard gives an example; if modelling of the same area is to be carried out with different resolution this would be the case:

[192] HoloOptics, 2011
[193] VTT Technical Research Centre of Finland, 2009
[194] Canadian Wind Energy Association, September 2007

If 9 km grid takes an hour to calculate, a 3 km grid takes 9x3=27 hours and a 1 km grid covering the same region takes 9x3x27=729 hours.

Ronsten and Nygaard also made some efforts to convert the computational hours to financial cost estimations. The estimations are based on the assumption that the projects can be coordinated and carried out in parallel. The predicted cost for using 4 different weather models and comparing them with:

a) Local results based on climatological data would cost approximately 600 kSEK.
b) The local results from two icing measurement seasons are estimated to be 1 MSEK.
c) Modelling of four winter seasons based on four tall mast measurements and four site measurements using one weather model is 1 MSEK.

These cost estimations are likely to be underestimations according to Ronsten.[195]

8.8 Expensive measurements of wind climate and icing

Icing of measurement instruments makes both measurements of the wind climate and measurements of icing more expensive. Icing of instruments often requires an increased demand of maintenance. The fact that there are no fully developed instruments is also a cause of a higher cost.

If instruments are iced up, measurements to fill the gaps of missing data are needed. Today measurements by SODAR are a common method.

In the wind pilot project Havsnäs conventional measurement methods are being compared to measurements by LIDAR and SODAR in order to lower the wind measurement costs. Information on the subject is provided to IEC for the next revision of performance standards.[196]

8.9 Cost evaluations

Icing makes an impact on wind power at several stages; in the planning process, in turbine and instrument research and development and foremost when in operation. Costs of icing could be assessed by evaluation of additional steps and activities of a wind power project. Technical Research Centre of Finland et al has developed guidelines of what should be taken into account when planning and developing a wind power project in cold climate.

8.10 Reflections

There are very little information on the actual costs of methods and techniques developed for de-icing etc. and there are no specific guidelines for assessing the economic impacts and risks associated with projects in extreme and arctic climates. It is difficult to estimate the additional costs when developing wind farms in cold climate. In order to draw any conclusions more projects needs to be analysed from scratch. But, it will always be difficult to tell the specific cost of a project until ic-

[195] Elforsk, 2008
[196] Nordisk Vindkraft, 2010

ing and wind climate measurements has been undertaken for the actual wind farm site. Better forecasts on costs may be possible to achieve by further development and verifications of forecast models.

A conclusion possible to draw is off course that de- and anti-icing systems are not economically profitable to install today when looking at production losses. This is shown by the fact that no new wind farms have these systems installed.

What is not known is if icing causes such loads and wear that de- and/or anti-icing are economically viable when looking at these factors during the turbine life time. There are no turbines in cold climate that has been in operation for such a long period of time that such conclusions or analyses have been able to be drawn.

Insurance costs are higher for wind farms in cold climates.

In case measures to cope with icing are needed on a wind farm it might be cost-efficient to adapt the strategy for de- or anti-icing to the severity and the length of time in which icing occurs. Though, as mentioned earlier, this is not a possibility today while there are no commercial techniques available.

9 Analysis

Based on the information gathered and the conclusions drawn during the study a wider analysis is presented. The chapter is divided into sections to facilitate the reading.

9.1 What is known?

In spite of some cases with standstills for several months due to icing, the deployment of wind power is accelerating in areas exposed to ice. The exploiters are apparently not regarding icing to be a significant obstacle. Further, icing does not seem to be one of the biggest down-time factors of wind power today.

The uncertainty in forecasting of icing and production losses may cause several problems for the wind power industry on planning and investment stage. Expected production losses due to icing can cause higher demands on high wind speed at wind farm site as well as demands for lower turbulence in order to secure an investment in the farm. A possible scenario is that demands from investors increase on wind farms planned in cold climate compared to farms planned elsewhere, which gives an advantage to farms planned in areas where icing is not expected. As we know, insurance costs for wind farms in cold climates are more expensive.

