SWEDEN'S BOLD ACTIVITIES IN MEASUREMENTS AND MAPPING OF ICING AND DE-ICING OF WIND TURBINES

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***Abstract**:* In a European perspective, the support for development of wind energy technologies adapted to icing climates has since long been non-existing. To be blamed is a Catch-22-like situation involving a lack of market studies caused by a lack of mapping of icing. The Swedish Energy Agency is currently spending some 30 MEuro during a five-year period on wind farms and the development of wind energy technologies adapted for icing climates. The activities include synoptic icing measurements, mapping of icing, de-icing of wind turbines and the evaluation of performance and loads with respect to icing.

1. INTRODUCTION

The goal of any wind farm owner is to keep the turbines in operation. Iced up wind turbine blades poses a significant challenge to wind turbine manufacturers as well as wind farm developers and owners in certain cold climate regions around the world. The main reasons for the concern are: personal safety, loss of production, increased noise and influence on the expected life of components.

2. RESULTS AND DISCUSSION

Synoptic ice and icing measurements are, mainly thanks to the work carried out in the EU-project COST 727-Atmospheric Icing of Structures, being carried out in a large number of stations across the country. Data from each wind farm site, built or planned, is accompanied by data from a similar installation in a tall mast located between 30 to 50 km away.

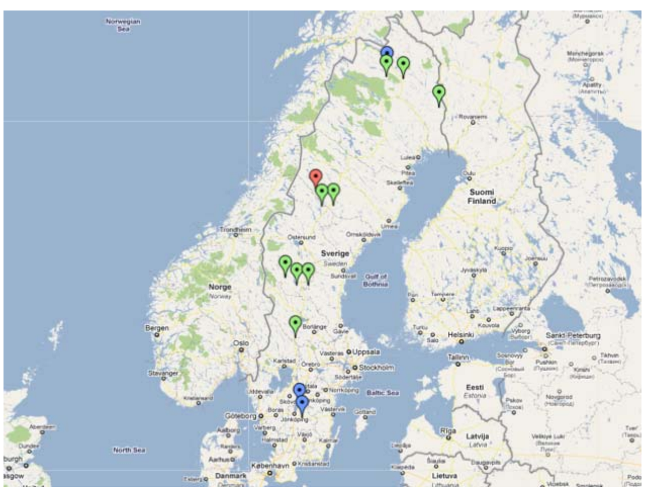

Figure 1: Distribution of ice measurement stations in one of the projects (O2)

At each measurement stations there's a camera installed to enable verification of the icing measurements. These cameras have turned out to be an effective means to support the development of empirical theories for melting and sublimation. Although inherently difficult to calculate, one may also capture brittle ice breaking into pieces at low temperatures.

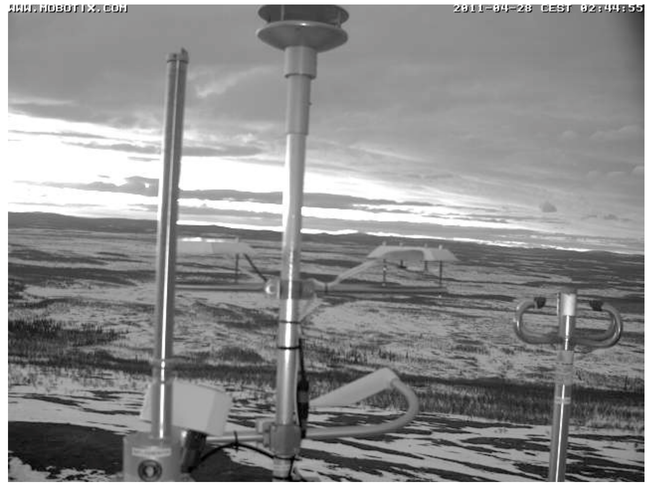

Figure 2: A view of the instruments at the Sjisjka measurement station. This particular mast is 60 m tall.

The ice collected on a wind turbine blade has been photographed as the blade was replaced.

Figure 3: Ice collected on a wind turbine blade.

3. CONCLUSION

Results from the evaluations of modelled and measured icing and power performance show a) icing periods to be captured relatively well in time, b) the magnitude of icing to be difficult to estimate correctly and c) the production losses due to iced up wind turbine blades to be surprisingly large.

