July 2016

IEA Wind Task 19

Available Technologies of
Wind Energy in Cold Climates

iea wind

Wind Energy in Cold Climates Available Technologies - report

Edited by:

Ville Lehtomäki

VTT Technical Research Centre on Finland Ltd

IEA Wind Task 19

May 2016

Available Technologies for Wind Energy in Cold Climates

Andreas Krenn, Energiewerkstatt Verein, Austria
Pieter Jan Jordaens, SIRRIS OWI-LAB, Belgium
Matthew Wadham-Gagnon, Technocentre éolien, Canada
Neil Davis, DTU Wind Energy, Denmark
Niels-Erik Clausen, DTU Wind Energy, Denmark
Ville Lehtomäki, Technical Research Centre of Finland Ltd, Finland
Tuomas Jokela, Technical Research Centre of Finland Ltd, Finland
Saara Kaija, Technical Research Centre of Finland Ltd, Finland
Zouhair Khadiri-Yazami, Fraunhofer IWES, Germany
Göran Ronsten, Windren, Sweden
Helena Wickman, Meventus, Sweden
Rebecka Klintström, Meventus, Sweden
René Cattin, Meteotest, Switzerland

May 2016

Photo: Rivière-au-Renard wind farm owned and operated by Technocentre éolien, Quebec, Canada [1]

Foreword: The International Energy Agency Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems (IEA Wind) is a vehicle for member countries to exchange information on the planning and execution of national, large-scale wind system projects and to undertake co-operative research and development projects called Tasks or Annexes. IEA Wind is part of IEA's Technology Collaboration Programme or TCP.

Disclaimer: The IEA Wind agreement, also known as the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems, functions within a framework created by the International Energy Agency (IEA). Views, findings, and publications of IEA Wind do not necessarily represent the views or policies of the IEA Secretariat or of all its individual member countries.

The solutions and technologies presented in this report represent only the findings of the Task 19 working group, and thus do not represent 100% coverage of all available technologies worldwide. The listed solutions and technologies are all based on public data sources or collected via questionnaires from solution providers. In case of missing solutions or references, please contact the Task Operating Agent for further guidance how to add missing details to the next edition.

Abstract

For the wind industry, cold climate refers to sites that may experience significant periods of icing events, temperatures below the operational limits of standard wind turbines, or both. There is vast potential for producing electricity at these often windy and uninhabited cold climate sites. Consequently, the International Energy Agency Wind Agreement has, since 2002, operated the international working group Task 19 Wind Energy in Cold Climates. The goal of this cooperation is to gather and disseminate information about wind energy in cold climates and to establish guidelines and state-of-the-art information. In this report, the available technologies for cold climate wind energy are presented.

This, the first Available Technologies report, is a reference report allowing one to quickly and easily find potential solutions to some of the most demanding challenges in cold climate wind energy. The target audience for this report is an R&D design engineer, analyst, researcher, or similar professional with a technical background and basic knowledge about wind energy. For best practices and recommendations on how to apply these technologies, please refer to the Recommended Practices report from Task 19.

Contents

1 Executive summary

Wind Energy in Cold Climates (CC) refers to sites that may experience frequent icing events, temperatures below the operational limits of standard wind turbines (WT), or both. Apart from lower energy production, which directly influences a wind farm's cash flow, liability issues, such as ice throw and increased noise, may raise development risks. Additionally, one needs to consider fatigue loading and operation and maintenance (O&M) aspects particular to CC. WT operating in cold climates are located around the world, including sites in Asia, North and South America, Europe and even in Africa.

Resource assessment with respect to icing – Icing maps are useful as first source of information for assessing icing related risks. More detailed, site specific meteorological modelling can reveal more information about site icing conditions and related safety and financial risks but model validation is critically important. CC sites also have additional requirements for wind resource measurements and often require special sensors. The influence of ice on or near the sensors will decrease data coverage and increase the uncertainty of measurements.

Ice detection - Dedicated and reliable ice detectors are useful for measuring ice effects for a planned wind farm on safety (ice throw) and potentially reduced energy yield and for turbine control purposes in operational wind farms. For ice effects to safety and energy yield, the occurrence of ice (yes/no), icing intensity (kg/m/h), type of ice (rime, glace) and ice load (kg/m) are useful inputs for analyses. Specific turbine ice detection solutions are available for turbine control and controlling active ice protection systems.

Ice models – Modelling of ice accretion is important to estimate the impacts of ice on objects. Advanced models are used for detailed assessment of ice type and shape for aerodynamic analyses whereas simplified ice accretion models are used to estimate icing rate and mass on objects typically in weather model applications. Ice removal models are very important for wind energy but are relatively immature compared to ice accretion knowledge.

Cold Climate adaptations for wind turbines – Special low temperature adaptions are needed for turbine materials, lubricants, heating etc. to ensure safe and efficient operation. Ice accumulation on turbine blades can be mitigated with blade ice protection systems and many technological solutions exist on the market from both turbine manufacturers and independent 3rd party system providers. Dedicated turbine control features for turbines with ice are also needed.

Assessment of ice throw and ice fall – During the approval phase of a project, the risk of ice throw and ice fall has to be assessed. In some areas, the use of empiric formulas that give a rough indication of the maximum throw distance is sufficient. However, in many cases, authorities may demand detailed risk assessments that take into account the local icing conditions and the likelihood of people in the danger zone. Mitigation measures like warning signs and flashing lights are widely used to lower the actual risk levels.

Operation and maintenance – The risk of ice injuring service staff or the general public must be taken very seriously in icing climates. Road and turbine access for maintenance staff in areas with significant snow fall can prove to be a challenge. Icing forecasts can improve O&M planning.

Standards and certification – Standards are needed to have the same baseline and minimum requirements for all actors in the industry from turbine design to site ice assessment. Icing and cold climate related standards exist for modelling ice, defining ice induced loads for turbines, and characterizing offshore sea ice effects. Certification practices typically follow existing standards.

Testing – The testing of new designs and innovations for cold climate regions is an essential part of a product development cycle. Dedicated test facilities have been set-up for CC with climate chambers and icing wind tunnels for testing small products like sensors, and large components like gearboxes or even fully installed wind turbine assemblies.

Further needs for technology research and innovation – Low temperature and icing introduces special challenges for wind energy and many technology areas need further research and new innovations (R&I). In order to streamline and focus new R&I efforts nationally and internationally, Task 19 proposes a prioritized list of research and innovation needs for the cold climate wind energy community. Top 3 topics for near future R&I are:

1. *Standards, certification and recommended practices*
2. *Assessment of reduced production prior to deployment, financial risks and uncertainties*
3. *Ice protection systems, equipment and procedures*

2 List of abbreviations

BB	Black blades
BF	Blade frequency ice detection (or just rotor blade)
CC	Cold climate
ET	Electro thermal ice protection system
H&S	Health & safety
HA	Hot air ice protection system
HSE	Health, safety and environment
IC	Icing climate
IPC	Ice phobic coating
ID	Ice detection
IEA	International Energy Agency
IOM	Ice Operation Mode
LTC	Low temperature climate
LWC	Liquid Water Content
MW	Mega Watt
MVD	Median Volumetric Diameter
NI	Nacelle based ice detection
OEM	Original Equipment Manufacturer
PC	Power Curve ice detection
PS	Preventive shutdown
R&D	Research and development
R&I	Research and innovation
TH	Temperature and humidity
VTT	VTT Technical Research Centre of Finland Ltd
WT	Wind turbine

3 Introduction

In 2002, the International Energy Agency (IEA) Wind Program initiated a new Task 19 Wind Energy in Cold Climates. This international collaboration between the participating countries has the main objective to gather and disseminate information about wind energy in cold climates and establish guidelines and state-of-the-art practices.

Information is gathered and disseminated on the project website http://www.ieawind.org/task_19.html

The operating agent of the task is VTT Technical Research Centre of Finland Ltd and participating institutes along with VTT are WindREN and Meventus from Sweden, Meteotest from Switzerland, Technocentre éolien from Canada, Fraunhofer IWES from Germany, Energiewerkstatt Verein from Austria, CARDC/CWEA form China, OWI LAB/SIRRIS from Belgium and DTU Wind Energy from Denmark.

According to the 2012 BTM World market update, 69 GW of wind energy were located in cold climates at the end of 2012, and from 2013 to 2017 a staggering 10 GW/year installation rate was forecasted for cold climates [2]. This means that cold climate wind energy is one of the largest "non-standard" markets in wind energy today. However, the technological solutions for this market are still novel, and there are no uniform means to compare existing technologies with each other. The vast market size and technology options were the main drivers for writing this Available Technologies report.

This report is a reference report designed to help the reader quickly and easily find potential solutions to some of the most demanding challenges in cold climate wind energy. The target audience for this report are R&D design engineers, analysts, researchers or similar professionals with a technical background and basic knowledge about wind energy. For best practices and recommendations on how to apply these technologies, please refer to the Recommended Practices report from Task 19.

The report is divided into sections that cover specific topics, and each subsection has a similar structure, so the format will be familiar after reading one subsection. The core results per subsection are summarized into tables that include the solutions, advantages/disadvantages or technical specifications, and their references. All references are divided into three categories starting from scientifically most reliable sources e.g. peer-reviewed journals (shortly *Paper*), performance related information from e.g. conference proceedings (shortly *Perf*) and other sales oriented material in the format of website, brochure or similar (shortly *Other*).

4 Definitions and site classification

Cold Climate -- Cold Climate (CC) areas are regions that experience frequent atmospheric icing or periods with temperatures below the operational limits of standard IEC 61400-1 ed3 wind turbines. CC conditions may impact project implementation, economics, and safety. Areas that have periods with temperatures below the operational limits of standard wind turbines occur are defined as Low Temperature Climate (LTC) regions, whereas areas with atmospheric icing are defined as Icing Climate (IC) regions. In some areas wind turbines (WT) are only exposed to either atmospheric icing or low temperature events, while in other regions both low temperatures and atmospheric icing may take place. Therefore, a site can be in a Low Temperature Climate, or an Icing Climate, or both, but in all cases they are still denoted as Cold Climate sites. These definitions are further illustrated in Figure 1.

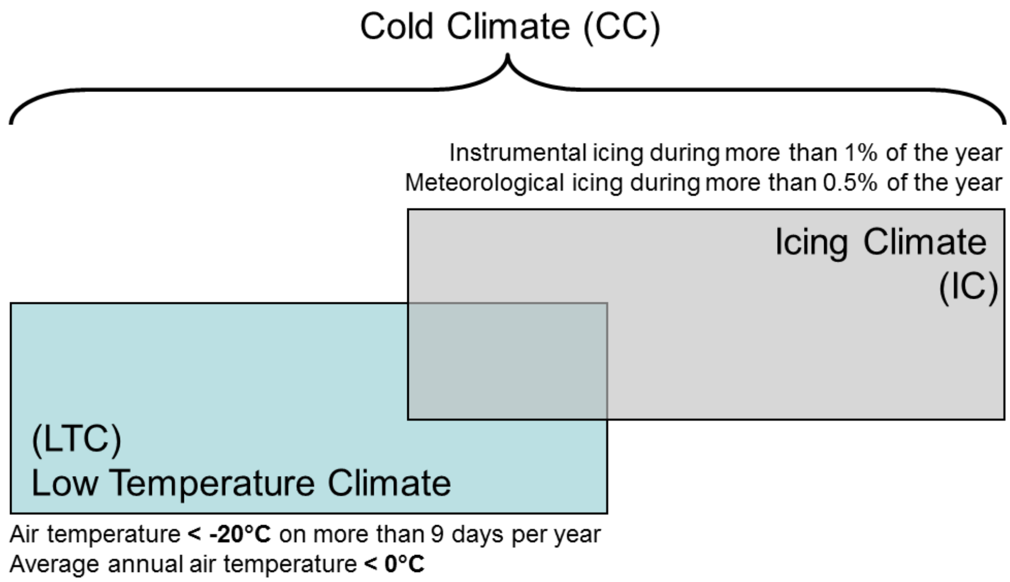

Figure 1. Definition of Cold Climate, Low Temperature Climate and Icing Climate

Atmospheric icing – Atmospheric icing is defined as the period of time where atmospheric conditions exist for the accretion of ice or snow on structures, which are exposed to the atmosphere, to occur. In general, the different types of atmospheric icing that impact wind turbine development are in-cloud icing (rime ice or glaze) and precipitation icing (freezing rain or drizzle, wet snow).

In addition to the different types of atmospheric icing, the ice itself can take different forms which can be described as follows:

- **Rime ice**: Supercooled liquid water droplets from clouds or fog are transported by the wind. When they hit a surface, they freeze immediately. If the droplets are small soft rime is formed, if the droplets are bigger hard rime is formed.

Rime ice formation is asymmetrical, located only on the windward side of a structure. It can occur at temperatures down to -20°C.

- **Glaze ice**: Glaze ice is caused by freezing rain, freezing drizzle, or wet in-cloud icing and forms a smooth, transparent, and homogenous ice layer with a strong adhesion on the structure. It usually occurs at temperatures between 0 and -6°C, and has the highest density. Freezing rain or freezing drizzle occurs when warm air melts the snow crystals and forms rain droplets, which afterwards fall through a freezing air layer near the ground. Wet in-cloud icing occurs when the surface temperature is near 0°C. During glaze ice growth, the water droplets that hit the surface do not freeze completely. The non-frozen water forms a layer that, due to wind and gravity, may flow around the object and freeze on the leeward side.
- **Wet snow**: Partly melted snow crystals with high liquid water content become sticky and are able to adhere to the surface of an object. Wet snow accretion, therefore, occurs when the air temperature is between 0 and +3°C.

Phases of an icing event

Figure 2 shows the evolution of an icing event. An icing event can be described with the following terms, applicable to structures, instruments, and wind turbines exposed to atmospheric icing:

- **Meteorological Icing**: Period during which the meteorological conditions (temperature, wind speed, liquid water content, droplet distribution) allow ice accretion.
- **Instrumental Icing:** Period, during which the ice is present/visible at a structure and/or a meteorological instrument.
- **Rotor Icing**: Period during which ice is present at the rotor blade of a wind turbine. Due to differences in dimension, shape, flow velocity and vibrations, rotor icing is typically not equivalent to instrumental icing. Typically, incubation and ablation time for rotor icing are shorter than for instrumental icing. Furthermore, the duration of rotor icing strongly differs for a wind turbine at stand still compared to a wind turbine under operation.
- **Incubation**: Time between the start of meteorological icing and the start of instrumental/rotor icing, dependent on the surface and the temperature of the structure.
- **Accretion:** Period of ice growth (active ice formation).
- **Persistence**: Period during which the ice remains persistent (no growth, no ablation).
- **Ablation**: Period during which ice is being removed through ablation. Ablation includes melting, erosion, sublimation and shedding of ice. It is also the delay between the end of meteorological icing and the end of instrumental/rotor icing.

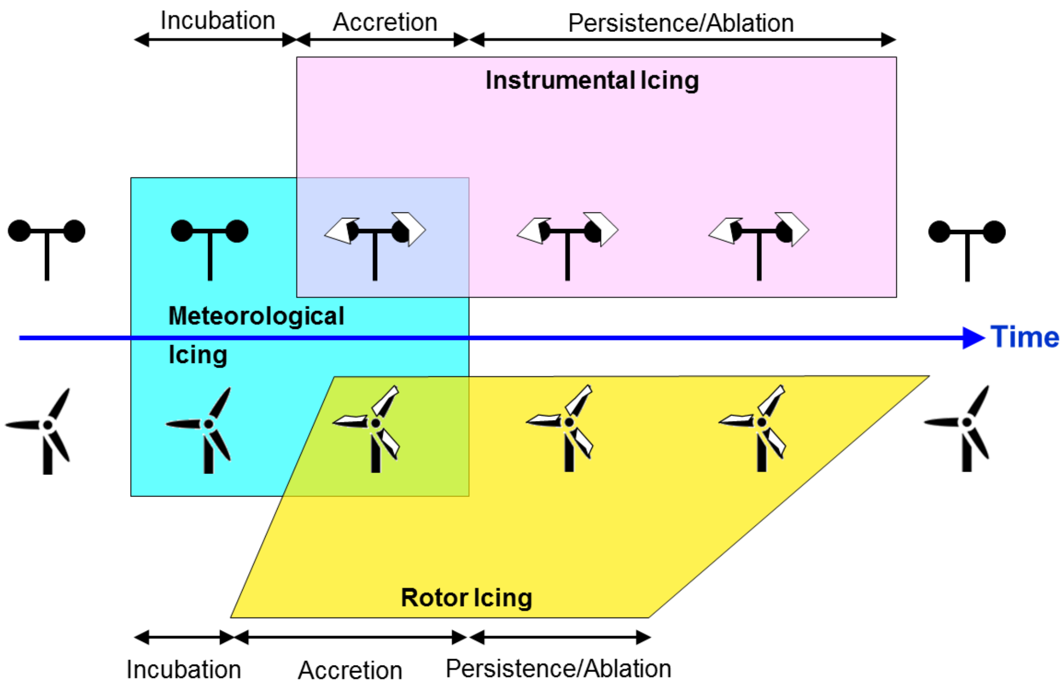

Figure 2. Definition of Meteorological Icing, Instrumental Icing, Rotor Icing, Incubation, Accretion, Persistence, and Ablation

Low Temperature Climate site classification

Figure 3 shows the occurrence of LTC and IC with respect to ambient temperature. The following definitions apply for a LTC site:

- An average of nine days per year with minimum hourly temperatures at or below -20°C from long term measurements (preferably ten years or more) or
- The long term average air temperature of the site is below 0°C.