Further the developers have to deal with uncertain forecasts of turbine energy production at sites due to the lack of possible icing measurements. Therefor it is a great challenge for the developer to find a wind turbine that is sufficiently adapted to the icing climate on the specific site. Today, decisions have to be made on assumptions on energy production (i.e. production losses due to icing) in order to judge if an investment in de-icing equipment will be profitable or not.

Icing of wind turbine blades and in combination with influence from forest in terms of turbulence and wind speed increases demands for higher wind speeds and pushes the development up on even higher elevations. This decreases the amount of available land for wind power further and increases risks of icing since icing depends on height. The taller turbines the higher is the icing rate. Indirectly, this raises the demands on wind measurements, and gives yet another incitement for development of reliable measurement instruments.

As if this was not enough, unfulfilled power curves causes difficulties for turbine manufacturers to meet their warranty levels, which in turn can reduce the sell-will of turbines to cold climates.

Cold climates do not only cause problems for wind power due to icing, there is also a need for solutions on problems caused by the chill per se. Such problems have not been discussed earlier in this report while they are not a big issue for the development of today. The chill cause damages, insufficiencies and malfunction of turbine components. Normally a turbine is fit for operation in temperatures down to -20º C. Today there are turbines available for even lower temperatures with an operation range down to -30º C (in operation at for example Storrun wind farm). By selecting the right steel and with special hydraulic units in the hub, the wing tip brakes, special hydraulic oil etc., most of these problems can be solved. Heating systems have been developed for use in the tower and in the nacelle to ease maintenance work in cold weathers. Most manufacturers can offer such solutions today. The use of cold resistant steel does not increase the costs significantly. An interesting question is why this kind of development and solutions has been developed by the manufacturers while there is such little interest in development of icing prevention systems etc.

Another problem is the freezing of the grounds. When turbines are erected in an area with wet grounds in combination with a cold climate this could create icing underneath the foundations. In turn, this would make the foundations instable when the ice melts. Renewable Energy Systems Ltd. (Nordisk Vindkraft) has developed a method that isolates the foundation to prevent build-up of ice which at the same time drains the redundant groundwater. The method will be evaluated in a pilot study.

9.2 What will the near future probably look like?

The development of wind turbines is still moving forwards in terms of dimensions and power output. Old turbines are being replaced with new larger and more efficient turbines.

An increased number of wind farms are planned in the north or in areas where icing is likely to be an issue.

As the development of wind power continues in the northern regions of Scandinavia, the statistics might change. The development might show that icing is a significant factor for down-time even if it is not regarded so today, as mentioned above.

Another result of an increased number of turbines operating in icing regions is that the knowledge and information about the effects of icing increases. If measurement and operation data from the sites could be used this would be a significant advantage for the wind industry in Scandinavia. This would provide statistics on icing conditions for build-up and verification of icing prediction models.

Solving the problems of standstill of wind turbines due to icing possibly could create a decrease in opposition against wind power. Arguments as "wind turbines are not useful in our northern climate due to standstill when we need the electricity most" would be diminished. Another advantage of eliminating the down-times due to icing is that the turbines are allowed to operate at every occasion when there is an available wind resource for energy production. This is of importance for the communities in Scandinavia both economically, environmentally and in terms of electricity supply.

Even though there is an identified problem with icing developers do not hesitate to build turbines in the northern regions, at in least Sweden. If the information and knowledge from these sites could be used by for example Kjeller Vindtekknik and SMHI in producing icing maps the models could be better verified and give a statement on the actual icing conditions in Sweden. As for Denmark, Finland and Norway, other measures must be undertaken (e.g. political), especially for Finland where no big development is at hand.

In Denmark we may see the same effects of icing as in Sweden when smaller turbines are replaced by larger ones. As for Norway icing may not be present to such an extent that it will be a significant problem due to the coast and the Gulf Stream and the fact that the inland areas are too rough for wind power developments. Although, measures show that there is a significant increase in icing rate at higher elevations. It is possible that Norwegian turbines will be exposed to icing if high enough turbines are built at exposed sites.