Swedens's bold activities in measurements and mapping of icing and de-icing of wind turbines

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***Abstract*: In a European perspective, the support for development of wind energy technologies adapted to icing climates has since long been scarce. To be blamed is a Catch-22-like situation involving a lack of market studies caused by a lack of mapping of icing. The Swedish Energy Agency is currently spending some 30 MEuro during a five-year period on wind farms located in cold climates and the development of wind energy technologies adapted for icing climates. The activities include synoptic icing measurements, mapping of icing, de-icing of wind turbine blades and the evaluation of performance and loads with respect to icing. If the reader is unable to wait, please find the most recent cold climate related presentations from Winterwind 2011 in [1].**

Keywords: wind energy, icing, measurements, mapping of icing, de-icing, production losses

Legend and Abbreviations

CC	*Cold Climate, both LT and icing*
IEA	*International Energy Agency*
EM	*Swedish Energy Agency*
LT	*Low Temperature (not icing)*
LWC	*Liquid Water Content*
MVD	*Median Volume Diameter*
RD&D	*Research, Development & Demonstration*
Task 19	*IEA WG dealing with CC challenges*
WG	*Working Group*
WT	*Wind Turbine*
10 SEK	*1 Euro (exchange rate)*

Introduction

The goal of any wind farm owner is to keep the wind turbines (WT) ready to operate when there's wind, i.e. maintain a high availability. Iced up WT blades poses a significant challenge to WT manufacturers as well as wind farm developers and owners in cold climate regions around the world. The main reasons for the concern are: personal safety, loss of production, increased noise and an expected reduction of the life of components. The sponsors[a] of the national IEA RD&D, Task 19 project made funding available for making this presentation.

[a] *Sponsors: The Swedish Energy Agency, Vindforsk, Dong Energy, O2, Skellefteå Kraft, Triventus and Vattenfall*

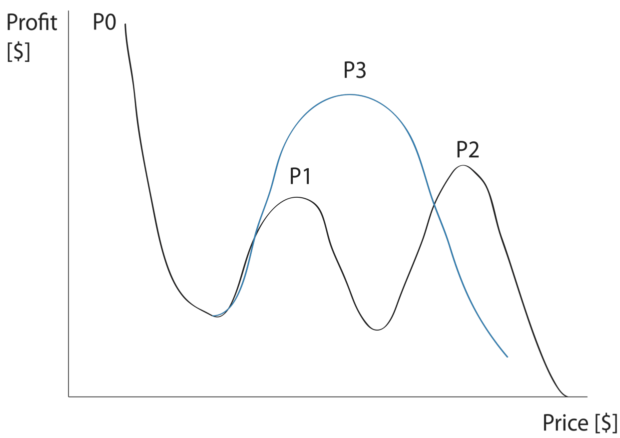
I. Motivation

A. Not producing when expected will be expensive

Electricity produced in Swedish wind farms is sold via long-term contracts at fixed prices or on the Nordic spot market to the marginal, i.e. most expensive, current production price. Not producing due to iced up wind turbine blades when production has been forecasted based on wind only isn't a major problem if the wind energy production capacity is small. A large increase in wind capacity in northern Sweden will, however, require the large-scale implementation of de-icing systems.

B. Two profit maxima depending on the price of the wind turbine

Imagine if you as a gift would receive a wind turbine located at an ice-infested location. Would you initially care if the turbine was equipped with a de-icing system or not, although the turbine might be standing still for weeks from October to April?



Figur 1. Today's profits versus cost for a wind turbine a) without de-icing system provided as a gift, b) bought without a de-icing system (P1), c) purchased with a de-icing system (P2) and d) tomorrows profit using a cost-effective de-icing system (P3).

The maxima P1 will disappear once many large-scale wind farms have been built in locations exposed to icing. Unfortunately, this development isn't obvious to developers and owners with fixed price contracts, which only indirectly pay the cost for balancing of power.

C. *Icing will reduce the reimbursement for electricity in long-term contracts*

Before a standard wind farm has been built, the developer focuses on four issues; wind, wind, wind (power is proportional to the third power of the wind speed) and infrastructure.