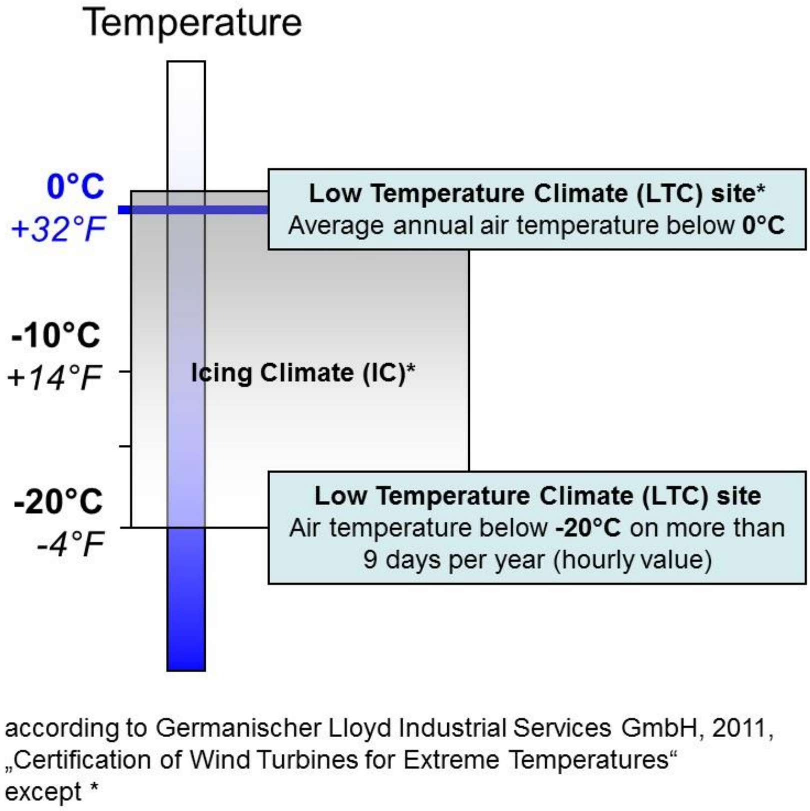

Figure 3. Low Temperature Climate and Icing Climate with respect to ambient temperature

Icing Climate site classification

The IEA site classification is based on the frequency of instrumental and meteorological icing. In order to classify a site, the following simplifications apply for assessing the duration of meteorological and instrumental icing (referring to an unheated structure).

In order to describe the icing characteristics of a site, the following simplifications apply:

- Incubation time = 0, i.e. meteorological and instrumental icing start at the same time
- The duration of meteorological and instrumental icing refers to an unheated structure, typically an fully unheated anemometer or heated camera on a mounting boom

In addition to the above simplifications, please see IEA Recommended Practices and updated IEC standards [3] for more detailed recommendations.

Table 1. IEA Icing Climate site classification.

IEA Ice Class	Meteorological Icing	Instrumental Icing	Reduced Production
	% of year	% of year	% of annual production
5	>10	>20	> 20
4	5-10	10-30	10-25
3	3-5	6-15	3-12
2	0.5-3	1-9	0.5-5
1	0-0.5	<1.5	0 - 0.5

5 Resource assessment with respect to icing

When developing a wind farm in a cold climate region, it is important to determine the impact icing may have on its installation, operation and maintenance. During the site prospecting phase, it can be useful to investigate icing maps. Icing maps (section 5.1) provide an overview of regions which are likely to experience significant icing impacts. After identifying a site of interest, a combination of a validated meteorological modelling approach (section 5.2) and onsite measurements of wind (section 5.3) are used to evaluate the energy yield potential of a site. Icing conditions affect the underlying wind resource by reducing the available energy yield that the wind turbines are able to capture.

5.1 Icing Maps

Figure 4 Icing maps showing number of meteorological icing hours (source: [4])

What: Icing maps provide an overview of the relative geographical distribution of icing conditions.

Why: The icing maps are intended to provide information about icing intensity, duration, or impact to the developer in the planning phase of a project and to enable a rough comparison of sites.

How: Icing maps are created using meteorological information either from mesoscale atmospheric model simulations (section 5.2), meteorological measurements combined with an icing model (section 7), or empirical evidence from observed wind farm reduced production (often also called production loss but as icing losses can potentially be recovered, the term "reduced production" is used in future in this document) or icing observations. The limitations of the numerical weather models will be described in section 5.2. For the meteorological measurements and observations the main limitations are the sparse nature of the observational network, and the limited parameters that are measured. Currently icing maps have more technological than climatological challenges. After estimating the icing frequencies or rates using an icing model, the icing maps are created. The most common type of icing map involves applying threshold values to the icing rates in order to estimate the duration of icing at each location.

Recently maps of reduced production have been created. These maps use an additional model relating icing rates to turbine production, or are based on actual observed reduced production from a number of wind farms across a region. Methodologies for creating icing maps involve to use of generic turbine models (including control features) ,excluding ice protection system impacts and using generic meteorological icing information that may differ from actual site specific conditions.

Table 2 presents an overview of method used to create icing maps as well as the different values of icing presented in maps.

Table 2. Icing map overview

Solution	Advantage	Disadvantage
	Method	
Empirical	• Uses measurements • Computationally cheap	• Sparse observational network • Spatial interpolation
Numerical weather model	• Includes dynamical interpolation • Includes non-measured variables • 3D representation of the atmosphere	• Relies on model performance • Computationally expensive • Limited validations
	Estimated values	
Meteorological icing hours	• Information for design of ice protection systems • Comparison of sites possible • Rough IEA Icing Climate site classification possible	• Limited validation available • No information about duration or number of icing events
Instrumental icing hours	• Ice throw risk period • Rough IEA Icing Climate site classification possible	• limited validation • ablation models are uncertain • No information about duration or number of icing events
Reduced production	• Validation possible with wind farms • Useful for economic calculations	• Ablation models are uncertain • No information of specific turbine model and ice control strategy
Ice Load	• Criteria for power lines • Worst case analysis	• Not as useful for turbine performance • No temporal resolution

Table 3 presents a list of available icing maps per country.

Table 3. Available icing map solutions.

Region	Specifications	Refs
Finland	• mesoscale AROME weather modelled (2011) • 5 year and monthly averages • Meteorological icing hours; Instrumental icing hours; Reduced production	Paper: [5] Perf: [6], [7] Other: [8] [9]
Canada	• Freezing precipitation from 160 weather stations • 10 years (1957 -- 1966) • Meteorological icing hours	Paper: [10] Perf.: Other:
Sweden	• Data from 20 operational wind farms • Empirical fit to elevation • Reduced production	Paper: Perf.: Other: [11] [12]
Czech-Republic	• Frozen precipitation from 32 sites • Mapped with kriging interpolation of elevation • 15 years (1999 -- 2008) • Instrumental icing days	Paper: Perf.: Other: [13]
Germany	• Observations from 74 + 35 stations • 20 years (1980 – 1999) + 10 years (1980 – 1989) • Linear fit to elevation • Meteorological icing hours	Paper: Perf.: Other: [14]
Europe	• Airport observations • 16 year (1982 – 1997) • 3 different approaches to analysing icing • Meteorological icing hours	Paper: Perf.: Other: [15]
Global	• 4500 observational stations • Between 20 and 34 years of data at each station • Based on cloud base height and temperature • Reduced production	Paper: Perf: [16] Other: [17] [9]
Canada - Quebec	• North America Regional Reanalysis (model) data • 32 years (1979 – 2010) • Used cloud water, wind speed and temperature • Index	Paper: [18] Perf.: Other:
Romania	• 49 Meteorological stations • 20 years (1980 – 1999) • Freezing precipitation • Meteorological icing hours	Paper: Perf.: Other: [19]
Russia	• Meteorological icing hours	Paper: Perf.: Other: [20]
Russia – Sochi	• 1254 direct icing observation sites • 58 years of data • Maximum load	Paper: Perf.: Other: [21]

Sweden; Norway; Finland	• WRF mesoscale model • 1 year high resolution and lower resolution adjustment to long-term conditions • Meteorological icing hours	Perf: [22] Perf.: Other: [23] [24] [25] [4] [26]
Sweden	• AROME mesoscale model • Multiple time periods • Meteorological icing hours	Paper: Perf.: Other: [27] [28]
Great Britain	• WRF mesoscale model • 50 year return period load	Paper: Perf.: Other: [29] [30]
Canada - Gaspé	• Gaspé airport observations • 24 year period (1980 – 2013) • Adjusted for topography • IEA Ice class; Reduced production	Paper: Perf.: Other: [31]
Great Britain	• Combined mesoscale modelling and weather station observations • Empirical fit to elevation • Maximum ice load	Paper: [32] Perf.: Other:

5.2 Meteorological models for icing

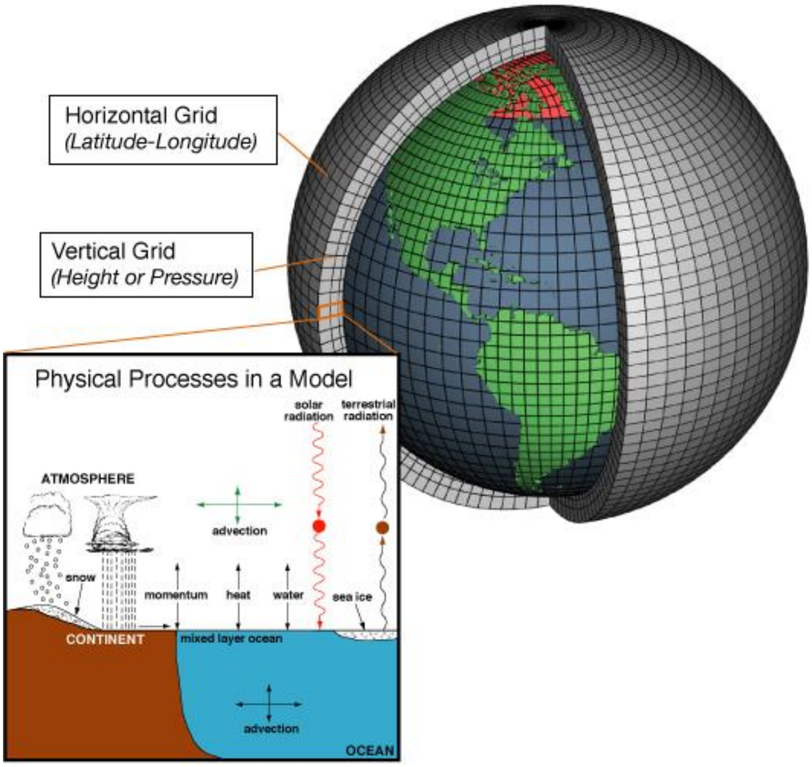

Figure 5 Meteorological models are run on a 3 dimensional grid, and include many physical processes for modelling the atmosphere (From [33]).

What: Numerical weather prediction (NWP) models simulate the evolution of atmospheric conditions based upon a full set of dynamical equations. The model dynamics are able to simulate processes that occur at scales similar to the models horizontal grid resolution. To represent sub-grid scale processes, NWP models include parameterizations. The most common parameterizations are cloud microphysics, radiative transfer, convective clouds, and turbulence in the atmospheric planetary boundary layer (PBL).

NWP models can be broken into two broad categories, global models and regional models. Global models only have boundary inputs from the model surface, while regional models rely upon output from the global models for horizontal boundary conditions.

In addition to boundary conditions, NWP models need input conditions to initialize the state of the numerical atmosphere. For global models this is commonly done through data-assimilation where global measurements of atmospheric parameters are used to adjust the model data until the model physics and the measurements are in relative agreement. Regional (mesoscale) models are commonly initiated either using the data-assimilation process or directly using outputs from the global models.

Why: NWP models are used to help fill gaps in the measurement of atmospheric processes that are significant for cold climate wind energy. These gaps can be related to time, where forecasting using NWP models allows for the prediction of the conditions that will come in next few days. They can also be related to spatial gaps by providing estimates of atmospheric conditions in locations where there are not measurements, and finally they can be used to fill parameter gaps where the key parameters of interest are not measured. This last form is particularly important for the challenge of atmospheric icing as cloud parameters are not typically measured.

How: Most commonly, data from a mesoscale atmospheric model simulation are used to provide the spatial weather information needed to create icing maps. Mesoscale models are limited by the parameterizations used and the horizontal and vertical resolution. Simulating clouds, which are discontinuous features that are the result of sub-grid scale interactions, is an area where model uncertainties are typically large. In addition, cloud estimates are dependent on the accurate simulation of many other variables, particularly temperature and moisture. Finally, due to the relatively coarse resolution of mesoscale model simulations, the surface fields, particularly the topography, are coarsely represented. The coarse resolution leads to a smoothing of the topography, underestimating the elevation of hills and overestimating the elevation for valleys.

Solution alternatives

The choice of numerical weather model should not impact the results of a study to a great degree, but one should ensure that the model domain is reasonable for a site, and that the model is run at a high enough resolution to capture the topographical features of the wind farm and surrounding terrain. The smoothing of the terrain can also result in sheltering effects not being captured correctly if the resolution is too coarse.

Table 4 presents a list of common models used for icing related studies. Three of these models were developed for operational weather forecasting. This means that they were designed to create daily forecasts provided by national meteorological offices. These models have a fixed configuration for a certain period, but will see changes over time as improved algorithms are added. The WRF-ARW model, in contrast, is a research model. This means that the model has a large number of different algorithms included, which the model user has to configure at start up. It is useful to get information about the options that were used, as it has been shown that these can have a significant impact on the icing result.

Table 4. Numerical weather models that are commonly used in wind energy icing studies

Model	**Description**	**Paper**	**Other**
AROME	Regional model developed by and operational at Meteo-France. AROME is also used by 15 other countries in Europe, and is increasingly used as a research tool.	[34]	[35]
COSMO	Consortium model developed by several national meteorological services.		[36] [37]
GEM-LAM	Local area model developed and used operationally by Environment Canada. The core of the model is identical Environment Canada’s global model GEM.	[38] [39]	
WRF-ARW	Community model guided by the National Center for Atmospheric Research (NCAR) in the United States. This model has many parameterizations, and these can lead to results that differ as much as using a different NWP model.	[40] [41]	[35]

5.3 Wind measurements

Figure 6. Testing different wind anemometers in severe icing climate (source: [42])

What: A good quality wind measurement is the key to successful resource assessment, power curve measurement, and wind turbine monitoring. In order to measure wind conditions in cold climate regions (and especially in icing climates), it is essential to carefully select the measurement instruments. Suitable instruments are commercially available for sites exposed to different icing climate severities, and the technology is continuously being developed and evaluated by manufacturers and users.

Why: It is important to use measurement instruments that are suitable for the climate conditions at the site. Ice growth on sensors and/or the meteorological (met) mast can lead to measurement errors and loss of data. Ice on anemometers and wind vanes may cause them to stop or slow down, and ice build-up on booms or lightning rods may also impact the measurements. Measurement errors will give the wrong conclusions regarding the wind resource of the site. The increase in uncertainty in an energy yield assessment due to low data coverage and increased maintenance during the measurement campaign warrants an appropriate investment.

How: Wind speed can be measured by several methods, for example, a simple rotational cup, measuring the difference in static and total pressure, or by analysing the change in the reflective properties of light or sound waves due to air movement. The most widely used anemometers, cup and ultrasonic, require a met mast.

The solution for accurate wind measurements in icing climates is the use of properly heated anemometers and wind vanes. If cup or propeller type anemometers are used, the anemometer's cup or propeller, shaft, and post should be heated in order to prevent ice from accumulating and impacting measurement quality. Heated cup anemometers have moderate to low power consumption (roughly 50-100W). Even when fully heated, cups and shaft or measurement probes and main body, these sensors do not always remain ice free in heavy icing conditions [43] [44]. Ultrasonic anemometers can be more robust sensors in icing conditions than cup anemometers but require calibration and heating similarly to cup anemometers. Since ultrasonic anemometers have no moving parts, there are no mechanical effects that influence the measurement of the mean, minimum, and maximum wind speeds [45]. Additionally, it is relatively easy to supply sufficient heating power to the important anemometer parts. One weakness of the ultrasonic anemometer, at least in its early days, was the internal electronics sensitivity to moisture when not connected to an uninterrupted power source. In general it is important to note that heated sensors tend to be less sensitive to low wind speeds and to changes in wind speed than unheated sensors thus having an impact on the wind measurement quality and turbulence assessment. Some of the sensors, both heated and non-heated, are also sensitive to flow that is not horizontal [45]. In icing climates, attention must be paid also to the positioning of the anemometer and wind vane. In severe icing conditions, the accuracy gained through heating is quickly lost if neighbouring objects such as booms and masts are allowed to collect ice. Therefore, these surrounding objects need to be heated as well.