9.3 What do we ought to know?

Since measurement methods and instruments do not currently fully work it is not possible to draw any significant conclusions from existing reports. In order to draw any conclusions, equipment, methods etc. needs to become more reliable. Hence, the instruments for measurements of icing must work even if the instrument itself gets iced up.

Due to the lack of reliable studies of production losses etc. it has not been possible to map the economic consequences of icing. A certain percentage of loss of energy production may cause significantly different effects on a project´s economy due to the size and number of turbines in the project.

Thus, based on the information gained in this study, it´s not possible to verify the cost of icing with any certainty. Furthermore, it´s difficult to relate the icing cost to the cost of prevention technologies. In order to do that, more studies are needed. On the other hand the wind power market has not yet identified icing as a significant problem.

9.4 What should we do?

Research is on-going, but further development is needed to find appropriate solutions and techniques to cope with the effects of icing, both in planning and operation of wind farms. In planning, it would be useful with a well-developed icing measurement technique and equipment, easy to install in regular wind measurement masts. This would prevent wind power from being built on sites with risk of severe icing. In addition, adequate measurements would give developers a possibility to act on forehand to plan for ice preventing or de-icing systems to be used.

Today, much of the technique development is being carried out by the developers themselves in cooperation with companies, active in for example the aviation industry. It would be an advantage if the future holds cooperation between these actors and the turbine manufacturers, in order to create a supply of turbines adapted for cold and icing climates. Preferably, public bodies would manage the development while manufacturers’ can´t cooperate in product development to the extent needed due to competitiveness. Public funding contributes to make the research accessible to all.

Based on available research and knowledge additional research is needed in order to develop existing measurement technologies for measurements of icing and standard climate parameters to become an integrated technique.

It is not very meaningful to develop icing and low temperature frequency maps on a large scale before they can be verified and the resolution must be at sufficient level (high) in order to show regional and local variations. The maps presented for entire nations available today are not enough tools in the localisation process of wind farms or in the planning of site layout.

When such icing maps have been developed, they can in combination with wind energy resource measurement be a tool in estimation of energy production losses.

To answer the question ***“what needs to be done”*** a priority list has been composed:

Step 1: Find reliable methods to more secure find out how big the actual problem of icing is.

Step 2: Find out how much the icing actually cost.

Step 3: A documentation of what methods there are to cope with the problems of icing and what is their cost.

Step 4: A mapping of what effects there will be if possible measures are to be used, i.e. what will be gained from the decrease in production losses.

Step 5: A cost-benefit analysis; will the necessary actions reach the intended effects at a reasonable cost? Is it economically feasible to take action? Is there reason enough to avoid development of wind power in areas where severe icing occurs?

Future research and technology development will have to be our guide.

9.5 What is important to consider?

It is important to have in mind that icing is not a phenomenon strictly connected to cold climate. Icing occurs in certain conditions when temperature is approximately 0° C, which is usual in the Scandinavian regions.

It is also important to remember why the research is being undertaken and what goals need to be reached. A significant amount of research is already available on conditions for icing to occur; from e.g. aviation and construction work. The main task for development of reliable measurement technologies is to get knowledge on icing at a specific site and which prevention technology that is most appropriate, as shown in Finnish and Swedish studies.

Another question to be addressed is the development of different strategies for de- and/or anti-icing adjusted for different types of ice, icing conditions and the severity of icing. It might be desirable both from an energy saving point-of-view as wells as economically to apply different technologies. But in a state of no available technique, what should the research and development be focused on?

A lot has been done and several projects are on-going, especially in Sweden and Canada. These projects will hopefully straighten several questions out. A main task is to get the developers to share their information with the industry, each other, researchers, politicians, investors etc. Though, further research and development is likely to be needed.

Furthermore, in Sweden there is available research on design of offshore foundations due to expose of ice loads.