Once the wind farm has been built and the normalized annual energy production is known, the income will be dependent on wind speed, electricity price and, in the case of Sweden and Norway, the price of the green certificates. On a liberalized electricity market the most stable parameter of wind, electricity price and reimbursement for green certificates is… the wind and thereby the energy production.

Icing will in the near future, unless a large-scale deployment of de-icing systems is carried out, reduce the payment for electricity in long-term contracts, as the cost for balance of power will have to be indirectly charged. Luckily, icing doesn't influence the price of the green certificates, which can be saved and sold anytime of the year.

II. Why didn't we start mapping of icing earlier?

Before the start of COST Action 727 in April 2004 Sweden had carried out a number of cold climate wind energy evaluation projects, participated in IEA RD&D Task 19 and been involved in the EU-project NEW ICETOOLS. No new cold climate projects could be foreseen by the Swedish Energy Agency (EM) as the plans for large scale offshore wind energy were ambitious.

The wind turbine manufacturers were only seemingly interested in adapting the turbines to cold climates until early 2005 when long backlogs at the wind turbine manufacturers made niche segments like wind energy in icing climates uninteresting for all but Enercon. Only one cold climate wind pilot project was ordered by EM as offshore was at focus until March 2007. At this time, the utility E.ON announced that the compensation for offshore wind farms in Sweden was insufficient and surprisingly handed 70 MSEK (7 MEuro) in wind pilot project support back to the EM.

One challenge encountered in European wind energy research development, from an icing point of view, is the one-sided focus on offshore. A Catch-22 situation appears when European funding for the development of de-/anti-icing systems requires market studies, which require mapping of icing, which requires the development and verification of icing forecasts. All of a sudden we're, no surprise, once again back at the core of COST 727 and IWAIS, measuring and modeling atmospheric icing on structures.

Would de-icing systems be available on WT today if only mapping of icing would have been carried out earlier? Probably not. Wind energy activities, at least in Sweden, were part of a political façade until a proposition was put forward by the Government in 2006, which promoted a large-scale deployment of wind. On the other hand, the appropriate computer models, computational power and icing measurements were not available until recently. Consequently, a market study is yet to be carried out.

III. National funding was made available based on intuition rather than on a market study

In March 2007, the message from E.ON to the EM was clear, "offshore is too expensive". EM ordered another 4 cold climate related wind pilot projects with a total budget exceeding 200 MSEK (20 MEuro). The wind turbine manufacturers' backlogs shrank when the financial crises hit also the wind turbine manufacturers in August 2008. Additionally, an increased international competition has since made many more wind turbine manufacturers, active in areas prone to significant icing, interested in finding cost-effective de-/anti-icing solutions.

Living in a cold climate makes people, at least in the wintertime, aware of the challenges associated with iced up objects. During the winters, the hit, near-hit or even the risk of falling ice from tall buildings are in the news multiple times per week. It is therefore no wonder if the EM in 2009 decided to promote the development of wind energy in icing conditions, in four separate projects through its wind pilot project program, without having access to either a market study or a national icing map. EM's best option was to encourage the WT manufacturers to provide WT equipped with de-icing systems.

IV. The wind pilot projects

Skellefteå Kraft (35 MSEK or 3,5 MEuro) - The first wind pilot project to be ordered by EM at a cost of 3,5 MEuro was awarded the utility Skellefteå Kraft and aimed at deploying 10 of WinWind's 3 MW WT on the mountain of Uljabuouda in the municipality of Arjeplog. A modern version of the JE de-icing system developed by VTT for Bonus (now Siemens) in the 90's was used on blades from Euros. The project did successfully reach its goals although quite a few obstacles had to be overcome. One official hurdle was the lack of WT manufacturers interested in offering de- or anti-icing solutions for this demanding site, which resulted in a delay of the project. Another challenge was carrying out icing measurements prior to wind farm construction as the measurement masts had a tendency to be iced up and fall, [2].

Skellefteå Kraft's experiences from two winter seasons with anti-icing systems on Uljabuouda are:

- 13% losses compared to ideal production during evaluation period (winter).
- Power consumption of system <1% of production
- Close to zero stops due to icing.
- Higher sensitivity to lightning.