Remote sensing devices offers an option for parallel or alternative use for anemometers mounted on masts for obtaining wind measurements. Due to its measurement principle, LiDAR and SoDAR measurements are not directly influenced by icing [46] [47]. With an adequate power supply, remote sensing devices perform well in cold climate. However, the data availability of LiDAR and SoDAR in low temperature climates could decrease due to the low number of atmospheric particles at very low temperatures under clear conditions. In contrast, increased air particles from fog or low clouds can influence the data availability of remote sensing devices at high level by reducing the distance the signal can reach [46] [48].

Figure 7 shows wind measurements from several anemometers during an icing event. The LiDAR measurement (black) correlates well with the measurement from the fully heated anemometer (magenta). The unheated cup anemometer (blue) and bearing heated cup anemometers (red, turquoise) are clearly affected by icing. Heated bearing anemometers are usually rotating at lower speeds during icing events.

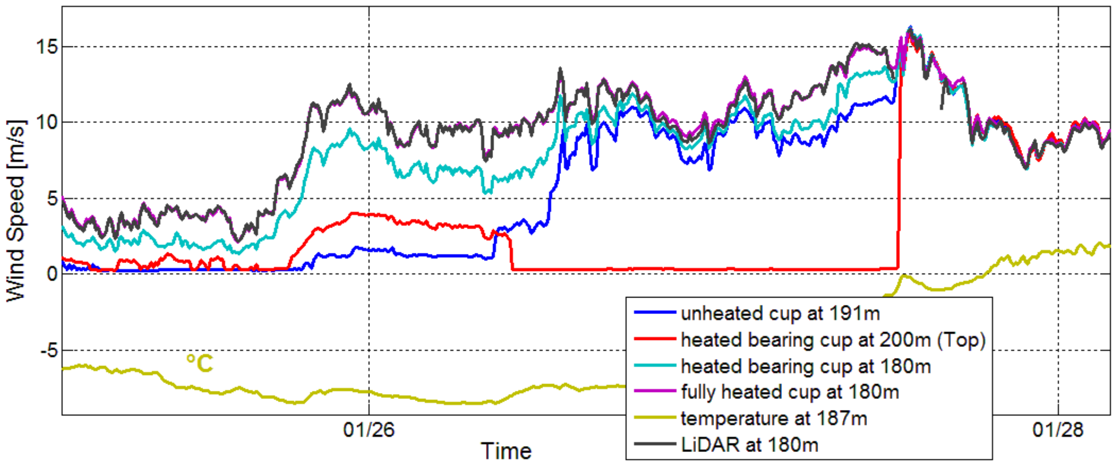

Figure 7: Comparison of LiDAR (black), fully heated (magenta), two heated bearing (turquoise and red) and unheated anemometer (blue) during an icing event [46].

Met masts are usually very thin and slender constructions. The more slender the met masts are the less will they influence the measurements. Therefore, compromises between robustness and accurate measurements need to be made when choosing a met mast for a cold climate site. Before erecting a met mast in a region with icing conditions, calculations of the highest ice load and the highest wind load should be performed. For permanent masts, the standard ISO 12494 [49] states that a combination of ice load with a 3 year return period should be combined with a wind speed with 50 year return period. For the non-permanent constructions, the return periods can be reduced. Lattice towers as well as Tubular (Telescopic) met masts are the most common types of masts. A properly designed lattice tower is usually a better solution, in cold climates.

A sufficient power supply system is needed for cold climate site assessment and measurement campaign. In a perfect world, access to an electricity grid is available. If there is no grid access, a stand-alone power supply arrangement that is sufficient for sensor and other heating is a must. Such power supply systems are commercially available. A cold climate adapted power supply system may consist of batteries and a diesel generator, solar panels, a small wind generator, and/or a fuel cell [50] [51]. Solar panels or other weather dependent power sources are usually not sufficient for properly heated instruments that will maintain their accuracy, as power requirements up to 1500 W are needed.

Table 5. Wind measurement devices (sensors and remote sensing)

Solution	Advantage	Disadvantage	References
Fully heated cup anemometer	+ Proven standard technology (conforms IEC power curve measurements [52]) + Middle to low power consumption	- Less negative impacts of icing on the measurement quality and data availability - Poor accuracy (e.g. in complex flow)	Paper: [43] Perf.: [44] [45] Other: [52] [53]
Fully heated ultrasonic anemometer	+ Additional information (wind direction, temperature, status signals, vertical wind if 3D type…) + No impact from icing (if enough heating power is installed and available)	- High costs - High power consumption	Paper: Perf.: [45] Other: [54]
Fully heated wind vane	+ Proven standard technology	- Less negative impacts of icing on the measurement quality and data availability	Paper: Perf.: [45] Other:
Propeller Anemometers	+ Less prone to icing + Robust technology + Also measures wind direction	- Measurement data can be influenced or lost during icing events - Ice-influenced data is difficult to identify	Paper: Perf.: [45] Other:
Remote sensing (LiDAR / SoDAR)	+ Measurements are not affected by icing + LiDAR can be used as ice detector and for cloud base detection	- Poor data availability in case of clear atmosphere and during snow, rain, or fog events	Paper: Perf.: [46] [47] [48] Other: [55] [56]

	+ Includes wind direction	- No measurement of meteorological parameters at the measuring height (e.g. temperature, humidity, etc.)	

Table 6. Infrastructure for Wind measurements (met masts, power supply)

	Solution	Advantage	Disadvantage	References
Met masts	**Lattice Towers**	+ Can be very robust way to withstand severe loads of icing + Modular construction + Easy maintenance with climbers	- Concrete foundation required (construction permits from authorities need to be obtained) - Limitations in the possible directions of the booms (mast geometry) - Iced mast influences wind measurements - Expensive	Paper: Perf.: Other: [49]
	Tubular (Telescopic) met masts	+ Easy and fast installation + Steel plate as foundation + For installation no climbers or crane required	- Mast needs to be laid down, in most cases, for maintenance - Maintenance delays if snow depths are large	Paper: Perf.: Other: [49]
power supply	**Grid connection by laying of cables**	+ High availability + Low energy prices	- Installation costs dependent on cable length - Safety issues e.g. lightning protection and possible permits	Paper: Perf.: Other:
	Diesel/Petrol generator	+ High energy density + Fuel easily available + Not dependent on local energy from sun or wind	- High maintenance and regular refuelling - Poor utilisation factor in case of low energy demand - Possible environmental stipulations	Paper Perf.: Other:
	Fuel cell in combination with PV and wind	+ Energy production corresponds well to demand of sensors + Automatic self-preservation mode	- Special fuel - Not suitable for high operational hours - Limited providers	Paper: Perf.: [51] [50] Other: [57]
	PV and wind	+ Almost no maintenance required + No re-fuelling necessary	- Wind turbines and PV modules might ice - Oversizing of rated power and battery pack	Paper: Perf.: Other:

			necessary for 100% availability	
	Energy Management System	+ Reduced energy demand + Heating power required only during relevant time periods + Highly Advantageous for locations where access is hardly possible	- Benefit vs. efforts depends on site specific conditions	Paper: Perf.: Other:

6 Ice detection

Ice detection and ice measurements provide crucial information for resource assessment applications to assess the realistic energy yield potential for a given site. Ice detection measurements may also be used for validating icing maps (chapter 5.1) and meteorological models (chapter 5.2). In addition to resource assessment with respect to icing, turbine specific nacelle or rotor blade mounted ice detectors can be used for turbine control purposes in operational wind farms.

Figure 8: Ice detectors [source: Elforsk]

What: Ice detection aims to detect and measure meteorological icing, instrumental icing, ice load, and icing intensity. In the wind industry, ice detection is of interest both during the project development phase and during wind farm operation. Ideally, instruments would exist that are able to measure icing reliably and automatically, delivering information on the duration of meteorological and instrumental icing, as well as icing intensity and ice load measurements. It would also be ideal to have instruments that can measure liquid water content and the droplet size distribution to verify results from numerical weather models.

The current status of ice detection technologies is not as mature as described above, and even though progress has been made during the past decade, many ice detection technologies are still waiting on a proper validation.

Why: Icing can lead to reduced energy production; shutdown events, increased fatigue loadings, ice throw, and/or increased noise. Ice detection and measurement is important to enable an estimation of the effects on turbines and production, enable the efficient control of anti- and de-icing systems and turbines themselves, and ensure a safe environment for people working or visiting the wind farm.

How: Icing can be either detected or measured. Different technologies are available for ice detection and measurement, for example, ice load can be measured directly; cloud height, visibility, humidity, other meteorological parameters can be used to infer icing conditions exist; a deviation from a turbines' normal power curve can be due to icing, or cameras and image analysis can show icing. The type of technology and the parameter measured should be adjusted to fit the phase of the wind project. For example, power curve analysis is only possible when turbines are in operation, whereas, analysis of the icing climatology by means of measuring ice load, icing intensity, and the length of icing events is important in the project development phase.

Ice detection sensors can be installed on the turbine nacelle, turbine blade, or on a met mast. In addition, ice detection can be done using only standard sensors through algorithms that detect icing signals. The level of maturity differs a lot between different methods and sensors. The capability of a sensor can range between detecting ice/no ice, distinguishing between instrumental and meteorological icing, or detecting the severity and intensity of icing. Some sensors have functionality for detecting all of these, but with different reliability for the different capabilities. It is common that a sensor with functionality for measuring both instrumental and meteorological icing, as well as detecting ice/no ice, is only reliable enough to be used for detection of ice/no ice.

Methods

The available ice detector technologies are listed below in Table 7, for mast and nacelle based solutions, and Table 8, for turbine rotor based solutions. The information regarding capabilities (e.g. detection of meteorological or instrumental icing, icing severity, and whether the detector can be used for turbine control) is based on the references listed in this document, as well as statistics and user experiences from an ice detector survey performed by Task 19. The information that a detector has the possibility to detect, for instance meteorological icing, does not mean that the detector is suitable to use for detection of meteorological icing in all conditions and environments. Additionally, detectors identified as suitable for turbine control only means that the detector type, in one or more known cases, has been used for this application. It does not mean that the detector is reliable or precise enough for use in controlling anti- or de-icing systems.

Table 7 – Ice detector technologies for mast or nacelle application

Mast and nacelle detection					
Detector manufacturer	**Technical description**	**Applications**		**Sold items** [58]	**References**
HoloOptics T40 series	Uses the reflection of an infrared signal to detect ice on a vertical cylinder probe. Probe is heated when ice is detected until signal is back to normal.	Met. icing:	x	40	Paper: [59] [60] Perf.: [61] [62] Other: [63], [58]
		Inst. icing:			
		Icing rate:	x		
		Icing severity:			
		Turbine control:			
Combitech IceMonitor (ISO Cylinder)	Measures the weight of ice load on a freely rotating vertical cylinder according to ISO 12494 (30 mm in diameter and 0.5 in length).	Meteorological icing:	x	50	Paper: [59] [60] [64] [65] [66] Perf.: [61] [62] [67] Other: [68], [58]
		Instrumental icing:	x		
		Icing rate:	x		
		Icing severity:	x		
		Turbine control:			
PMS Icemeter	Measures the weight of ice load on a fixed vertical cylinder downwards (30 mm in diameter and 0.5 in length) Also provides air temperature humidity, wind speed and direction.	Meteorological icing:	x	80	Paper: [60] [69] [70] [71] Perf.: Other: [72], [58]
		Instrumental icing:	x		
		Icing rate:	x		
		Icing severity:	x		
		Turbine control:			
Heated versus unheated anemometer or wind vanes	Ice detection through comparison of readings of a heated and unheated anemometer or wind vanes.	Meteorological icing:		n/a	Paper: [65] Perf.: [61] [62] Other: [58]
		Instrumental icing:	x		
		Icing rate:			
		Icing severity:			
		Turbine control:	x		
Atmospheric conditions (Temp./Hum/ Visibility etc.)	Ice detection through measurements of low temperature and high humidity	Meteorological icing:	x	n/a	Paper: [65] Perf.: Other: [58]
		Instrumental icing:			
		Icing rate:			
		Icing severity:			
		Turbine control:			
Labkotec LID/ISD	Weakening of an ultrasonic signal,	Meteorological icing:	x	3000	Paper: [65] Perf.: [61]

3300IP	measured with a vibrating wire, is used as an indicator for ice formation. Wire is heated when ice is detected until signal is back to normal.	Instrumental icing: Icing rate: Icing severity: Turbine control:	 x x		[62] Other: [73] [74], [58]
Goodrich Campbell Scientific 0871LH1	Measures an ultrasonic signal on a vibrating probe. Indicates ice when a shift in signal frequency is observed. Probe is heated when ice is detected until signal is back to normal.	Meteorological icing: Instrumental icing: Icing rate: Icing severity: Turbine control:	x x x	700	Paper: [59] [60] [66] [64] [65] [75] [76] Perf.: [61] [62] Other: [77], [58]
Leine Linde IPMS (camera + temperature/ humidity)	Monitors meteorological conditions and gives a warning of icing when certain threshold values are met. Local conditions on rotor blades can then be inspected with the aid of installed cameras.	Meteorological icing: Instrumental icing: Icing rate: Icing severity: Turbine control:	x x x	40	Paper: Perf.: Other: [78], [58]
Webcams	Cameras combined with either manual or automated image analysis.	Meteorological icing: Instrumental icing: Icing rate: Icing severity: Turbine control:	 x 	n/a	Paper: [65] Perf.: [61] [62] Other: [58]
New Avionics IceMeister	Monitors the opacity and refraction of substances on the surface of a probe, based on the reflection of an infrared signal.	Meteorological icing: Instrumental icing: Icing rate: Icing severity: Turbine control:	 x 	n/a	Paper: Perf.: Other: [58]

Table 8 – Ice detector technologies for turbine/turbine rotor application

Turbine and turbine rotor detection				
Detector/Manufacturer	**Technical description**	**Applications**	**Sold items**	**References**

Power curve	Deviations in operating characteristics (wind, rotating speed, power output, blade angle) from theoretical power curve are used to detect ice.	Meteorological icing:		n/a	Paper: [79] Perf.: [80], [81] Other: [82], [58]
		Rotor icing:	x		
		Icing rate:			
		Icing severity:			
		Turbine control:	x		
Bosch Rexroth BladeControl (IGUS)	Measures changes in eigenfrequencies and natural oscillations of rotor blades to detect ice using piezo-electric accelerators glued inside the blade.	Meteorological icing:	x	1500	Paper: Perf.: [61] Other: [83], [58]
		Rotor icing:	x		
		Ice rate:			
		Icing severity:			
		Turbine control:	x		
FOS4X fos4IceDetection	Measures changes in eigenfrequencies and natural oscillations of rotor blades to detect ice using fibre-optic accelerators glued inside the blade.	Meteorological icing:	x	70	Paper: Perf.: Other: [84], [58]
		Rotor icing:	x		
		Ice rate:			
		Icing severity:			
		Turbine control:	x		
Wölfel SHM.Blade / IDD.Blade	Measures changes in eigenfrequencies and natural oscillations of rotor blades to detect ice using piezo-electric accelerators glued inside the blade.	Meteorological icing:	x	100	Paper: Perf.: Other: [85], [58]
		Rotor icing:	x		
		Icing rate:			
		Icing severity:			
		Turbine control:	x		
Eologix	Measures changes in impedance and capacitance on the rotor blade with a retrofit sensor taped on the blade surface	Meteorological icing:		20	Paper: Perf.: Other: [86], [58]
		Rotor icing:	x		
		Icing rate:			
		Icing severity:			
		Turbine control:	x		

7 Ice models

Ice accretion models are important for evaluating the process of ice accretion and removal on objects. Advanced ice accretion models (7.1) are used to investigate the detailed physics of the ice accretion process in studies ranging from single supercooled droplet trajectories to detailed 2D or 3D ice shapes on an object. Simplified, empirical ice accretion models (7.2) are useful when coupled with other simulation models such as mesoscale weather models. The newer ice ablation models (7.3) are very important for wind energy, as an accurate estimate of ice ablation rate is required to determine when the instrumental or rotor icing periods have ended.