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11 Appendix

R&D projects				
Project name	**Originator**	**Participants/Research institution**	**Objectives/ Research areas on wind power in cold climate**	**Period of time**
Canada				
Design of ice-free ane-mometers	TechnoCentre éolien & WESNet	Wind Energy Strategic Network (WESNet) & TechnoCentre éolien Coordinator: Jean Ruel, Université Laval	Design of ice-free anemometers	On-going
Wind turbine composite materials for the Cana-dian context	TechnoCentre éolien & WESNet	Wind Energy Strategic Network (WESNet) & TechnoCentre éolien Coordinator: Simon Joncas, ETS & Curran Crawford, University of Vic-toria	Wind turbine composite materials for the Canadian context	On-going
Ice accretion modelling	TechnoCentre éolien & WESNet	Wind Energy Strategic Network (WESNet) & TechnoCentre éolien Coordinator: Adrian Ilinca, UQAR & Guy Fortin, UQAC	Ice accretion modelling	On-going
Wind tunnel investiga-tions of icing impact on wind turbine blade pro-files	TechnoCentre éolien & WESNet	Wind Energy Strategic Network (WESNet) & TechnoCentre éolien Coordinator: Jean Perron & Guy Fortin, UQAC	Wind tunnel investigations of icing im-pact on wind turbine blade profiles	On-going
Forecasting icing events	TechnoCentre éolien & WESNet	Wind Energy Strategic Network (WESNet) & TechnoCentre éolien Coordinator: Robert Benoit, ETS	Forecasting icing events	On-going
Icing event monitoring	TechnoCentre éolien &	Wind Energy Strategic Network	Icing event monitoring	On-going

	WESNet	(WESNet) & TechnoCentre éolien Coordinator: Christian Masson, ETS		
Atlas of icing events at high resolution	TechnoCentre éolien & WESNet	Wind Energy Strategic Network (WESNet) & TechnoCentre éolien Coordinator: Christian Masson, ETS	Atlas of icing events at high resolution	On-going
Wind farm -Test site	TechnoCentre éolien	TechnoCentre éolien Coordinator: TechnoCentre éolien	R&D wind farm with two 2.05 MW Repower MM92 wind turbines, located in icing climate and complex terrain.	Commissioned in March 2010
Yukon Energy Corporation	Yukon Energy Corporation	Yukon Energy Corporation	Research program on a Bonus 150 kW MARK III turbine for adaption of commercial wind generating equipment to cold climate	1992- Report in 2001
Recommendations for risk assessments of ice throw and rotor blade failure in Ontario	Canadian Wind Energy Association , Garrad Hassan	Garrad Hassan in conjunction with the Finnish Meteorological Institute and Deutsches Windenergie-Institut as part of a research project on the implementation of wind energy in cold climates (WECO)	Present an assessment methodology for risk assessment of ice throw	June 2007
Denmark				
Measured Ice Loads on Avedoere 1MW Test Turbine	Risø National Laboratory	Risø National Laboratory	Trial of a case with measured glaciation in Denmark, the output became more stable compared with the ice-free case, and no increased loads could be detected.	1997
Research carried out in Denmark makes part of international R&D projects – IceWind and TopNano (see Joint R&D below)	Technical University of Denmark –Risö DTU (Danish National Laboratory for Sustainable Energy), iNano-centre at University of Aarhus.			On-going
Finland				

Power supply development in Northwest Lapland	VTT– Technical Research Centre of Finland, communities	VTT	Studies of power supply development in Northwest Lapland; options grid connection from central Lapland, local diesel generation, local generation or combinations of them (hydropower excluded, biomass not available)	1980´s
Ski resort developments	Ilmatieteen laitos -Finnish Meteorological Institute (FMI), communities	Ilmatieteen laitos -Finnish Meteorological Institute (FMI), communities	Studies on ski resort developments showing often too cool climate for that (wind + chill)	1980´s
Diversification of power supply in Lapland	Kemijoki Oy	Kemijoki Oy	Diversification of power supply in Lapland.	1980´s
Wind turbines and electricity supply for telecommunications		Telecomm	Electric supply for telecommunication, test turbines	1980´s
NEMO 1 & 2	Industry, Universities, research institutes, end-users; : Labko Oy, Kemijoki Oy, VTT (Technical Research Centre of Finland), Kone Sampo, Imatran Voima Oy, TTKK (Tampere University of Technology), Neste NAPS Oy, Vaisala Oy, Ilmatieteen laitos (Finnish Meteorological Institute) and Kumera Oy.	The Department of Technical Physics, Helsinki University of Technology	• wind resources and icing risk • instrumentation: wind anemometers and ice detectors, • development of measuring systems (data acquisition) • development of blade heating systems: principles of design, installation and measurements, • ice loads: measurements and predictions by means of computational tools The early years – NEMO 1988-1992 • wind measurements ~ 1990 (FMI) o resource assessment in fell areas, instrument behaviour and development o Pyhätunturi, Hetta • technology development	1988-1992 & 1993 - 1998