Skellefteå Kraft's activities in icing climates didn't stop with the wind pilot project on Uljabuouda. Four Nordex WT were erected on Jokkmokksliden in 2010. The following de-icing tests have been carried out and evaluated:

- Three different anti-icing systems and one reference WT
- A well equipped measurement mast
- Evaluation of performance during 2010/11.
- Decision of system for future turbines based on analysis.
- Delivery of 104 systems during 2012-2014. Investment decision taken.

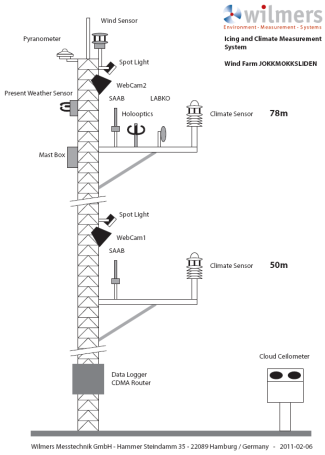


Figure 2. The icing measurement system used by Skellefteå kraft was developed by Wilmers.

Dong Energy (2.6 MEuro) - The Danish state owned utility Dong Energy has been testing hydrophobic coatings on some of the 12 Nordex N90 2.5 MW WTs equipped with LM Windpower blades. According to Dong Energy, no significant increase in production has been measured on the WTs equipped with hydrophobic coating. The main reason seems to be that if the WTs are iced up during stand-still or idling, the shear force required to remove the ice on the blade simply isn't present. Once a large blade area has been iced-up, restarting a turbine is equally difficult whether the blades are equipped with hydrophobic coating or not. Other issues under study in Dong Energy's wind pilot project are the effect from WTs on birds in mountain areas and a verification of orographic efficiency. The latter study will provide valuable data for micro-siting of WTs in complex terrain. Future work include:

Analysis

- *Further evaluation of anti ice coating*
- *Evaluation of production losses*
- *Better understanding of the conditions under which icing occurs*
- *Loads during icing*

Implementation

- *Other means of minimizing/removing ice*
- *Operation strategy for minimizing losses due to icing*
- *Implementation of the ice detection system with the WTG controller*

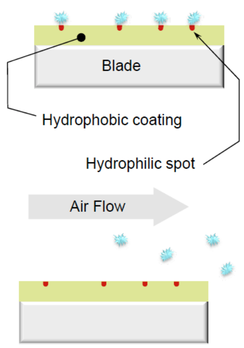


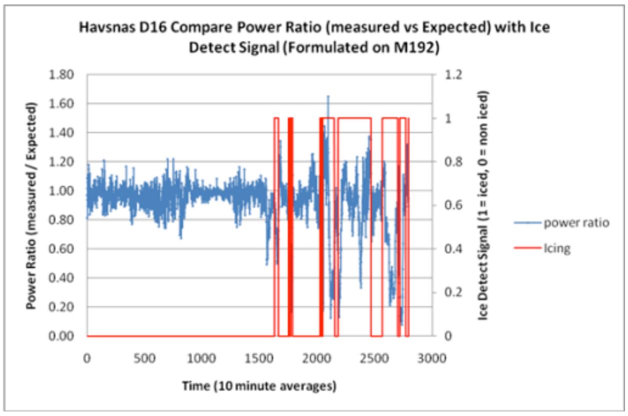
Figure 3. The basic idea from LM Windpower is for ice to accrete on the hydrophilic spots and for it to be easily removed by shear force caused by the airflow.

The latest presentation available can be found in [3].

Nordisk Vindkraft (2 MEuro) – Havsnäs wind farm is located in Strömsund municipality some 110 km north of Östersund. It consists of 48 Vestas V90 turbines of which 45 are rated at 2 MW and 3 at 1.8 MW. A total installed capacity of 95.4 MW makes it the largest on-shore wind farm so far in Sweden. The undertakings in the wind pilot project include verification of power performance with respect to ice and the development and verification of a foundation design suitable for deployment in wetlands exposed to extreme low temperatures. The tasks to be carried out include:

• Impact of shear extrapolation to hub height
– Agreement between 50m and hub-height (95m) mast predictions
– Impact of measurement heights on accuracy of derived shear profile
• Forest Canopy and Displacement Height
Use of Aerial Lidar Surveys to map tree heights/improve shear modelling.
• Shear Profiles Above Hub Height
– Comparison of extrapolated and measured profiles; seasonal impact
– Relating shear uncertainty to atmospheric stability indicators
• Wind Flow Model Validation and Tuning
– linear models
– CFD
– Mesoscale
– Tuning models to stability conditions
• Power Curves in Cold Climates
– Power Curve Measurement using Rotor Averaged Wind Speed (Lidar)
– Trialling of draft IEC 61400 12-1 rotor averaging procedures
– Effect of ice on turbine and wind farm performance
• Remote Sensing
– Testing of fuel cell lidar power supply in cold climate conditions
– Practical implications of lidar measurements in cold climates
– High shear/volumetric measurement error
– Low temperature effects
– Snow/rain/ice sensitivity
– Lidar data availability

Table 1: Tasks to be carried out in Nordisk Vindkraft's wind pilot project as presented in [4].



Figur 4: Measured versus expected power ratio and ice detection signal for Turbine D16 in the Havsnäs wind farm, [4].

O2 Vindkompaniet (7.25 MEuro) – The main objective for O2's wind pilot project is to promote the development of de-icing systems. 40 systems are to be installed by the end of 2012. As commercial de-icing systems are largely unavailable, 3rd party development has been encouraged with an aim to catch the interest of the WT manufacturers. De-icing systems from EcoTEMP

(CA) have been deployed on Vestas V90 and Siemens SWT 2.3 101 m blades. Kelly Aerospace Thermal Systems (US) has installed a number of de-icing systems on Vestas V90-2MW. Siemens has developed a first and a second generation de-icing systems for O2. The latter system is to be installed in 9 turbines in 2011.

A significant amount of ice collected on a wind turbine blade was photographed as the blade was replaced.

Figure 5. Ice collected on a wind turbine blade.

Synoptic icing measurements are being carried out in four tall masts from north to south and at neighboring wind farms or planned sites.

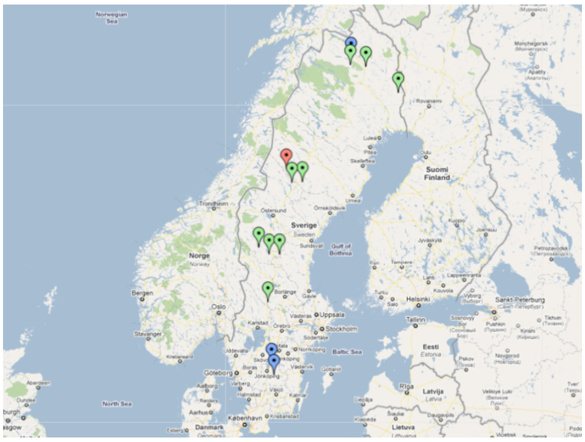


Figure 6. Distribution of ice measurement stations in one of the wind pilot projects (O2)

At most of measurement stations there's a camera installed to enable verification of the icing measurements. These cameras have turned out to be an effective means to support the development of empirical theories for melting and sublimation. Although inherently difficult to calculate, one has also captured brittle ice breaking into pieces at low temperatures.

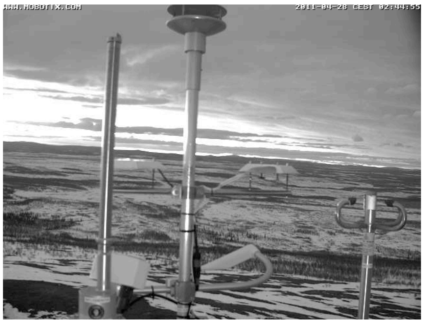


Figure 7. A view of the instruments at the Sjisjka icing measurement station. This particular mast is 60 m tall.

Monthly evaluations of icing measurements were carried out during this past season (2010/2011) by Weathertech (SE) and Kjeller Vindteknikk (NO). Leading Edge Atmospherics (US)/Finnish Meteorological Institute FMI (FI) and The Swedish Meteorological and Hydrological Institute SMHI (SE) are to deliver their monthly icing analysis during the winter 2011/2012. Results from this project was last officially presented at Vintervind 2010, [5].

Svevind (11.5 MEuro) – Possibly the largest planned wind farm in Europe, Markbygden 1101 will consist of 1101 Enercon WTs with an annual energy production of approximately 10 TWh, which is equivalent to 1/15 of the country's electricity demand. Funding for this wind pilot project is partly an investment subsidy as the EM specifically pointed out that the financial crises in 2008 could not be allowed to delay this project. Studies of the Enercon hot air based blade heating system indicate a gain in energy production in the order of more than 50% during one specific month, [6].