7.1 Advanced ice accretion models

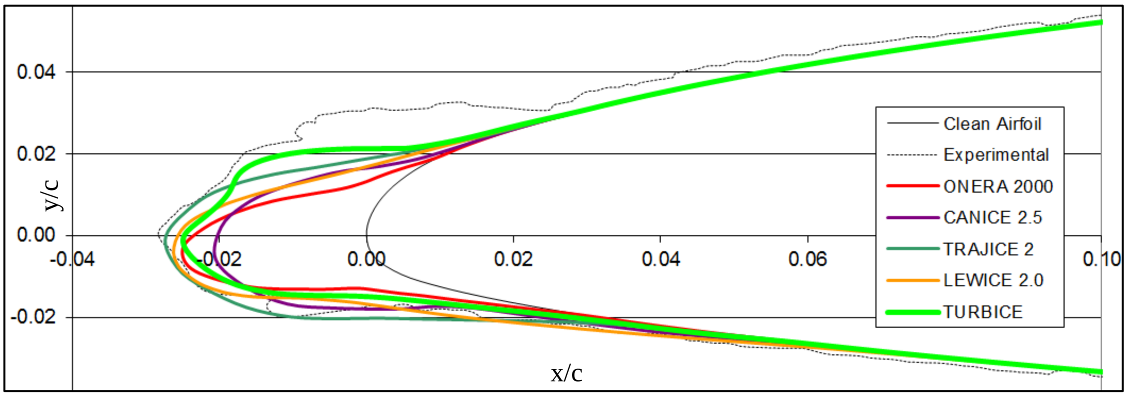

Figure 9: Comparing different advanced ice accretion models to experimental ice shape (source: VTT)

What: In general, all ice accretion simulation tools investigate the fluid-structure interaction of an object in icing conditions. Historically, most ice accretion models have been developed for the aeronautical field to aid in the de-icing and anti-icing systems design and the aviation certification processes. They simulate the ice-accretion process on for example the aircraft wings and the engine nacelles. Some of these codes have been modified for wind power use to simulate ice accretion on the wind turbine blades, and solutions tailored specifically for wind power studies are rare.

Why: Ice accretion models are used to identify the size and shape of the ice on an object. The size and shape of the ice on an airfoil can be used to investigate the aerodynamic penalties of iced airfoils causing increased drag and decreased lift. Some simulation models are used to identify where ice is accreted on an airfoil and how much heat is required to prevent such ice from forming on an airfoil enabling e.g. design on blade heating or other ice removal design solutions.

How: Typically, ice accretion models evaluate the thermodynamics of the freezing process that occurs when super cooled water droplets impinge on an object. The methodologies are typically based on the ice accretion theory presented in the ISO standard 12494 [49] or slightly modified versions of it. Generally, all the current ice-accretion models work in a similar four-stage sequence. First, they solve the flow field around the object. In second stage, the trajectories of the water droplets are calculated and their impingement rate on the object is determined. The third stage takes the surface roughness of the accreted ice and the boundary-layer characteristics into account. Finally, the thermodynamic model determines the amount and the geometry of the accreting ice.

Most of the models are run in a 2D or quasi-3D environment, but fully 3D models have also been developed. A 2D solution means that only one airfoil is simulated, whereas quasi-3D models use 2D solutions to solve for individual airfoils along the blade, and then combine the results to form ice accretion on a complete blade. Quasi-3D solutions do not take into account the 3D flow effects. Fully 3D solutions simulate the blade as a whole and also take the 3D flow effects into account. In 2D and quasi-3D solutions the flow solvers are usually based on the potential-flow equations whereas for fully 3D solutions the Navier-Stokes or Euler equations are used.

The main advantage of using dedicated ice accretion models is that they provide the most realistic and state-of-the-art fluid-structure interaction simulations. The model results can also reduce expensive testing costs in icing wind tunnels or field experiments.

The main challenge is that nearly all available models use slightly different physics models making it difficult for the end-user to know which one is best for a specific purpose. Most simulation models are 2D combined with simplified aerodynamics representations, thus simplifying the real complex flow conditions specifically around rough airfoil surfaces regarding local turbulences. All models lack erosion and sublimation physics.

Table 9. Solutions for simulating ice accretion on wind turbine blades.

Model	Specifications	References
TURBICE	• quasi-3D • potential flow panel method • heating demand calculations for de- and anti-icing • wind power applications • in-house tool *(limited availability)*	Paper: [87] [88] [89] [90] Perf: [87] Other:
LEWICE	• 2D • potential flow panel method • heating demand calculations for de- and anti-icing • aeronautical applications • commercially available	Paper: [91] [92] Perf: [93] [94] [95] Other: [96]
CANICE	• 2D and 3D versions • potential flow panel method *(2D)* • heating demand calculations for de- and anti-icing • research version CANICE2D-NS can be coupled with CFD flow solver	Paper: [97] [98] [99] [100] [101] [102] Perf: [99] [103] [104] [95] Other:

	• aeronautical applications • versions for research and Bombardier Aerospace *(limited availability)*	
TRAJICE2	• 2D • potential flow panel method • aeronautical applications • Defense Research Agency property *(limited availability)*	Paper: [105] Perf: [106] [95]
Multi-Ice	• 2D • potential flow panel method • can interface with other flow solvers • aeronautical applications • in-house tool *(limited availability)*	Paper: [107] [108] Perf: [109] [108]
LEWICE3D	• 3D external flow panel code • can interface with other CFD flow solvers • heating demand calculations for de- and anti-icing • aeronautical applications • commercially available	Paper: [1] [110] [111] Perf: [110] Other: [112]
CERTIF-ICE	• 3D • CFD-code with Navier-Stokes (RANS) • heating demand calculations for de- and anti-icing • aeronautical and wind power applications • commercially available	Paper: Perf: Other: [113]
ANSYS FENSAP-ICE	• 3D • can interface with other CFD flow solvers • heating demand calculations for de- and anti-icing • aeronautical and wind power applications • commercially available	Paper: [114] [115] [116] [117] Perf: Other: [118]
ONERA-2000 / ONICE / ONERA 3D / ONICE3D	• 2D and 3D • CFD • aeronautical and wind power applications • The French aerospace lab property (*limited availability*)	Paper: [119] [120] Perf: [95] Other:

7.2 Empirical ice accretion models

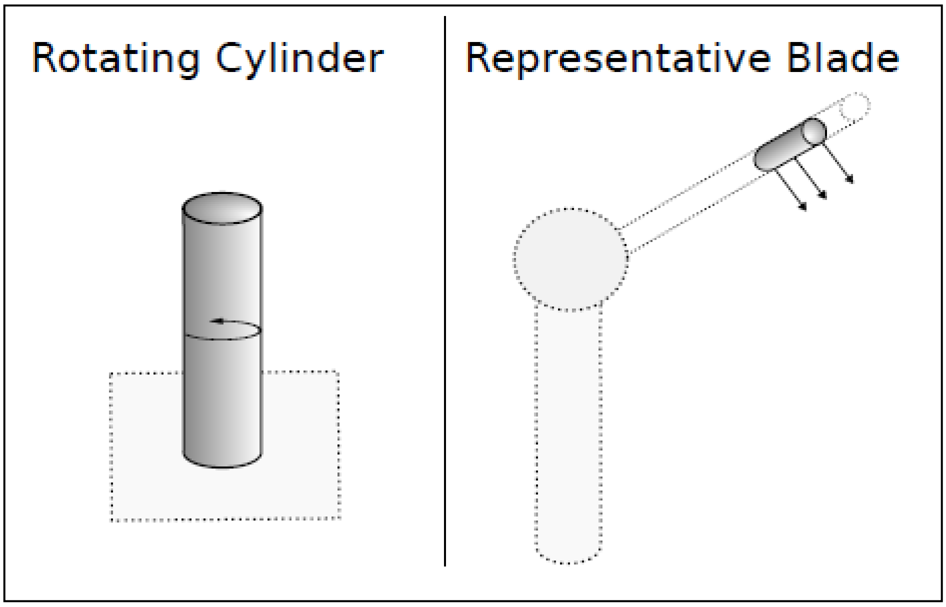

Figure 10: Stationary and blade cylinder (source: [121]).

What: Like the advanced ice accretion models, empirical ice accretion models have been developed to simulate the growth of ice on structures under different atmospheric conditions. However, these models use empirical relationships to solve the flow field rather than using more expensive CFD models. Because of these empirical relationships these models simulate ice growth on cylinders even when more complex structures are actually being represented.

Why: While empirical ice models are not as accurate as the more advanced CFD based icing models, they are able to provide results in a much shorter period of time, and therefore are commonly used when either forecasting icing periods (sec. 10.3), which have a limited time window of interest, or when generating icing maps (sec 5.1), which often need to be run for decades. In both of these cases, a less precise answer provided in less time is useful.

How: The most common icing model is the Makkonen model which is referenced in the ISO 12494 standard [49]. The Makkonen model is a flexible model framework based around three ratios. The collision efficiency is a ratio that describes how many of the water, ice, or snow particles impact the structure being studied. The sticking efficiency explains, the amount of particles that stick to the object rather than bouncing off, and the accretion efficiency is based on how much water can be frozen given the thermodynamic conditions of the atmosphere. By using this general framework, different models of each of those ratios can be used to customize the model for the phenomena being studied. For example, the Makkonen model was recently updated to include a more detailed treatment of wet snow ice growth [122]. This flexibility allows the model to be used for a wide range of icing problems. As simplified accretion models can be run quickly, these models are often coupled to numerical weather prediction

(NWP) models to provide an estimate of the risk under different meteorological conditions.

Table 10 presents different empirical ice accretion models and their main technical specifications.

Table 10. Empirical ice accretion models

Model	Specifications	References
Makkonen Model	• General framework for modelling ice growth • Optimized for rotating cylinders • Included as an appendix to ISO standard • Used as basis for most other empirical icing models	Paper: [123] Perf: [41] [22] Other: [49] [122]
Kjeller Ice Model	• Based on the Makkonen Model • Adjusts cloud amount for errors in NWP terrain height	Paper: Perf: [24] [124] [122] Other: [22] [125]
iceBlade	• Based on the Makkonen Model • Includes rotational speed of turbine blade • Heat transfer coefficient based on airfoils • Cylinder size doesn't change during ice growth	Paper: [41] [126] Perf: Other:
OMNICYL	• Similar structure to Makkonen • Scaled density term • Developed for static cylinders • Also estimates ice shape	Paper: Perf: Other: [127] [121]
WICE	• Based on Makkonen model • Includes rotational speed of turbine blade • Uses the cloud water profile over the entire disc rotor.	Paper: Perf.: Other: [128] [129] [130] [131]
Environment Canada Model	• Includes different models for different types of icing (Freezing rain, wet snow, in-cloud) • May double count freezing rain icing	Paper: [39] Perf.: Other:

7.3 Ice removal models

What: Ice removal models simulate the various natural ice ablation processes. The three types of natural ice ablation processes are sublimation, melting, and wind erosion. Additionally, most ice removal models include a shedding algorithm that is most often related to the melting of accumulated ice. Sublimation and wind erosion both cause a loss of ice even at temperatures below 0 °C, while melting only occurs when the temperature of the ice reaches the melting point.

Why: Ice removal models can provide information about how long ice would remain on the wind turbine. This can help in determining the impact of ice on wind park performance during the assessment phase. When forecasting ice loads, knowing how long the ice will persist can aid in the operation of the wind park, allowing the operator to either down-rate the turbine to accumulate less ice, or activate de-icing systems. With this knowledge, the wind park operator can determine the most cost effective way of preparing for each ice event.

How: Melting and sublimation are both based on the energy balance at the surface of the ice. When there is incoming energy to the ice surface, either through heat transfer, humidity differences, or incoming solar radiation, it will cause the ice to be removed through phase change. When the temperature is above 0°C this will occur through melting, but when the temperature is below 0°C sublimation will occur. In most of the models, the ice is removed from the blade rapidly once melting occurs as it is assumed that the ice de-adheres from the turbine, and be thrown from the blade due to the rotational forces.

Table 11 shows the existing ice removal models.

Table 11. Ice removal models

Model	Specifications	References
iceBlade	• Includes sublimation, wind erosion • No melting as all ice sheds at 0°C • Empirical wind erosion fit to kinetic wind energy	Paper: [41] [126] Perf.: Other:
Environment Canda Model	• Includes melting from net radiation • Included in the accretion model, so both inhibits ice accretion and causes ice removal	Paper: [39] Perf.: Other:
Kjeller	• Includes sublimation, melting, and wind erosion • Wind erosion is a multiplier on sublimation rate	Paper: Perf.: Other: [132]
WeatherTech	• Includes sublimation, melting and shedding • Melting and shedding are based on a threshold temperature • Tested with a simplified de-icing system	Paper: Perf.: Other: [128] [131]
VTT	• Sublimation only • Uses a steady-state heat balance equation	Paper: Perf.: Other: [133]

8 Cold Climate adaptations of wind turbines

Picture source: OWI LAB

In cold climate regions, low temperatures and the risk for atmospheric icing present additional challenges for wind turbine systems compared to 'standard' wind turbines operating in moderate climates. The operational limit of a standard wind turbine is set to –20°C, but most manufacturers have cold climate adaptations of their technologies that allow wind turbines to operate at temperatures as low as –30°C and remain structurally safe even at –40°C [134] [135]. Some OEM's even guarantee structural, operational or start-up performance below -40°C [136]. For most cold climate sites this temperature specification is sufficient. Cold temperatures can cause problems and failures if not properly taken into account, therefore cold climate adaptations have been introduced in the market. These adaptations include using different materials and lubricants, modified control strategies, additional heating for certain components, and anti and de-icing technologies to allow the rotor blades to cope with icing events [137] [138].

With respect to low temperature applications, material choice is important because the changes in physical properties due to cold might impact the reliability and safety of the machine [139]. Also ice accretion on structures and surfaces becomes an issue that needs special attention. Cold climate packages have been developed and marketed, in order to extend the operational and standstill temperature ranges of the wind turbine, and to ensure safe and reliable operations in cold climate locations.

8.1 Low temperature adaptations

What: Cold weather packages include low temperature adaptations for all components in a wind turbine. Examples of low temperature adaptations include the use of low temperature oil and greases, different material choices than used for standard wind turbines, heated sensors, additional sealing of the nacelle, specific heated turbine components, and many more [140].

Why: Low temperatures adversely affect the different materials that are used in wind turbines. The mechanical properties of steel, composite materials, polymers, grout, and concrete – are all subject to physical changes as the temperature changes [75]. At low temperatures, materials tend to become brittle (reduced ability to deform without damage) and become less tough (capacity to absorb energy upon impact, as expressed by the Charpy value). Differential thermal expansion of materials must also be addressed with respect to low temperatures. Certain components may have high internal temperatures when starting up while the outside is still cold, for example, bearings need to be able to cope with differential thermal expansions with respect to their tolerances. Composite materials, for example those used in the rotor blades, can have unequal shrinkage of the fibre/matrix components leading to residual stress.

Micro-cracking can occur if the stress is sufficient and if this phenomenon is not taken properly into account. This potential failure applies not only to rotor blades, where both stiffness and impermeability are reduced, but also to electrical equipment that use isolation resin. Concrete or grouted structures [141] in a wind turbine need to be adapted for cold climates, as thermal cracking can affect the permeability of the structure and increase the risk for water infiltration, with an associated higher risk of corrosion.

Low temperatures can also damage electrical equipment such as generators, yaw and pitch drive motors [142], transformers, etc. When starting up a pitch drive in cold conditions, damage can occur in the stator due to the sudden increase in heat and the resulting differential thermal expansion in the cold machine. If not properly taken into account during the design, this can ultimately lead to failure or a decreased motor lifetime.

In liquid-filled transformers, heat generated by the internal losses generated inside the transformer windings may not be evacuated fast enough in cold-start scenarios [143]. Liquid filled transformers can be cooled down to -30°C or even -40°C depending on their location in the wind turbine, which can be either outside, in the base of the tower, in the mid-section of the tower, or in the nacelle. Due to the higher viscosity of the cooling liquids at such low temperatures, the natural convection cooling of the internal windings may be limited, as the oil is too stiff to circulate and loses its ability to remove heat [143]. Not only do liquid-filled transformer designs have additional reliability and safety risk in low temperatures, but cast-resin transformers are also at risk. In cast-resin transformers, the resin of the transformer windings can become brittle at cold temperatures and thermal stresses can cause micro-cracks.

Gearboxes, bearings, pitch and yaw systems and hydraulic components also suffer when exposed to cold weather. When temperature drops, the viscosity of the lubricants and hydraulic fluids increases up to a point when the oil is too stiff to be pumped (high pump loads), making it unable to lubricate gearboxes and bearings sufficiently. Insufficient lubrication of such components can damage gears in seconds if the oil is too thick to freely circulate. Also a higher viscosity of lubricant reduces the power transmission capacity of the gearbox and thus negatively impacts efficiency [144].

Seals for components dealing with oils and greases also need special attention during design to prevent leakage, as they tend to lose their flexibility at low temperatures.