			o testing of coatings (VTT) o development of TURBICE to study blade icing and design systems ice prevention or de-icing (VTT) o de-icing principles (VTT) o field observations and measurements of icing and loads (VTT) • test turbines o Pyhätunturi, 2.5 MW stand-alone turbine 1991 (VTT, Kemijoki) o Jyppyrä (Hetta) 65 kW grid connected test turbine, 1991 (Kemijoki), blade heating in 1993 <u>Growing interest – NEMO2 1993-98</u> • VILKE –project (VTT, FMI, KEMIJOKI) o Pyhätunturi test site with 220 kW grid connection test turbine 1993 o development of first blade heating solutions o e.g. measurements and modelling of turbine performance and loading, performance of instruments, flow over hill • industrial projects o after installation of blade heating in Jyppyrä test turbine o Lammasoaivi, 2x450 kW grid connected 1996, 600 kW grid connected 1998 (Kemijoki, VTT, demonstration o development of ice detection (Labko)	
NewIcetools	Supported by the Europe-	Finnish Meteorological Institute	Safety, availability and reliability of wind	2002-2004

	an Commission, performed by Finnish Meteorological Institute		turbines and their components and how to improve the economics of wind power production in icing environments.	
Technology for ice prevention development			• heating elements o the first experiments were made using heating foils with conducted elements in Al or Cu inside thin epoxy films o the later solutions are based on carbon fiber heating elements that are integrated into the blade structure o lamination of the blade was done to the surface of unfinished blades o after integration of carbon elements and lamination of protection lays for mechanical wear and tear the blades were coated normally • control o combination of ice detection, temperature and turbines status o ice detectors used also alone for safety	1990´s
Ice prevention system for wind turbines – first commercial demonstration	Kemijoki Arctic Technology Oy	Kemijoki Arctic Technology Oy	• Kemijoki Arctic Technology Oy continued the development of ice prevention system for wind turbines • projects o Olostunturi (Finland), 5x600 kW grid connected, 1998-99, (Kemijoki Arctic Technology Oy) o Suorva (Sweden), 600 kW, grid connected 1998 o Rodåvålen (Sweden), 600 kW,	1998-2003

			grid connected 1998 o Pori (Björneborg, Finland) 4x1 MW, 1999, with ice detector integrated in the blade development by Labko o Kotka (Finland), 2x1 MW, 1999 (JE –system dismantled in a blade repair in ~ 2003)	
O&M services	Vapo Oy	Vapo Oy	O&M services	2001-
Heating system development for other applications	Carbonel Oy	Carbonel Oy	Heating system development for other applications	2001-
Technology follow-up, concept development	VTT	VTT	Technology follow-up, concept development	2001-
Ice-repellent coating	VTT	VTT	Ice-repellent coating	2007-2009
Ice atlas for Finland	VTT, FMI	VTT, FMI		2009- Results will be published by the end of 2011
Measurements in icing conditions	VTT, manufacturer and FMI	VTT, manufacturer and FMI	Tests of LIDAR-measurements in complex terrain and cold climate conditions.	Measurements started in winter 2009-2010, a second round started in February 2011.
Norway				
Ice mapping	Norwegian Water Resources and Energy Directorate (NVE)	Kjeller Vindteknikk	Mapping of Norway´s wind resources on a spatial scale of 1km x 1km grids. The wind resource mapping is based on meso-scale modelling WRF (Weather, Research and Forecasting). The meso-scale	