V. CC RELATED R&D PROJECTS, IN ADDITION TO THE WIND PILOT PROJECTS

Mapping of icing, project V-313 (800 kEuro) – Uppsala University, Weathertech and the Swedish Meteorological and Hydrological Institute (SMHI) are in the process of carrying out mapping of icing of large parts of the country at 1 km model terrain resolution. The project is represented at IWAIS 2011 by two researchers; PhD student Petra Thorsson from Uppsala University and SMHI researcher Mr. Esbjörn Olsson. A presentation of the project was made at Winterwind 2011, [7].

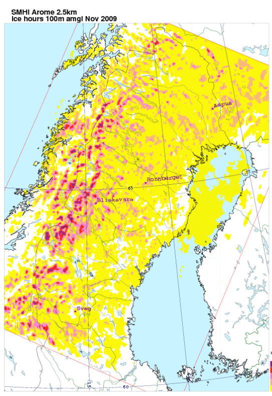


Figure 8: An icing map for northern Sweden for Nov 2009 based on SMHI Arome at 2.5 km model resolution.

IEA RD&D Wind, Task 19 – Wind Energy in Cold Climates (85 kEuro) – WindREN is to represent Sweden in IEA Task 19 from 2009 to 2012. In 2010, Sweden took an active part in inviting China to become a member of IEA RD&D Wind Executive Committee. The primary tasks for the group are to produce a "Recommendation for developer" report and a State-of-the-art report. Previous such reports can be found at IEA Task 19's web page, [8]. WindREN's participation at IWAIS 2011 is made possible through funding from the sponsors of the project; The Swedish Energy Agency through Vindforsk, Dong Energy, O2, Skellefteå Kraft, Triventus and Vattenfall.

Health and safety (70 kEuro) – The municipality of Strömsund has been granted funding from "The network for wind energy utilization", [9], to study H&S challenges for wind farm service staff with a particular focus on CC. Assessing the risk of ice throw and its consequences will be one of the most interesting and important tasks to investigate. A previous project carried out by the municipality of Strömsund, "Havsnäs, Wind- & Manpower" was presented at Winterwind 2011, [10].

Pre-study verification data for project V-313 (34 kEuro) – The goal of Vattenfall's[b] project is to develop a methodology to achieve high availability access to high-reliability icing data as input for numerical weather models. A measurement plan including what to measure, how to measure and how long to measure will be the result of this project. The project's origin is a frustration over having to apply two black boxes; numerical weather models and ice accretion models, without the possibility to verify the step in between. Measuring LWC and MVD is currently difficult as there are no field-enabled sensors for these purposes. The pre-study is to provide a basis for decision to the following project well before the icing season 2011/2012 will start.

Icing - complementary measurements to V-313 (100 kEuro) – Icing measurements will be carried out using the sensors proposed by the previous project. Additionally, a group of three heated NRG anemometers will be used to measure icing by deactivating heat on one anemometer, activating it on the second and only activate heat on the third anemometer if icing has been detected, [11]. The project will provide results by mid 2012.

VI. FUTURE PLANS AND ALTERNATIVES

In addition to the previously mentioned projects, there are quite a few studies remaining to be carried out within the field of wind energy in cold climates. Just to name a few:

Centre for cold climate wind energy research - The Swedish Energy Agency (EM) has received an application from a university proposing that a "Centre for cold climate wind energy research" is to be established. Traditionally, wind energy research in Sweden has been carried out at many different institutes and universities. Consequently, one option for EM is to form a virtual centre with a node at the applying university.

Development of de-icing systems - The Swedish Wind Power Technology Center (SWPTC) at Chalmers, [12], ought to be well suited to study and develop the next generatiosa of de-icing systems.

COST Action 1002 - Sweden ought to join COST Action 1002 – Weather intelligence for renewable energies. 26 other European countries have already joined this action. The main reason why Sweden ought to participate is explained on the first page of this paper; unpredictable production will be paid less in the future as penetration increases. A higher profit through more precise weather predictions is of course of interest also for WT and Photo Voltage owners with installations located on non-ice infested sites.