How: The checklist in Table 14 describes the adaptations and modifications that are typically found in cold weather packages. As stated, cold weather packages vary depending on the turbine manufacturer, as does the type of technology used to cope with specific low temperature challenges. The checklist in Table 14 could be used by developers to ensure that their cold climate adapted wind turbines are compliant with the challenging environmental conditions that occur on such sites

Advantage:

Low temperature adaptations and cold weather packages ensure an increased availability and reliability for wind turbines in cold climate sites. As production yield in winter time is typically good due to high average wind speeds and a higher air density, such customization for cold climate is beneficial for production revenues [145].

Challenge:

Although cold weather packages are beneficial for cold climates, they also require additional power consumption for heating the nacelle space and other turbine components. Lowering this power consumption and reducing cold-start times by using new control strategies that increase the efficiency and re-energizing time of the turbine are still challenges today. During the site evaluation, one should evaluate if such adaptations will pay-off based on historical climatic data.

8.2 Ice protection systems of wind turbines

Figure 11. Blade without (left) and with (right) ice protection system (source: VTT)

What: Ice protection systems for wind turbines are focused on mitigating ice build-up and its associated risks for turbine blades. Historically, different ice protection systems have been developed by research institutes, independent system providers, and turbine manufacturers since 1990s.

Why: Ice protection systems for wind turbine rotors have been developed to mitigate the risks of ice induced reduced production, including increased noise emissions and ice throw. Severe reduced production due to icing have been reported not only in Scandinavia and Canada, but also in moderate climates, such as, Spain, Portugal, the United Kingdom, and the Czech Republic. Ice on turbine blades can increase noise emissions, potentially violating building permit regulations. Ice throw can create a safety hazard for people in the vicinity of the iced turbines thus ice throw risks need to be managed and mitigated.

How: Ice protection systems can be divided to active (anti- [AI] and de-icing [DI] systems and other systems) and passive (coatings or no action).

For active systems, anti-icing is defined as a method to prevent significant ice formation on wind turbine blades while allowing the turbine to operate normally. De-icing is defined as allowing ice build-up on blades followed by a shutdown of the turbine, and then activating the ice protection system to remove ice. Other ice protection systems include e.g. preventative shutdowns of turbines and safety related curtailment or stops.

Technology alternatives

Here is listed the available ice protection system technologies

- Hot air ice protection systems have a heat source combined with a high powered fan to circulate hot air to different areas of the blade.
- Electro-thermal ice protection systems have heating elements, typically carbon fibre, placed on the outer surface on the blade.
- Microwave ice protection systems have a special outer coating on the blade surface that heats up when exposed to microwaves created by generators inside the blade.
- Passive systems use blade coatings with special material properties to passively (no energy required) mitigate ice induced risks.

- Mechanical removal systems include rope access or skylift manual de-icing and helicopter de-icing using hot liquids.

Most ice protection systems are controlled using a power curve detection method, using dedicated ice detectors on the nacelle or blade or a combination of these (Table 8). The power curve detection typically requires the nacelle temperature to be below 0°C, and requires a simultaneous underperformance from the expected power curve. Dedicated ice detectors, used for ice protection system control, are typically mounted on top of the nacelle. Some first studies using blade ice detectors are being done in near future.

Table 12 presents different ice protection systems divided by method and technology alternatives.

Table 12. Overview of different ice protection systems

Solution	Advantage	Disadvantage	References
Method			
Anti-icing (AI)	+ maximum AEP gain + prevents most ice from forming + no turbine stops required	- may require a lot of power from rotating hub - few technological options -	Paper: [146] [147] Perf. [148]: Other:
De-icing (DI)	+ many technological options + less power required than AI	- turbine stoppage required resulting in AEP losses - allowing ice build-up may increase turbine vibrations and noise	Paper: [146] [147] Perf.: [148] Other:
Technology alternatives			
Hot air (AI/DI)	+ simple, robust, long history + retrofit options for certain blade types + lightning risks small	- mostly DI, AI options limited - low efficiency: long distance from heat source to blade tip, and heat has to travel through the blade material to reach the blade surface	Paper: [146] [147] Perf: [149] [150] Other: [151] [136] [137] [152] [153] [138] [154]
Electro-thermal (AI/DI)	+ optimized power consumption: close to blade surface and can have spanwise heat control + long track record	- additional work to implement to blade manufacturing process - increased lightning risk - expensive repairs if damaged	Paper: [146] [147] Perf.: [155] [156] Other: [157] [158] [159] [160] [161] [162] [163] [164] [165] [166] [167]
Microwaves (AI/DI)	+ optimized power consumption + wireless, repair-friendly	- unproven in field - difficult to implement on the blade -increased lightning risk	Paper: [146] [147] Perf.: Other: [168] [169]

	+ minor radio/radar disturbance		
Mechanical removal	+ no initial investment to AI/DI systems + service providers available, buy-when-needed	- potentially expensive - potential damage to blade - potential long waiting time - health and safety issues for workers	Paper: Perf.: Other: [170] [171]
Coatings	+ low investment cost + easy to implement + no energy required + retrofit options	- non proven on turbines - lifetime non proven in lab - non proven efficiency for ice prevention and removal	Paper: [146] [147] [172] [173] [174] [175] [176] Perf.: [177] [178] [179] Other: [180] [181] [182] [183] [184] [185] [186]

8.3 Control system for operation in icing

Figure 12. Mont Copper Wind Farm, Canada, photo credit: Antoine Amossé, TechnoCentre éolien

What: The control system of a wind turbine (WT) may be modified such that its behaviour is different during icing conditions. The WT controller may change certain parameters, activate an ice protection system, curtail production, or stop completely.

Why: Changing WT control settings during icing conditions can be done in order to reduce aerodynamic penalties or reduce the risk of fatigue and/or extreme loads on the turbine and its components due to icing. They can also be modified in order to reduce the risk of ice throw.

How: First, the WT controller must be able to determine the presence of ice. Different ice detection methods are used by different OEM's (as seen in Table 15) ranging from nacelle based methods, power curve deviation or rotor ice sensors.

Power optimisation - Ice build-up on the rotor leads to reduced efficiency of the WT. Changing parameters such as pitch, tip speed ratio and/or torque can reduce stall due to icing and keep the turbine operating throughout an icing event.

Preventive stops - A preventive stop strategy consists of shutting down the WTs at the onset of an icing event in order to minimise ice accretion on blades, which is known to be worse when the rotor is turning, and resume production when the meteorological event is over. The underlying principle behind preventive stops is that the WTs will have a greater overall energy yield compared to running them throughout the icing event. At the moment, this strategy seems to be controlled manually by the wind farm operator.

Load reduction - The WT may also be limited in certain cases of severe icing in order to reduce the risk of fatigue and/or extreme loads on the turbine and its components due to icing.

Control strategy for ice protection system - All active ice protection systems provided by OEMs require a certain level of control from the turbine. Some ice protection systems, usually de-icing systems, will only be activated once the WT is stopped. While some anti-icing systems may operate independently from other turbine controls and parameters, they still may require the turbine to stop in specific, often severe icing conditions. It is also noted that certain OEMs offer farm level power consumption management to limit the overall consumption of the wind farm “in order to ensure net stability and avoid unnecessary fees” [151].

Ice throw risk mitigation - Certain WTs, due to local regulations, insurance obligations or to avoid liability, may shut down during icing events due to risks associated with ice being projected from the rotor while it is in operation. In these cases, the WT may have a designated operation mode for ice throw risk mitigation.

Table 13: Summary of turbine control options for operation in icing climate

Solution	Specifications	References
Power optimisation	• Pitch and tip speed ratio adjustments to increase power output during icing events	Paper: Perf.: [187], [188] Other:
Preventive stops	• Stop wind turbine during meteorological icing to get better power output after active ice accretion is done	Paper: Perf.: [189], [190] Other:
Load reduction	• Limit power output to ensure structural integrity	Paper: Perf.: [187], [191] Other:
Control of ice protection system	• Ice protection system control built in to SCADA	Paper: Perf.: [153] Other: [131]
Ice throw risk	• shutdown to reduce risk perimeter around the WT during icing events	Paper: Perf.: [192], [187]

mitigation		Other:

8.4 Summary of Cold Climate turbine adaptations

Figure 13: Olos fjell wind farm in Northern Finland (source: VTT)

Table 14 is provided as a checklist for developers to assist them in verifying that the cold climate packages being offered to them by wind turbine manufacturers meets their requirements regarding cold climate adaptations.

Table 14: Cold Climate Adaptations checklist

Low Temperature Features	
Additional nacelle and up-tower sealing and insulation	
Adapted safety and control strategy for cold weather shutdown and cold start-up	
Pre-heating and heating strategy in general	
Cut-off / cold weather shutdown at certain temperature limit	
Reduced power output at certain low temperatures	
Cold start-up	
Grid outage	
Additional heating systems on the following components:	
Nacelle space (including nacelle insulation)	
Yaw and pitch motors and cabinets	
Gearbox and lubrication unit	
Generator	
Slip ring	
Control cabinets	
Battery	
Special materials for low temperatures	
Special low temperature alloys materials for machine hub, tower and drivetrain components	
Special welding procedures	
Special concrete mixtures and grout solutions and installation procedures	
Special low temperature elastomers for seals, dampers, etc…	
Low temperature lubricants (synthetic), greases and hydraulic fluids	
Wind Sensors	
Bearing heated cup anemometer	
Partially heated anemometer	
Fully heated anemometer	
Ice Detection Sensor/Method	
Hub height ice detection	
Sensor/method 1:	
Sensor/method 2:	
Sensor/method 2:	
Blade ice detection	
Sensor/method 1:	
Sensor/method 2:	
Sensor/method 2:	
Ice Protection Systems	
Method: Anti-icing (AI) and/or De-icing (DI)	
Technology: Hot Air, Electro-Thermal, Coating, other (Specify:)	
Control System Features for Icing Climate	
Pitch	
Tip speed ratio	
Torque	
Turbine status/control based on icing severity classification	
Extreme ice load risk mitigation strategy	
Control strategy depending on ice throw risk assessment	
Farm level power consumption management (for turbines with ice protection system)	
Other features (specify here)	
ice throw risk mitigation	

Table 15 summarizes all turbine manufacturers that responded a detailed questionnaire sent by IEA WIND Task 19. Acciona, Alstom, GE, Gamesa, ENO Energy, Goldwind, Mervento, Sinovel and Vensys did not respond the questionnaire. The table summarizes when an original equipment manufacturer (OEM) released their first prototype, the cumulative quantity of turbines with a low temperature climate (LTC) technologies in megawatts, the ice detection (ID) method used and if the turbine technology has a specific SCADA control setting during icing, also known as an ice operation mode (IOM). The table also lists the method of ice protection system used, the year of the first prototype installation, and the cumulative capacity of turbines with the ice protection system, in installed MWs.

Table 15. Summary of available turbine manufacturers with cold climate solutions

Turbine OEM	**LTC**		**ID**	**IOM**	**Ice Protection System**			**References**
	1st proto	**MW**			**Method**	**1st proto**	**MW**	
Dongfang	2010	1000	NI + TH + PC		ET+HA	2014	100	Paper: Perf: Other: [193]
Enercon	2011	1400	PC	x	HA	1996	3100	Paper: Perf: [149] [150] [194] [195] [196] [197] [198] Other: [151] [136] [137] [199] [200]
Lagerwey	2009	20	TH & NI	x	PS	2015		Paper: Perf: Other: [201]
Nordex	2009	1300	NI & BF	x	ET	2011	600	Paper: Perf: [155] [202] [203] Other: [160] [161] [204]
Northern power systems	1999	5	PC	x	BB & IPC	1999	5	Paper: Perf: Other: [205]
Senvion	2007	1300	PC + NI, NI	x	HA	2013	140	Paper: Perf: Other: [187] [206] [207] [208]
Siemens	1994	6500	NI		ET	1994	800	Paper: [209] Perf: [156] Other: [162] [163] [164] [165]

Vestas	2007	6200	PC & BF	x	HA	2014	90	Paper: Perf: Other: [152] [153] [138] [154]

PC = Power Curve ice detection
NI = Nacelle based ice detection
TH = Temperature and humidity
BF = Blade frequency ice detection (or just rotor blade)
HA = Hot air ice protection system
ET = Electro thermal ice protection system
BB = Black blades
IPC = Ice phobic coating
PS = Preventive shutdown

8.4.1 Independent ice protection system providers

Figure 14: Retrofit electro-thermal ice protection system (source: ADIOS)

What: Independent ice protection system providers are 3rd party companies that are not wind turbine manufacturers. Independent ice protection system providers typically provide ice protection systems to various turbine manufacturers. One technology option, provided by independent system providers, is retrofit ice protection systems. These are an important technology option for turbines that have been built in icing conditions, but lack factory installed ice protection systems. The current retrofit solutions provided by independent suppliers require heating. Passive retrofit solutions mainly encompass icephobic coatings, but these solutions are not listed here due to their low technology maturity level (for more information. Please see Table 12).

Why: Several sites in Scandinavia and Canada are suffering from moderate to heavy icing related challenges. By installing retrofit ice protection systems, some of the icing challenges can be mitigated.

How: Active retrofit ice protection systems, which require heating, are typically peel-and-stick electro thermal tape-like solutions that are installed on the leading edge of the blade. When in operation, electricity is conducted from the hub to the heating elements to prevent or remove ice.

Table 16. Summary of independent ice protection system providers

Solution	Technical specifications	References
GreenWindGlobal (EcoTEMP)	• Electro thermal heating elements • Retrofit or factory peel-and-stick installation	Paper: Perf.: Other: [210]
Kelly Aerospace	• Electro thermal heating elements • Retrofit or factory peel-and-stick installation	Paper: Perf.: Other: [211] [212] [213] [214]
Adios	• Electro thermal heating elements • Retrofit or factory peel-and-stick installation	Paper: Perf.: Other: [215] [216]
Wicetec	• Electro thermal heating elements • Factory installation pre-fabricated elements inside blade	Paper: Perf.: Other: [157] [158] [159]

9 Assessment of Ice Throw and Ice Fall

Ice builds up on wind turbines during periods of meteorological icing (defined in section 4). The amount of ice accretion depends on the meteorological conditions and the operational mode of the wind turbines.

When this ice de-adheres from the blade, most commonly when the temperature increases above 0°C, or due to activation of a rotor blade heating system, ice fragments are either thrown (from a rotating blade) or drop from the blade (at standstill). Consequently, national authorities distinguish between ice throw and ice fall. However, falling ice fragments can cause harm to persons present in the danger zone, in either case. For turbines with rotor blade heating systems, the activation time of the de-icing system can be controlled to a certain extent.

Despite on-going and more recently finished projects, the so called Gütsch-Study [217] is still one of the most comprehensive publications with regard to the observation of ice throw events. The results of four winter seasons showed the ice throw direction to have a clear dependency on the prevailing wind conditions during icing events, and gave indications on preferred rotor positions for ice throw. It also showed that most ice fragments hit the ground directly underneath the rotor area. Figure 15 shows the distance and weight distributions identified in the Gütsch study.

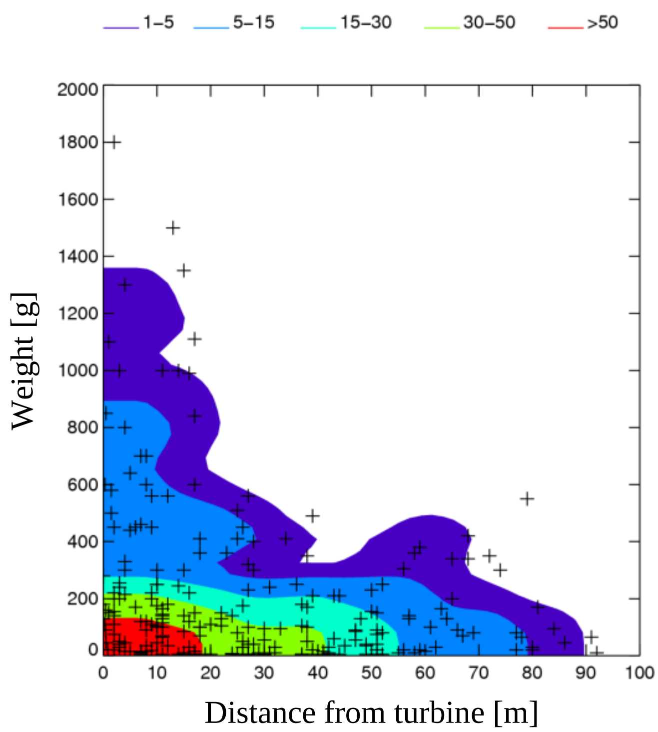

Figure 15: Distance and weight distribution for ice fragments, identified in the Gütsch study. A clear dependency between weight and distance is visible. [218]

As the investigated wind turbine at the Gütsch site is rather small compared to modern wind turbines, and since it was installed in an alpine location, it has to be questioned to what extent these results can be transferred to larger wind turbines and other locations. In addition, the difference between ice fall and ice throw was not included in the study.