			model also models moisture fields and temperature, and this has been utilized to calculate icing and produce a map of icing conditions. The icing is calculated by using the icing rate (dM/dt) from the WRF model. High resolution topography is used to interpolate to 80 meter above ground level, and number of hours with icing rate higher than 10 g/hr. on an ISO cylinder (length: 1 meter, diameter: 30mm) is summed up.	
Nygårdsfjellet	Nordkraft Vind, University of Narvik	Nordkraft Vind, Prof. Per Arne Sundsbö at University of Narvik	Rate the snow. The surveys will be used as a basis to build a draft screen and do other actions that can minimize problems with snow in the operational phase from 2012. Several reports are available.	
Sweden				
Vindforsk II project V-151 - Synopsis measurements of icing The site of the measurement is also included in the EU-project COST 727 – Measuring and forecasting atmospheric icing of structures.	Vindforsk, The Swedish Energy Agency, Elforsk	Saab Security, Göran Ronsten	Make it possible to carry out measurements at different geographic sites at the same period of time in the future. Instruments from IceMonitor (Saab Security), HoloOptics, Campbell and Vaisala were used. Publications: Elforsk report 09:24 - *Measurements of icing in a high mast* *Influence of icing on the power performance of a V90-2MW wind turbine*	2008-2009
Vindforsk II, Feasibility	Vindforsk, The Swedish	Göran Ronsten, WindREN AB	Publications:	2008

study on mapping of icing	Energy Agency, Elforsk		Elforsk Report 08:40 - *Mapping of icing for wind turbine applications – A feasibility study*	
Vindforsk I & II, project V-153 - Ice distribution on wind turbines after detection	Vindforsk & ADL datalab	Rolf Westerlund, HoloOptics	The project had three different objectives • To calibrate an icing sensor, according to the amount of ice on the rotor blades. • To determine at which degree of icing measures has to be taken to reduce the risk of public health hazards due to ice throws. • To give a general indication of the performance losses due to icing. Publications: Elforsk Report 09:06 - *Is på vindkraftverk- - Detektering, utbredning, personskaderisk – minimering och produktionsbortfall* *Development of a RetroOptical ice indicator*	2004-2008
Vindforsk III project V-303 - Sluttest av issensor	Vindforsk, The Swedish Energy Agency, Elforsk	Rolf Westerlund, HoloOptics	Enable comparisons of different icing and ice load measurement instruments. The subject for the calibration was a sensor for measuring the rate of ice deposition on structures developed by HoloOptics. In the project the sensor was calibrated with measurements in the icing wind tunnel of VTT in Esbo, Finland. Publications: Elforsk Report 10:05 - *Kalibrering av givare som mäter istillväxt*	October 2010,
IEA Task 19 & Swedish Wind pilot study, o2 Vindkompaniet – Aapua	Vindforsk, The Swedish Energy Agency, Elforsk,	Göran Ronsten, WindREN AB	Aapua is located in Tornedalen, approximately 200 km north of Luleå and 100 km from the Olostunturi in Finland, and was built in the summer of 2005. It con-	2009

			sists of seven NM82 with a rated power of 1,5 MW each. Publications: Elforsk Report 2009:59 - *Influence of icing on the Power Performance of Seven NM82 – 1,5MW Wind Turbines in Aapua, Elforsk report 09:59*	
Vindforsk II, project 30988-1/V-238 - New Technologies for de-icing Wind Turbine blades	The Swedish Energy Agency	Lars Bååth and Hans Löfgren, Halmstad University	Pilot study of new ways to either avoid icing or de-ice wings of wind turbines by choosing the right blade structure and other characteristics and by using micro-waves. Publications: *New Technologies for de-icing Wind Turbines*	2008
De-icing, MW Innovation	The Swedish Energy Agency	MW Innovation	Develop a de-icing technique with graphite based resistor elements.	
Wind pilot studies	The Swedish Energy Agency	Dong Energy – Storrun wind farm Partners: Nordex AG, LM Glasfiber, Uppsala University, Mankiewicz AG	Improved adjustments for icing losses in production estimates and reduced production loss due to icing of blades with the overall aim to generate experience on wind turbine operation in cold climate. The studies include activities such as: • Determine extent of icing problems • Calculate and validate estimates of production loss • Testing of anti-icing coating • Testing of blade monitoring systems • Optimization of start-stop procedures Model loads of blade loads	2009-2011