Test sites for wind energy in cold climates – A few Swedish municipalities are exploring the interest among WT and component manufacturers to establish one or more test sites. The main objectives of these sites would be testing and certification of equipment adapted for low temperature and icing conditions. For development, but likely not for certification, one alternative to establishing fixed test sites could be for the Swedish Energy Agency to provide warranty replacement funding for new commercial wind farms, as has done in the wind pilot projects.

IEA RD&D Wind, Task 19 – Wind Energy in Cold Climates – There's an interest, although no funding is readily available, among the present participants[c] of IEA RD&D Wind, Task 19 to continue this task and expand the number of participants to include Russia, Japan, Italy and Spain to name a few. It could, from a buyer's point of view, be considered irresponsible of WT manufacturers to sell their products knowing they're to be located at sites with meteorological conditions, mainly icing, well beyond the envelope of their low temperature versions. Classification of sites, sensors and WTs as well as the development of adapted technologies are activities that will continue well beyond 2012. Since 2002, Task 19 has failed at initiating a market study for wind energy development in cold climates.

Market study for wind energy in cold climates – The market incentive to build large-scale wind farms has been present in Sweden since 2006. Unfortunately, a Catch-22 situation, starting with a lack of mapping of icing data, has prevented a market study of wind energy in cold climates to be established. It ought to make sense to the Swedish Energy Agency to promote BTM, MAKE or some other established market research company to study the potential of wind energy in cold climates with the aim to make the manufacturers aware of both the challenges and the opportunities.

Winterwind 2012 and beyond –The Boreas series of conferences dealing with wind energy in cold climates were arranged 7 times from 1992 to 2005. In Sweden, a single cold climate wind energy conference was arranged by the University of Gotland and held in Östersund in 1999. Since 2008, two Vintervind conferences (in Swedish) and two Winterwind ditto (in English) have been arranged, the three latter by the Swedish Wind Power Association. These conferences have been great

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[b] Vattenfall is a Swedish Government owned utility.

[c] AT, CA, CH, CN, DE, FI, NO, SE and US.

success with the number of participants increasing from 150 in 2008 to more than 300 in 2011. Due to the planned big wind energy expansion in the north, it is believed that the Winterwind series of conferences will be arranged during many years to come. The next Winterwind conference will be held in Skellefteå (SE) February 8-9, 2012, [13].

VII. RESULTS AND DISCUSSION

Evaluations of modeled and measured icing and power performance show a) icing periods to be captured relatively well in time, b) the magnitude of icing to be difficult to estimate correctly and c) the actual production losses due to iced up wind turbine blades to be surprisingly large, although generally smaller than the modeled losses.

Knowledge regarding the surprisingly large energy production losses caused by icing comprises sensitive information for the WT owners and is therefore generally kept confidential. The major drawback of this secrecy seems to be that developers in general aren't able to put sufficient pressure on the WT manufacturers to offer de-icing systems. Another drawback of the secrecy seems to be that authorities, for better and worse, are largely unaware of the challenges associated with wind farming in icing conditions. It will likely not in the near future be cost-effective to build large wind farms without de-icing systems. Authorities might want to interfere if ice is causing an unacceptable increase in noise and risk of ice throw.

The Swedish Energy Agency is using significant resources to actively promote a rapid development of wind energy in cold climates. A major hurdle for the developers is to make WT manufacturers include icing in the technical availability (95%). If the buyers' purchasing powers are being used wisely, the WT manufacturers will have to provide cost-effective de-icing solutions. In fact, if such anti-/de-icing systems would be capable of handling medium and severe icing conditions, we wouldn't need to carry out either mapping of icing or a market study. At Winterwind 2011, Enercon, WinWind, Siemens and Nordex announced the availability of active de-icing systems. This is a major step forward as Enercon has been alone on the market offering its hot air-based de-icing solution for light icing conditions for almost a decade.

References [14]-[17] are recent reports dealing with icing in general as well as icing on anemometers and WT blades.

ACKNOWLEDGMENT

The author would like to thank all those involved in various cold climate related projects in Sweden for contributing, actively or passively, to the content of this paper. It's also worth mentioning that the Swedish Energy Agency luckily didn't need a market study to realize that icing of WT blades can be a showstopper.

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