According to the legislative requirements in most countries, the danger of getting hit by ice fragments needs to be assessed during the planning phase. The aim of this requirement is to minimise accidents, and to ensure that the risk to people passing through the area surrounding the wind turbine is lower than the commonly accepted risk. A rough overview of the legislative requirements of the partner countries in IEA Task 19 can be found in [219] [220].

In general, either empirical formulas or ballistic models are used to assess the danger zone around wind turbines. The following empirical formulas are commonly used to identify the maximum possible distances for ice throw and ice fall [221], [222].

For 'Ice Throw': $d = 1.5(D + H)$

For 'Ice Fall': $d = v\frac{(\frac{D}{2}+H)}{15}$

d = Maximum falling distance of ice fragments [m]
D = Rotor diameter [m]
H = Hub height [m]
V = Wind speed at hub height (maximum 10 minutes' average) [m/s]

When using the empirical formulas, only the maximum distances for ice throw and ice fall are calculated. It is not possible to determine the actual risk level for people near the wind turbine. In many cases, the usage of empirical formulas is linked to specific requirements (e.g. warning signs/lights along roads must be placed further than the calculated distance).

In addition to the empirical formulas, Ballistic Computer Models are commonly used to determine the actual risk level for areas around the wind turbine. These models simulate the trajectories of ice fragments that are either thrown away from a rotating blade or dropped off a blade at standstill. Based on the type of wind turbine and its operational mode, risk zones can be calculated for the area surrounding the wind turbine, taking into account the prevailing meteorological conditions (i.e. wind speed frequency distribution and wind direction distribution, as well as the number of icing events per year and the icing intensity). The ballistic models provide their results in terms of the probability of ice fragments hitting the ground [per m^2].

In a second step, this probability of hits per m^2 is linked with the probability of having a person at the specific spot. From this, the likelihood of a damage event can be calculated. The extent of loss is in most cases defined as the death of a person from being hit by an ice fragment. Therefore, the minimum size and weight of an ice fragment that would result in a person's death has to be defined.

Finally, the calculated risk levels (i.e. the extent of loss times the probability of occurrence) need to be compared with the so called commonly acceptable risk level. The thresholds for the commonly accepted risk vary from 10^{-4} to 10^{-6}. A typical approach to determine the acceptable risk is the ALARP (As Low As Reasonably Possible) principle, which is recommended in the UK Health and Safety law [223].

In many cases, modifications to the standard operation of the wind turbine are required to reach the required level of risk (e.g. shutting down turbines with iced-up blades to avoid ice throw). The detailed risk assessments can also be used to provide other safety measures, such as warning signs or lights. However, in many countries, authorities require the use of additional measures according to fixed patterns (e.g. warning signs and flashing lights at the entrance point of the wind farm). The actual effectiveness of different measures is difficult to assess. For this discussion not only technical, but also legal aspects need to be taken into account. More information about possible measures can be found in section 10.1.

Advantages/challenges of empirical formulas and detailed risk assessment

The main advantage of empirical formulas is that no detailed investigation of the site-specific conditions is required. Therefore, they can be applied very easily. The major drawback of the formulas is the fact that crucial parameters like the icing intensity of the site or the likelihood of peoples' presence around the turbine are neglected. Furthermore, the formulas do not provide the resulting risk level and do not consider wind and icing conditions at the site.

A site-specific risk level, and its comparison with the commonly accepted risk, has become a legislative requirement in many countries. This requires the use of ballistic computer models. Also, the selection of useful measures to further reduce the risk can be assessed, to a certain extent, using this risk level. However, up to now there is no clear standard defining the parameters or the detail that needs to be considered. Open questions are the preferred blade position for an ice fragment to be thrown off the blade (upward or downward motion of the blade), the typical shape of an ice fragment and its flying characteristics, and the effect of ice break-up while flying through the air. Finally there is a clear lack of validation data for the simulation results. (see [224].)

The pros and cons of the two approaches are listed in the following table:

Solution	Advantage	Disadvantage	References
Empirical formulas	+ Fast, long history + Easy to understand + Widely used by authorities	- Does not provide the actual risk level - simplistic and inaccurate - Site-specific conditions cannot be considered	Paper: [221] [225] [226] [227] [228]
Ballistic models	+ Results can be used as a basis for risk assessments compared to accepted risk levels + Site specific conditions can be considered + precise	- Mathematical model required (e.g. Monte Carlo Simulation) - No established standards- not validated	Paper: [224] [229]

Table 17. Solutions for assessing ice fall and ice throw from wind turbine blades

Case example: Comparative Results for Ice fall and Ice Throw

Figure 16 illustrates the danger zones for an ice-fall-event (left) and an ice-throw-event (right). The empirical formula results are presented as a red circle with no further information about the corresponding risk level. The coloured areas indicate the results of a ballistic model simulation, in terms of the probability of ice fragments hitting the ground per m^2. The strong dependency from the locally predominant wind directions is clearly visible.

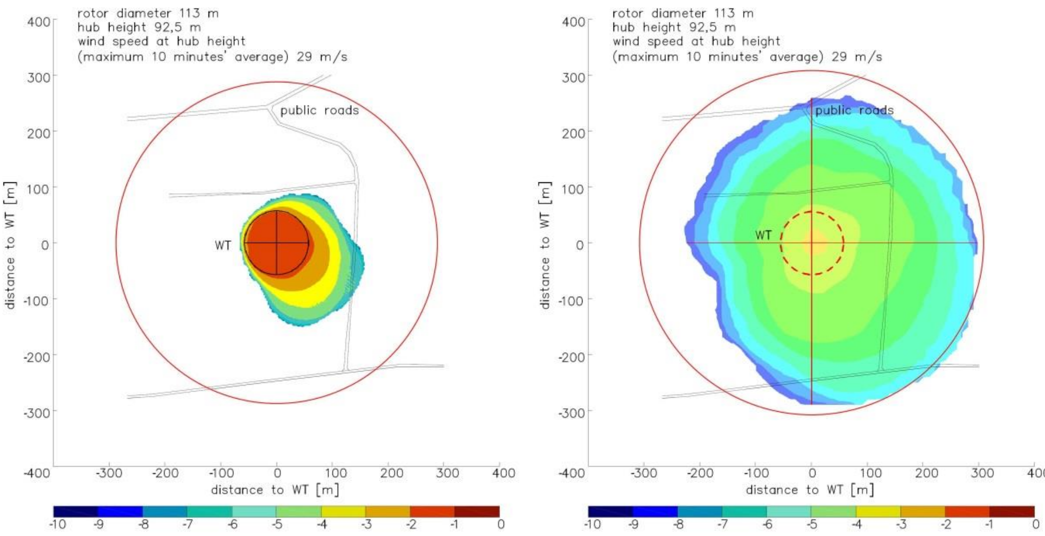

Figure 16: On the left hand side, the results are presented for 'Ice Fall', on the right hand side for 'Ice Throw' for the same amount of ice fragments.

10 Operation and Maintenance

This chapter will discuss available technologies to mitigate risk associated with ice throw, methods to access turbines in the winter as well as how ice forecasting can be used in an O&M strategy.

10.1 Ice throw risk mitigation

What: Technologies that help protect service staff as well as the general public from the risk of injury due to ice fall from turbines.

Why: When placed in icing climates, ice will inevitably form on a wind turbine. Therefore, safety concerns associated with falling ice must be addressed.

How: Under the right conditions, the risk of injury for staff and the public due to pieces of ice thrown from a WT is increased. This increased risk, might prevent operation of a WT. The risk can be mitigated through the use of warning signs, warning systems, de- and anti-icing systems, vehicle shelters near the WT entrance, shutting down the WT, or by preventing access to the site.

Table 18: Summary of ice throw risk mitigation strategies

Mitigation strategy	Advantages	Disadvantages	References
Warning signs	Low cost, identifies beginning of risk zone	Can be ignored	Paper: Perf.: [230], [231] Other:
Warning systems (e.g. lights, sirens)	More difficult to ignore Can warn only when the risk is present	Higher cost to implement	Paper: Perf.: [230], [231] Other:
SMS Warning System	Notifies staff or neighbours when there is a risk	List management, people not on SMS list won't get warnings	Paper: Perf.: [230] Other:
Forecasts	Advanced warning can enable better O&M planning	Possibility of false alerts and missed events	Paper: Perf.: [230], [231] Other:
Ice Protection Systems	Reduces risk of ice throw	Does not prevent ice throw or ice fall from areas of blades, nacelle, and tower without IPS	Paper: Perf.: [231] Other:
WT shutdown during icing event	Reduces risk zone	Loss in energy production, requires reliable ice detection	Paper: Perf.: [231] Other:

Reinforced roof on vehicles	Staff can approach or drive near iced turbines	Staff cannot leave vehicles without additional protection when in risk zone	Paper: Perf.: [232] Other:
Reinforced roof over turbine access door	Staff can access turbine (provided they can safely approach turbine)	Additional expense	Paper: Perf.: Other:
Mobile Protective Roof	Staff can access turbine (provided they can safely approach turbine) Only need one for several turbines	Requires towing between turbines	Paper: Perf.: [233] Other:

10.2 Road and turbine access

What: Different types of vehicles available for accessing wind turbines during the winter, particularly in locations with significant snowfall.

Why: Significant snowfall can make access to wind turbines, for planned or unplanned maintenance, difficult or even impossible with regular service vehicles. A snow removal strategy may not be a financially feasible solution.

How: A cost/benefit analysis must be done to determine whether it is better to employ a snow removal strategy or to equip the service team with specialised vehicles. This analysis should account for parameters such as the cost of solutions, distance travelled (number of km of access roads), estimated annual snowfall accumulation and frequency, Health & Safety, training, etc. According to a survey conducted by the TechnoCentre éolien among Canadian wind energy operators in 2014 [232], most respondents use a combination of solutions.

A snow removal strategy (Figure 17) may enable regular vehicles (fitted with winter tires) to access wind turbines. When a complete or partial snow removal strategy seems excessively expensive, specialised vehicles may be part of the solution. These include tracked vehicles (Figure 18), snow mobiles and regular service vehicles fitted with special tracks (Figure 19). Advantages and disadvantages of these solutions are provided in Table 19.

Innovative solutions have also been developed to enable unplanned maintenances of power lines and padmount transformer replacements during the winter months (Figure 20). GDF Suez has developed a mobile ice roof that can enable access to turbines even when there is a risk of ice shed, as seen in Figure 21, [233].

Figure 17: Snow removal allows for easy access to turbines with regular service vehicles but can be very expensive [232]

Figure 18: Examples of tracked vehicles (snow cats) used to access wind turbines [232]

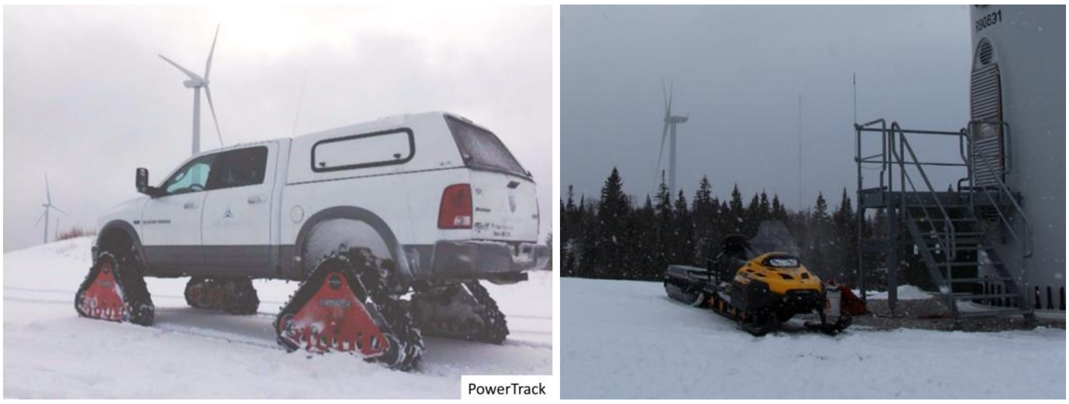

Figure 19: (Left) Service vehicle fitted with tracks, (Right) Snowmobile [232]

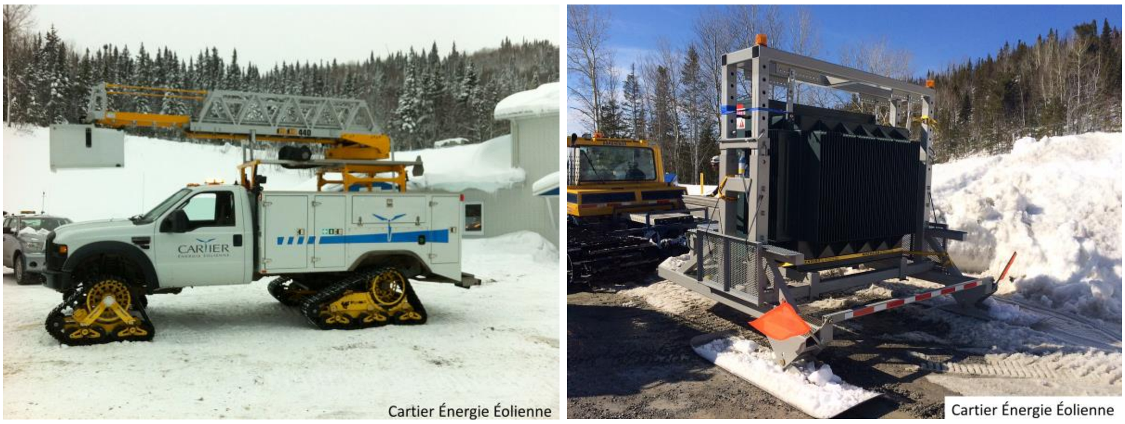

Figure 20: Innovations by Cartier Énergie Éolienne to reduce costs associated with unplanned maintenances in the winter [232].

Figure 21: Mobile roof built by GDF Suez at Caribou wind parc to access wind turbines requiring maintenance when there is a risk of ice throw [233]

Table 19: Summary of wind turbine access options during winter

Solution	Advantage	Disadvantage	References
Snow Mobile	Quick access to turbines	Requires experienced / trained users Limited solution in heavy snow and/or steep access roads	Paper: Perf.: [232] Other:
Special Tracked Vehicle	Highly reliable in most snow conditions	Can be slower	Paper: Perf.: [232] Other:
Tracks Fitted to Truck	Use of regular service vehicles	Limited reliability in certain snow conditions	Paper: Perf.: [232] Other:
Snow	Use regular service vehicles	Can cause delayed access to	Paper:

Removal	(with winter tires!) Makes safety evacuation procedures easier	turbines during or shortly after a snow storm	Perf.: [232] Other:

10.3 Icing forecasts

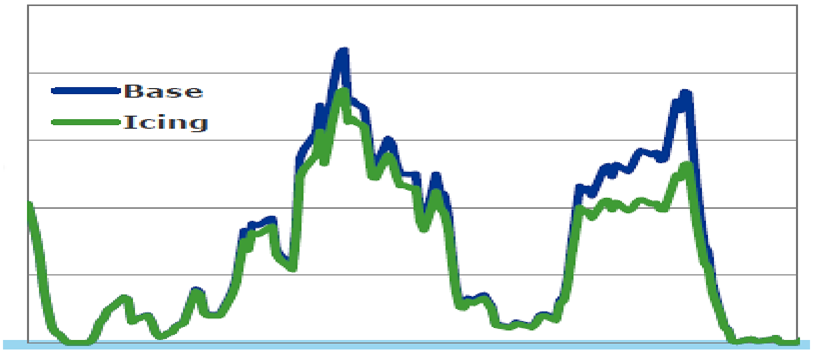

Figure 22: Power prediction with icing forecast information included (Source: [234])

What: A site-specific forecast of ice occurrence, ice loads, and icing intensity at a wind park for the next 1 to 8 hours (short term forecast) or for the next 24 to 96 hours (day ahead forecast), provided at least once a day, but preferably updated more frequently.

Why: With a large penetration of wind energy, accurate production forecasts increase in importance in order to keep the grid stable and to sell the energy on the spot market. During light to moderate icing events, the forecasted power will be too high if icing impacts are not taken into account. During strong icing events, the influence of icing on wind energy production can be seen as a special kind of ramp, where power production quickly drops, or even comes to a full stop within short time. If this occurs at a large wind park, there will suddenly be much less energy available than was expected, which can reduce grid stability. This can be predicted by relating the wind parks power production to a prediction of the ice mass and ice duration. Some companies are already using icing forecasts in order to enhance their power production forecasts [121]. Depending on the forecast horizon, icing forecasts can also support the planning of wind park maintenance, inform the public of potential safety risks, and guide the operational strategy during an icing event. In addition, some icing forecasts also include forecasts of ice removal. This can help in the operation of de-icing technology as it will allow the wind park operator to determine if it is worth turning on the de-icing tools.