			Storrun wind farm in Jämtland is situated 150 km northwest of Östersund. The farm consists of 12 Nordex N90 2.5 MW turbines on an altitude of approximately 700 m. The farm was taken into operation autumn 2009.	
		Nordisk Vindkraft – Havsnäs wind farm.	Havsnäs wind farm consists of 45 Vestas V90 2 MW and 3 Vestas V90 1.8 MW turbines with a hub height of 95 m. The farm was taken into operation in 2010 by owner Nordisk Vindkraft and is situated in Strömsunds municipality, in Jämtland. The wind farm is spread over 3 hills on an altitude of 510-650 m. The area of the farm is strongly affected by the Atlantic Ocean in terms of wind and precipitation. The average temperature in January is between -7 to -11 ^{o}C and the area has an annual average precipitation of 500-1 500 mm.	2009-2011
		O2 Vindkompaniet – Sjisjka, Bliekevare, Glötesvålen, Aapua, Tåsjö and Dundret wind farms (and others)	Main aim to develop de-icing systems and to perform measurements on icing for prognosis and mapping. • Impact of shear extrapolation to hub height o Agreement between short (50m) and hub-height (95m) mast predictions o Impact of measurement heights on accuracy of derived shear profile • Forest Canopy and Displacement Height o Use of Aerial Lidar Surveys to map tree heights/improve shear model-	2009-2013

			ling. • Shear Profiles Above Hub Height o Comparison of extrapolated and measured profiles; seasonal impact o Relating shear uncertainty to atmospheric stability indicators • Wind Flow Model Validation and Tuning o linear models o CFD o Mesoscale o Tuning models to stability conditions • Power Curves in Cold Climates o Power Curve Measurement using Rotor Averaged Wind Speed (Lidar) o Trialling of draft IEC 61400 12-1 rotor averaging procedures o Effect of ice on turbine and wind farm performance • Remote Sensing o Testing of fuel cell lidar power supply in cold climate conditions Practical implications of lidar measurements in cold climates	
		Skellefteå Kraft – Uljabuouda wind farm	Main aim to develop de-icing systems and to perform measurements on icing for prognosis and mapping. The objective of the measurements on icing is to verify general measurement- and calculation methods for icing and wind speed, in order to make better calculations on investment needs and on	December 2013

			needs for equipment specialized for icing conditions on specific sites.	
		Svevind – Dragaliden and Gabrielsberget wind farms	Testing of Enercon´s de-icing system. The objective of the testing was to increase the efficiency of the de-icing system due to the input energy in the heating elements and to determine how efficient the system was compared to operation without it. The wind farm at Dragaliden consists of 12 Enercon wind turbines equipped with Enercon´s de-icing system.	
WindREN	Göran Ronsten		Participates in conferences etc. on behalf of Swedish research on icing of wind turbines.	
Joint R&D´s				
IceWind – (Scandinavia)		Risø DTU (DK), Vestas (DK), VTT (FI), Gotland University (SE), Kjeller Vindteknikk (NO), Met.no (NO), Statoil (NO), Offshore windservice (NO), AGR§ (NO), Icelandic Met Office (IS), University of Iceland (IS), Landsvirkjun Power (IS), Offshore services for O&M, National Power company of Iceland (IS) Coordinator: Risø DTU, Denmark	Improved forecast of wind, waves and icing; A key issue is to share knowledge among the five Nordic countries and to work in areas where differences in knowhow exist and where barriers or challenges prevent or slow down a large penetration of wind energy in the Nordic grid. The overall objective of the project is to support the development and integration of wind energy in the five Nordic countries by focussing on three main areas: 1. Icing on wind turbines (atlas, forecasting and losses) 2. Integration of wind energy on land (Iceland) 3. Offshore wind energy (forecasting and	September 2010 – August 2014