How: In order to forecast icing, different approaches are used. There are physical and statistical models. On the one hand, the physical models try to capture all processes that lead to icing and incorporate the physical relationship into one formula [124]. The basic background of the physical model is typically a numerical weather prediction model, as described in section 5.2, coupled with an ice accretion model, as described in section 7.2. On the other hand, statistical approaches simulate the empirical relationships between icing and multiple predictors. These models converge (approximate) the empirical relationship between input (numerical weather prediction model) and output (icing) parameters, using regression, clustering, and classification methodologies. The outcome of statistical approaches can be either a deterministic forecast (single-valued) or a probabilistic forecast [235]. The probabilistic forecast assigns a probability to each of a number of different outcomes. This is also called ensemble forecast.

A combination of physical and statistical approaches is also possible. With the availability of site-specific measurements (SCADA data, cameras etc.), statistical methods can be also used to post-process and improve the accuracy.

Table 20. Solution for icing forecasts

Solution	Specifications	References
Physical approach	- NWP model and ice accretion model - The majority of accretion models are developed for static cylindrical objects	Paper: [124] [236] [237] [238] Perf.: [239] Other: [240]
Statistical approach	- NWP model and Statistics - It could be deterministic forecast or probabilistic forecast (ensemble forecast) - Need for a large amount of historical data - Need for computing power - The physical relationship is hard to understand	Paper: [241] Perf.: [235] Other: [242]
LOWICE	- Combines the power of icing-relevant observations and numerical model output - Estimate critical icing parameters at hub height - LAPS-LOWICE produces hourly, 3-km grids of icing-relevant fields across Scandinavia, based on FMI’s version of the Local Analysis and Prediction System (LAPS) model	Paper: [243] [244] Perf.: Other:

Table 21: Companies providing icing forecasts

Company	Description	References
Kjeller Vindteknikk	- Physical approach - Icing forecast up to 48 h as a map (icing intensity, ice load, ablation, wind farm power loss, wind farm ice risk zones)	Paper: Perf.: Other: [240]
Finnish meteorological institute	- Day ahead icing forecasts for icing conditions	Paper: Perf.: Other: [245]
Swedish meteorological and hydrological institute	- Day ahead icing forecasts for icing conditions	Paper: Perf.: Other: [246]
Vortex	- Statistical approach - Long term icing forecast	Paper: Perf.: Other: [247]
WeatherTech	- Blended physical and statistical approach	Paper: Perf.: Other: [248]
Leading Edge Atmospherics	- LOWICE	Paper: Perf.: Other: [249]
DNV GL	- Statistical model - Day ahead icing forecast	Paper: Perf.: Other: [234] [238]

11 Standards and Certification

What: Standards and certification processes in wind energy are used to ensure safety and performance of wind turbines and other technological equipment. International standards are needed to ensure minimum design and safety requirements for wind turbines and other technological products, to serve as fair, best practice guidelines, and to ensure sufficient quality of the design for funding sources, such as banks. Independent certification bodies ensure that the product specifications provided by the original equipment manufacturers meet the expected performance. On a general level, the current maturity level for most relevant international standards and certification processes is low, with regard to specific cold climate wind challenges. However, issues related to cold climate challenges are being investigated for inclusion through an updating process of some international standards and certification that is currently on-going.

Why: Certifying wind turbines for cold climate regions requires reliable procedures for predicting the amount of ice accretion during standstill and operation. Low temperature climates may require the installation of cold climate versions that include special components, materials, lubricants, etc. Iced turbine operation may cause additional wear-and-tear of components and reduced production (operational and standstill related) thus specific, iced turbine load cases are important.

How: Some international design standards and certification guidelines take cold climate effects into account by having lower temperature requirements than standard climate turbines, and possibly taking icing load cases into consideration. To date, no specific cold climate wind standard exists, and, for certification, only the Germanischer Lloyd (GL), today known as DNV GL, guideline for low temperatures is available.

IEC 61400-1 ed4 “Wind turbines – Part 1: Design requirements” is currently under revision and is an update to the ed3:2005 (amended 2010) standard [3]. This standard covers the structural integrity of a wind turbine design. The new revision will include many cold climate related updates, e.g. new iced turbine design load cases and a cold climate turbine class.

IEC 61400-3 ed1 [250] “Wind turbines - Part 3: Design requirements for offshore turbines” from 2005 took into account sea ice load effects on fixed and floating foundations in a very general manner. The latest IEC 61400-3-1:2015 is in a Committee Draft for fixed offshore foundations and has more extensive sea ice assessment requirements.

GL Technical Note 067 rev4 [251] includes supplementary information to previous GL Technical Notes [252] and [253], this includes various assessments and indicators for low temperature sites and the requirements for wind turbines operating in these regions.

A GL Technical Note on Blade Icing is currently under preparation, and it will be an extension to IEC 61400-1 ed4 regarding the assessment of blade icing impacts on turbine structural integrity

ISO 12494:2001 [49] describes the general principles of determining ice load on structures for applications such as met masts, towers, antennas etc. This standard has defined different ice types and ice severity classes, but it is not widely used in wind energy.

The GL guideline for certification of wind turbines [253], which extends and refines the minimum requirements from IEC 61400-1 ed3, includes some iced turbine design load cases in the form of blade ice mass only.

SAE International has published its own standard AIR5666 "Icing Wind Tunnel Interfacility Comparison Tests" [254]. The objective of the testing activity was to establish a benchmark that compared ice shapes produced by icing wind tunnels available for use by the aviation industry and to use that benchmark as a basis for dialogue between facility owners to improve the state-of-the-art of icing wind tunnel technology. However, this standard is for aviation industry and cannot as such be translated to wind energy applications.

Following national standards have some cold climate related details:

- Canadian national standard CSA-S37-01 "Antennas, Towers, and Antenna-Supporting Structures" includes a design load case for met masts assuming 40mm of ice covering the met mast with a simultaneous gust of 57 m/s [255].
- German national standard DIBt "Directive for Wind Turbines Effects and stability analyses for towers and foundations" [256] has an iced turbine design load case, which is similar to the GL certification guideline. The German guideline assumes an ice mass imbalance on the turbine rotor for 7 days per year when assessing fatigue load.

12 Testing

Wind turbines consist of several mechanical, hydraulic, electrical and structural components. All of these components have to function in a safe, reliable, and efficient way to ensure optimal performance, especially for cold climate sites [257]. Therefore, validation testing is performed during the overall development process to verify that wind turbines and their components are implemented as designed, and meet their design specifications. Figure 23 shows that testing is an important step in the development cycle, and helps prevent and avoid failures of wind turbine systems. Failure avoidance is particularly important at cold climate wind power sites, since maintenance is expensive at such locations. .

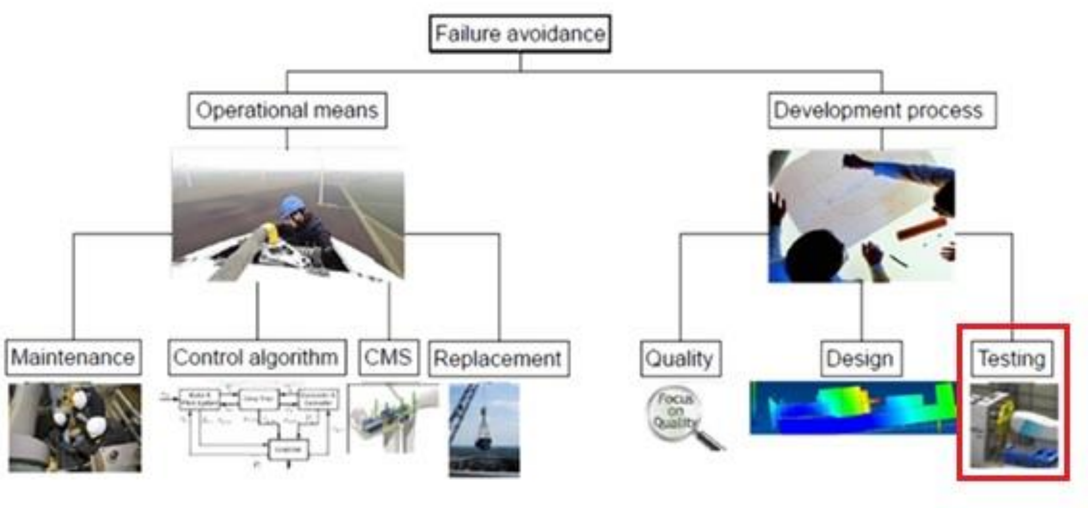

Figure 23: Testing as part of the development process to avoid failures in wind turbine systems (Source: Fraunhofer IWES)

Testing is performed at different levels as indicated in Figure 24, which represents the so called ‘test pyramid’. Testing processes can occur in-house, or with the help of public test laboratories at universities and knowledge centres. The main goal of testing is to validate computer models, verify functionality and reliability, prove performance, obtain certification, and learn the limits of the design, with respect to wear, tear, and fatigue for a certain system.

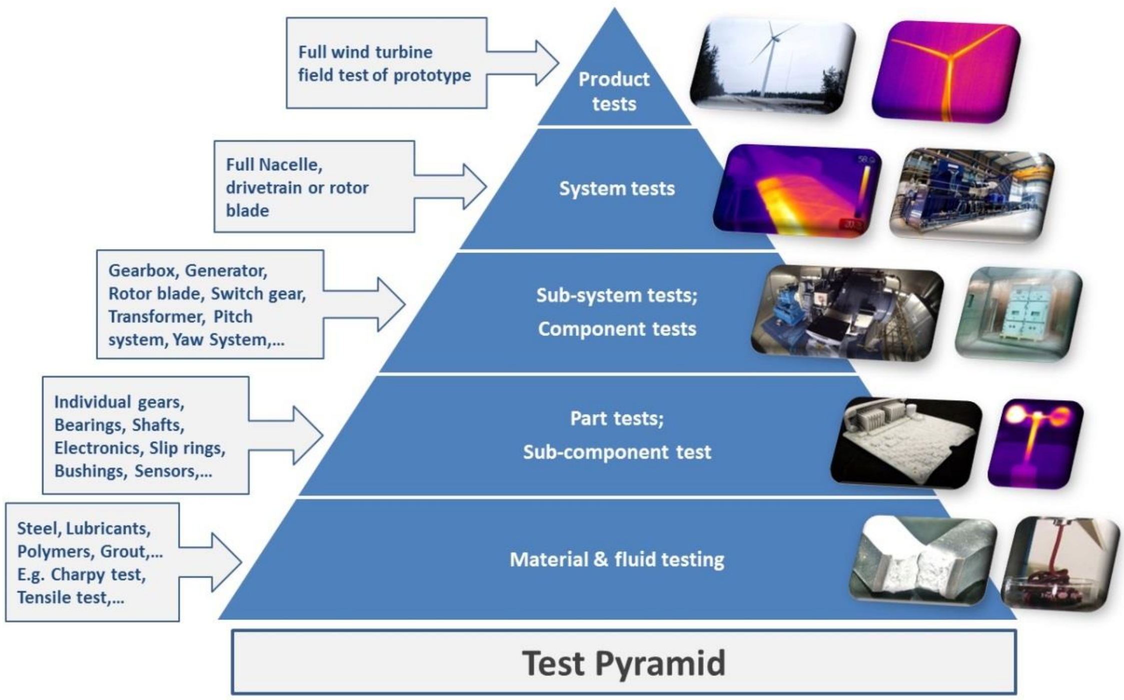

Figure 24: Test Pyramid – levels of testing (Source: OWI-Lab)

Testing of components that are critical in low temperatures and/or icing conditions is needed to prove that design errors have been eliminated during the design and manufacturing process. Various tests are, therefore, performed at different integration levels of the wind turbine assembly. Engineers sometimes struggle to find appropriate test infrastructure for cold climate compliance testing of designs and/or products, with regard to low temperatures or icing conditions. Figure 25 gives an overview of solutions that fulfil cold climate compliances, either for small products like sensors, anemometers, or material coupons, for large components like gearboxes, pitch and yaw systems, or transformers, or even fully installed wind turbine assemblies.

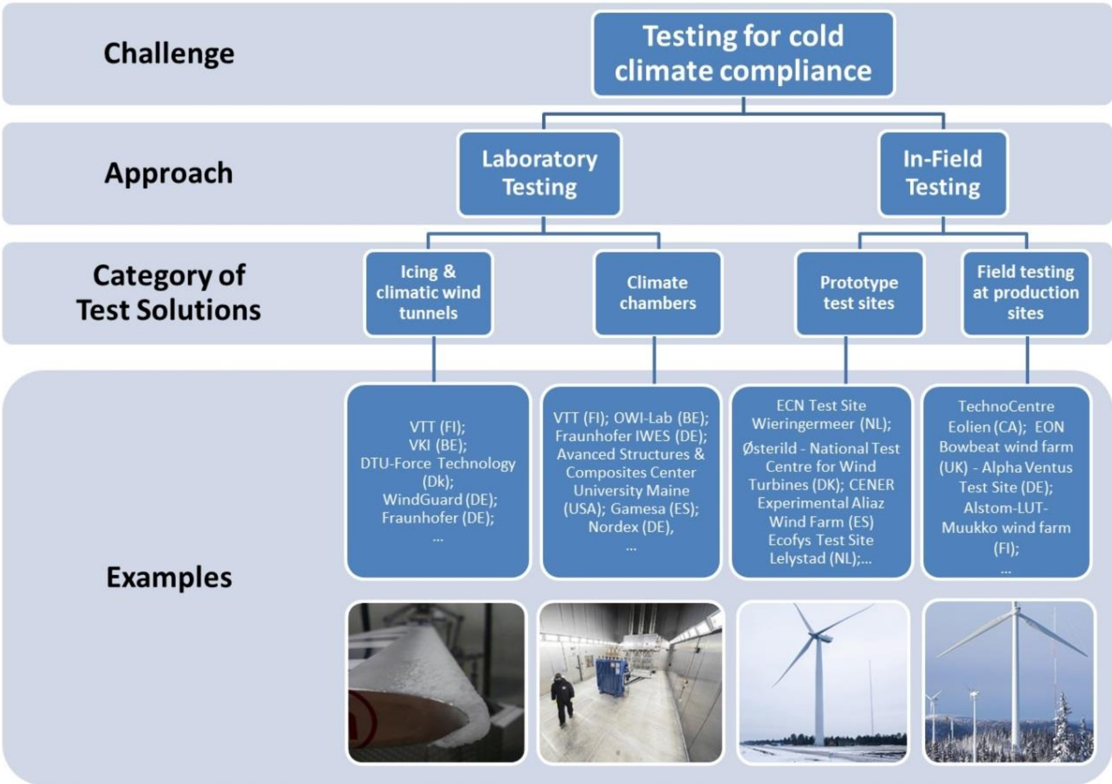

Figure 25: Overview of test solutions to meet with cold climate compliance (Source: OWI-Lab)

12.1 Icing Wind Tunnels

What: An Icing Wind Tunnel (IWT) is a laboratory facility where it is possible to simulate real icing conditions (in-cloud icing, freezing rain etc.). The ice accretion test conditions in the wind tunnel must be repeatable and resemble natural icing conditions.

Why: Cold Climate solutions in the wind power industry, especially the different anemometer, ice detector, and coating solutions, are not uniformly tested or rated. At the moment, there are no standards and/or guidelines to evaluate or even compare the instruments and coatings being offered for Cold Climate conditions. Therefore, a controlled laboratory environment is needed to verify that the solutions perform as promised. Additionally, there is an essential need for better understanding of the ice accretion process for wind power applications. It is important to know more about how accreted ice interacts with different materials, and how it would be possible to prevent ice growth. It is also essential to get more verified experimental data about the performance of ice-detectors, anemometers, and ice prevention systems during in-cloud icing conditions. Finally, verified and experimental wind tunnel data is needed during the R&D process for new instruments and wind power related products for wind power applications in icing climates.

How: Icing wind tunnels include a cooling unit, and a spray bar to simulate icing conditions, while also studying different flow parameters, such as turbulence or wind speed. These systems, allow for the user to control both the temperature and water droplet distribution to create repeatable tests.

Table 22 lists the available icing wind tunnels. Most tunnels have also activities outside wind energy.