			access) 4 PhD projects planned: Two in Iceland, one in Denmark and one in Sweden. The results of PhD on forecasting wind turbine icing conditions are expected to lead to better forecasts of wind and waves. Maps of icing occurrence and losses, better knowledge on wake losses in very large wind farms, wind and ice atlas of Iceland, Integration study of wind in Iceland and better understanding of the interaction between hydro and wind in the Nordic system. Overall budget 20.8 million NOK, Financial support TFI 12.3 mill NOK Extern financing 8.5 mill NOK	
Wind Energy in Cold Climate – WECO - Task 19 – Wind Energy in Cold Climates	International Energy Agency (IEA)	Technical Research Centre of Finland VTT, The Swedish Energy Agency/WindREN, Kjeller Vindteknikk, Norway, the National Renewable Energy Laboratory (NREL), USA, ENCO A, Switzerland, Natural Resources Canada, ISET, Germany.	1. To collect information on ice mapping to support early phases of project development. 2. To collect experiences related to icing forecasts with numerical weather models 3. Find new solutions for wind resource assessment in cold climate 4. Collect information on the anti- and de-icing and coating solutions 5. Review the current standards and recommendations - cold climate perspective 6. Find an improved method for the esti-	2009-2012

			mation of the effects of ice on energy production 7. Clarify the significance of ice induced extra loading on wind turbine components 8. Initiate a market survey for cold climate wind technology 9. Improve the understanding of the risks and the mitigation strategies regarding ice throw 10. Reporting	
Cost 727 - “Measuring and forecasting atmospheric icing on structures”		Austria, Bulgaria, Czech, Finland, Germany, Hungary, Norway, Slovakia, Spain, Sweden, Switzerland, United Kingdom Coordination is divided in 3 working groups dealing with modelling, measurements and forecasting of icing.	The ultimate goal of COST727 is to bring about continuous synoptically and ice observations to support the development of icing analyses and forecasts. Main objectives: • to develop the understanding of icing (especially in-cloud icing) and freezing raining the atmospheric boundary layer (ABL) • to produce information on distribution of icing over Europe • to improve the potential to o observe icing o monitor icing o forecast icing Research and development work • WG 1:Iceloads and forecasting	Phase 1 finished (2005-2006):

			• WG 2: Icing measurements Publications: *Atmospheric Icing on Structures Measurements and data collection on icing: State of the Art"* - report	
TopNANO	Technical Research Centre of Finland (VTT), Ytkemiska Institutet (SE), Aarhus University (DE), Kungliga Tekniska Högskolan (SE)	YKI, the Institute for Surface Chemistry in Stockholm is leading the project together with industrial and research partners from four different Nordic countries, among others Saab Aerosystems, Vestas, Vattenfall and Akzo Nobel. Coordinator: YKI, the Institute for Surface Chemistry in Stockholm	The aim is to develop sustainable and efficient methods based on nanotechnology to reduce problems and costs with ice build-up. Research Institute of Sweden will focus on robust super hydrophobic surfaces (to which the ice will not stick) and surface spectroscopy analyses. Finnish VTT brings expertise on the physics of ice. Aarhus University in Denmark and their iNano centre works on mimicking nature's way of avoiding freezing inside cells. For participating industrial companies the TopNANO project will run in parallel with already existing projects and activities in wind, aircraft and heat exchangers. Of key importance for TopNANO is the transfer of knowledge to Nordic industry, and more importantly, through direct industry-academia collaborations evaluate new surface materials and benchmark against systems used today and to use the project and partner group as a platform to mount EU projects.	September 2010-August 2013
HIRLAM		Danish Meteorological Institute, Estonian Meteorological Institute,	The aim of the HIRLAM programme is to develop and maintain a numerical	1985-

		Finnish Meteorological Institute, Icelandic Meteorological Institute, Irish Meteorological Institute, Royal Netherlands Meteorological Institute, The Norwegian Meteorological Institute, Spanish State Meteorological Institute, Swedish Meteorological and Hydrological Institute, Lithuanian Hydrometeorological Service	short-range weather forecasting system for operational use by the participating meteorological institutes	