Table 22: List of available icing wind tunnels

Institute& Country	**Specifications:** **Test section: [h x w x l]** **Temp. range:** **Wind Speed range:** **LWC:** **MVD:**	**Example tests**	**References**
Deutsche WindGuard Engineering GmbH: Wind Tunnel Centre / Icing Wind Tunnel – Germany	0.8m x 0.6m x 0.8m -20°C…+40°C 1 m/s … 20 m/s up to approx. 3 g/m^3 ?	- Survey on icing probes for met masts - Operational behaviour on sonic anemometers under icing conditions with- and without heating	Paper: Perf: Other: [258] [259] [260]
Rail Tec Arsenal Fahrzeugversuchsanlage GmbH (RTA): Vienna Climatic Wind Tunnel – Austria	3.5m x 2.5m x 3.0m -30°C…-2°C 10 m/s … 80 m/s 0.06 g/m^3… 1.0 g/m^3 20 µm … 40 µm More detailed information from RTA Web-pages!	- Tests for scaled or full scale components for helicopters or small aircrafts in the real flight conditions	Paper: Perf: Other: [261] [262] [263]
National Research Council Canada (NRC): 3 m x 6 m icing wind tunnel	4.9m x 3.1m x 6.4m ambient temperature u < 67 m/s No spray bar system in the 3 m x 6 m icing wind tunnel	- Ground icing simulations with rain spray system to simulate freezing drizzle and rain - Aircraft de/anti-icing fluid testing - Icing of bridge cables and decks	Paper: Perf: Other: [264]
National Research Council Canada (NRC): Altitude Icing Wind Tunnel	0.33m x 0.52m x 0.60m -35°C … +40°C 10 m/s … 180 m/s 0.1 g/m3… 2.5 g/m3 8 µm … 120 µm	- Used to simulate in-flight atmospheric icing conditions - Development, testing or calibration of aircraft or cloud physics instrumentation - Development and testing of de- and anti-icing systems	Paper: Perf: [265] [266] [267] [268] [269] Other: [270]
University of Manitoba, Renewable energy research Icing Wind Tunnel – Canada	0.9m x 0.9m x ? min -35°C up to 42 m/s 10 µm … 1000 µm ? ?	- Research and development facility for academic researchers, non-profit organizations and private	Paper: Perf: [271] [272] Other: [273] [274]

		companies	
University of Chicoutimi - Anti-Icing Materials International Laboratory (AMIL) - Canada	0.6m x 0.5m x 1.5m -50°C...+25°C up to 85 m/s 0.1 g/m^3 … 1.0 g/m^3 20 µm … 200 µm	- Ice cable shedding - Icephobic coating tests	Paper: [176] Perf: Other: [275]
VTT Technical Research Centre of Finland Ltd (VTT): Icing Wind Tunnel – Finland	0.7m x 0.7m x 1.0m -25°C...+23°C up to 50 m/s 0.1 g/m^3 … 1.0 g/m^3 17 µm … 35 µm	- Validating and testing opportunities: - heated wind instruments - ice detectors - scaled air foils - blade heating systems - coatings & ice adhesion tests - Tests can also be recorded into the video	Paper: [276] Perf: [277] Other: [278] [279] [280]
Tampere University of Technology: Icing Wind Tunnel - Finland	0.3m x 0.3m x 0.3m down to -40°C up to 25 m/s 0.1 g/m^3 … 1.0 g/m^3 25 µm … 1000 µm	- Centrifugal coating tests	Paper: [281] [282] Perf: Other:
Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM - Germany	0.20m x 0.155m x 0.95m +10°C …-30°C 35 m/s… 95 m/s 0.9 g/m^3 … 6.0 g/m^3 (status 01/2016) Not measured yet, status 01/2016	- Anti- and de-icing tests - Coating & ice adhesion tests - IR camera system for studying icing processes & the heat distribution on surfaces	Paper: Perf: Other: [283] [284]
China Aerodynamics Research & Development Center (CARDC): Icing Wind Tunnel – China	0.3m × 0.2m × 0.65m ? up to 210 m/s ? ?	- Component research & development - Icing test techniques development - Research of aircraft anti-icing/de-icing technology - Aircraft wing ice accretion mechanism - Aircraft component and icing instrument tests	Paper: Perf: Other: [285]
FORCE Technology & Technical University of Denmark (DTU): Climatic Wind Tunnel – Denmark	2.0m x 2.0m x 5.0m T > -5°C up to 25 m/s 0.4 g/m^3…1.0 g/m^3 10 µm … 50 µm	Issues related: - civil engineering, cases like bridges & buildings - maritime vessels & structures - ships & offshore structures	Paper: [286] Perf: [287] [288] [289] [290] [291] [292] [293] Other: [294] [295] [296]
Italian Aerospace Research Center (CIRA): Icing Wind Tunnel – Italy	2.4m x 2.3m x.7.0m (max) T > -40C up to 220 m/s 0.3 g/m^3… 2.0 g/m^3 18 µm…40 µm	- Airplane engine inlets - Air foil sections - Airplane landing gear	Paper: Perf: [297] Other: [298]

		- Airplane ice protection system tests & certification	
Iowa State University of Science and Technology Icing Research Tunnel (IRT) – USA	0.4m x 0.4m x 2.0m -30°C…+20°C 5 m/s … 60 m/s 0.05 g/m^3...10 g/m^3 10 µm…50 µm	- Icing physics research for aircraft and wind energy applications - R&D work on the anti- and de-icing applications	Paper: [299] [300] [301] [302] Perf: [303] [304] Other: [305] [306] [307]
NASA Glenn Research Center: Icing Research Tunnel (IRT) – USA	1.83m x 2.74m x 6.10m -38°C … +10°C 25 m/s...180 m/s 0.2 g/m^3…3.0 g/m^3 15 µm…50 µm	- Tests full-size aircraft components: models of airplanes & helicopters - Develops, tests, and certifies methods to prevent ice build-up on aircraft	Paper: Perf: Other: [308] [309] [310]
PennState AERTS - USA	?m x 1.4m x ?m -25°C … +20°C 25 m/s...180 m/s 1.0 g/m^3…5.0 g/m^3 10 µm…50 µm	- Centrifugal coating tests - de-icing tests	Paper: Perf: Other: [311]
Von Karman Institute (VKI) Cold Wind Tunnel (CWT-1) – Belgium	0,1m x 0,3m x 1,6m min -40°C up to 75 m/s max 1 g/m^3 80 µm … 160 µm	-Specially designed to study the motion of films of anti-icing fluids applied to aircraft wings during a simulated take-off -Aerodynamic acceptance of aircraft de/anti-icing fluids -Study of perspiration heating on porous wing panels for de-icing purposes	Paper: Perf: [312] Other: [313] [314]
Cranfield University Icing Tunnel - UK	0.76m x 0.76m x? -30°C …+30°C 35 m/s – 170 m/s 0.05 g/m^3…3.0 g/m^3 15 µm…80 µm	- Study of ice formation within aircraft fuel pipes - Mixed phase icing and the effective threate to aircraft engines & probes - ice protection in gas turbines	Paper: Perf: [315] Other: [316] [317]
University of Kanazawa KAIT Icing Wind Tunnel - Japan	0.3m x 0.1m x 1.0m (closed type) 0.5m x 0.5m (open type) min -40°C 0 m/s – 95 m/s 0.1 g/m^3…1.0 g/m^3 up to 40 µm	- Testing and development of ultrasonic wind sensor - Testing anti- and de-icing devices, ice detectors - Testing ice phobic coatings	Paper: Perf: [318] [319] [320] [321] [322] [323] [324] [325] [326] Other: [327]
National Research Institute for Earth Science and Disaster Prevention –	3 m x 5 m (table) -30 ℃ ... +25℃ 0 m/s …- 10m/s	-Characteristic change of deposited snow due to air	Paper: Perf: [328] Other:

Snow and Ice Research Center – **Cryospheric Environment Simulator(CES) - Japan**	? ?	temperature and solar radiation - Mechanism of drifting snow blown off by wind - Movement of deposited snow on a slope and mechanism of snow avalanche generation - Deposition of snow on/around a building under windy conditions	

12.2 Climate chambers

What: A climate chamber, also called climatic test chamber or environmental chamber, is an isolated chamber typically installed in a laboratory that has accurate temperature and/or humidity control within a certain temperature range. Most chambers are designed so they can compensate for a certain heat load, as well. Such laboratory test equipment can have a volume from 1m³ to 1000m³ or more depending on the purpose of testing, and the industry that it was designed for. This kind of advanced test infrastructure is typically used to test the effects of specific climate conditions (e.g. hot, cold, humid, ice, snow, rain, corrosion, or a combination) on materials, fluids, components, sub-components, and full assemblies of a product. For cold climate wind turbines, climate chambers are often used to verify the cold start-up performance of prototype machinery, either on the sub-system or the full assembly level. They are also used to validate the reliability of machinery with respect to cold climate compliance. Icing conditions can be tested if spray nozzles are used in the test chamber.

Climate chambers are described as a requirement by OEM’s or certification bodies, so they can ensure that components conform to certain standards or technical guidelines. These standards include, the suitability of wind turbines in cold climate conditions, storage testing (to comply with transportation and storage environments as suppliers ship their components from different regions in the world to each other) and cold climate system testing under load.

Many different systems used in a wind turbine assembly are tested in a climate chamber these include: material coupons, scaled rotor blade parts, hydraulic units, anti/de-icing systems, pitch and yaw drives [142], batteries, service cages [329], gearboxes [330] [331], generators, transformers [143], and more. Climate chamber testing on system level is common practice in other industries, such as the aerospace, defence, or automotive industry.. Additional attention is paid to the environmental requirements of wind turbine machinery, especially cold start-up behaviour and the effect of frozen cold soaked equipment.

Figure 26: Climate chamber examples for testing electro-mechanical wind turbine systems
(Source: OWI-Lab [143] , Nordex [332] , Ishibashi [333])

Why: Wind turbine OEM’s, and their suppliers need to perform climate chamber tests to check and validate that their systems are capable of operating in differential temperatures, and that they are capable of surviving extreme climatic events [140]

[257]. Products intended for cold climate sites need additional testing in low temperatures during the product development cycle, since materials tend to become brittle and lubricants become thicker in such climatic conditions. Climate chamber testing helps to identify of potential failures caused by extreme temperatures (e.g. differential thermal expansion problems, brittle materials and potential cracks, highly viscous oils and associated additional load on pumping equipment, etc.) early in the development phase. Laboratory testing is essential to the delivery of robust and reliable products.

When compared to field tests, laboratory tests in a controlled climatic test chamber allows for the reproduction of certain climatic conditions, without waiting nature to provide them. In-field testing is typically more expensive and more time-consuming than climate chamber testing.

How: Certain wind turbine machinery (e.g. the full nacelle, drivetrain gearbox, transformer, pitch system assembly, etc.) is placed inside a climate chamber that is set to specific climatic conditions, and is tested for serval days or even weeks depending on the test requirements and validation methodology. When a storage test is performed, no additional test auxiliaries are needed except for the measurement devices that monitor certain climatic and/or machinery parameters. The required temperature and/or humidity is set based on requirements provided by the customer or on industry standards. Depending on the type of machinery and the test standard, temperature and humidity cycles can also be programmed.

When performing functional system testing in a climate chamber, for example, a cold start-up test of a gearbox [144] or wind turbine transformer [143], additional testing infrastructure needs to be included to simulate the real life scenario. Examples of these additional infrastructure needs are electrical load, rotation and torque, etc.

Advantage

Having a climate chamber, or having access to public laboratories with environmental test infrastructure, is beneficial for a fast design verification of wind turbine prototypes. These structures help companies gain insight to the performance and reliability of their systems during cold events early in the development cycle. In comparison with in-field testing, laboratory testing is less time consuming, since one does not have to wait for nature to provide cold snap events, which can take a year or longer. Climate chamber testing can also be a valuable alternative to simulation modelling, which is time-consuming, complex, and requires relevant real life data.

Challenge

Depending on the dimensions, temperature and humidity test ranges, weight requirements, etc., climate chambers are quite expensive when system, nacelle, or turbine testing is required. Also, climate chamber testing is relatively infrequent compared to end-of-line testing. Climate chambers also need to be specifically designed for wind turbine applications, since they require additional mechanical and/or electrical test infrastructure for system testing, and their components tend to be much larger and heavier than e.g. automotive components. Therefore, publicly assessable climate chambers designed for the automotive industry cannot be used by the wind industry.

- Zarges is a component supplier (service cages and wind turbine lifts) and has tested a new cold climate version wind turbine lift down to -40°C in a climate chamber in order to meet customer requirements [329].

- Fraunhofer IWES has developed a special offshore test chamber that is able to simultaneously simulate and test mechanical and environmental loads at the material level. This climate chamber focusses on small material testing and can cool down to -30°C [334]. The facility is publicly available for testing and R&D projects.

- OWI-Lab houses one of the largest climatic test chambers (10.6m x 7m x 8m) in Europe, and has been set-up to test large size and large weight machinery like gearboxes [144] [331], transformers [143], pitch & yaw systems, generators, converters, switch gears, etc. The facility is mainly used for cold start-up testing for cold climate compliance [140]. The test chamber is unique in that it has the ability to cool down to -60°C, and has a high cooling power to compensate for heat loads. The facility is publicly available for testing and R&D projects.

- Ishibashi, a wind turbine gearbox supplier, has set-up its own climatic test chamber that can cool down to -40°C. This chamber is mainly used to inspect the lubrication system of a speed-up gear under cold conditions. Cold-weather tests are also performed in this climate chamber to formulate extreme start-up events [333].

- VTT has climate chambers for material testing, in particular building materials as concrete and grout [335]. The concrete materials laboratory has several climate chambers that can cool down to -196°C.

- Nordex has invested in its in-house climate chamber in order to submit certain wind turbine parts (slip rings, pitch systems) and components to extreme climatic endurance testing. The climate chamber can test in a range of -40°C to +60°C [332].

- Gamesa has built its own in-house climate chamber to evaluate the performance of wind turbines and their components when exposed to extreme conditions (temperatures ranging from -35ºC to +35ºC) prior to installation. The climate chamber was used to test a 4.5MW machine that is used in the Simo wind farm in the north of Finland [336].

- The Offshore Wind Laboratory of the Advanced Structures and composites centre at the University of Maine houses an environmental test chamber which can be used to test structures in extreme climatic conditions. The main purpose is to perform fatigue testing within the climate chamber. The climate chamber has large dimensions (6.8m x 6.8m x6.1m) and can cool down to -40°C [337].

12.3 Prototype test sites

What: Wind turbine manufacturers install full prototype versions of their machines after sub-component, component, and system testing is fully completed at prototype test sites to verify the full installed wind turbine assembly and obtain certification.

Why: Certain testing can only be done on the full-scale system level, and not in a laboratory or test bench. For example, load measurements, verification of the technical availability, power curve verification, power performance, power quality verification, and certification of the full turbine are typically done prototype test sites [88].

How: OEM's or wind farm developers lease space at specific test sites for long periods, often a couple of years at a time. New wind turbine prototypes are installed and tested at such sites to carry out further research and development on the prototype at full scale.

Advantage

Real life tests on the full-scale product level provide proof of performance, and allow for the collection of large amounts of real life data that can further optimize the product. Real life load cases can only occur at such test sites.

Disadvantage

- At this moment, there are no specific cold climate test sites. Instead, most of the test sites are located in moderate climates.
- There are no specific certifications for cold climate sites with regard to icing and/or de-icing.
- Changing large and heavy parts of the prototype at a test site is more difficult and expensive in this stage of the validation process. Therefore, a lot of the lab and test bench testing is done before taking the prototype into the field.
- Field testing is expensive and take significant time.
- There is a lack of field test sites.
- It is not possible to accurately control the environmental loads, unlike certain laboratories and test benches.

Challenge

Wind turbine manufacturers need to make sure that design flaws are identified and eliminated early in the design process, since changing parts in the field can be very costly. With regard to the topic of cold climate and icing, there are no test sites with either extreme cold temperatures or heavy icing.

- DTU operates seven test stands at its Østerild test centre [338], where new wind turbine prototypes can be tested and validated. The site is located in a moderate climate, so no information about extreme cold weather or icing is available.

- CENER in Spain owns the Experimental Aliaz Wind Farm [339] that has space for six wind turbine prototypes, and allows for wind turbine certification in complex terrain conditions with high wind levels. The site is located in a moderate climate, so no information about extreme cold weather or icing is available.

- ECN and Ecofys each have a wind turbine test site located in the Netherlands. Ecofys operates the Lelystad test site that has space for 10 wind turbines [340], [341]. The site is mostly used for certification testing and has a grid connection that allows for a combined capacity of 30MW. The ECN wind turbine test site has 11 test turbines installed [89]. Extreme low temperatures and heavy icing events do not occur at either location as they are located in moderate climates.

12.4 Field testing at production sites

What: Certain products, such as new monitoring tools for ice detection, sensors (for example anemometers or wind vanes [342]), retrofit de-icing systems, etc., can be tested by installing them at existing wind farms. The data from existing wind farms can also be used to optimize the next generation of wind turbine platforms, or to make modifications and upgrades to existing wind turbine platforms. Data obtained at production sites can also be used to understand certain icing conditions and are useful for updating icing and weather models.

Why: Since there are no cold climate test sites, wind farms that are located cold climates can be used to investigate certain technologies used in the wind turbines. Additionally, experience from wind farm sites in cold climates, should find its way back to the manufacturers to optimise the next generation of wind turbines.

How: Wind farm owners allow companies, universities, or knowledge centres to implement new technologies. Data from the tests is typically shared by both parties.

Advantage

Testing and validation of various technologies at production sites is a good alternative to traditional test sites. It allows developers, manufacturers, and others to gain knowledge about the behaviour of different components and technologies at cold climate sites. Retrofits of certain sensors, monitoring tools, ice-detection systems, and some de-icing systems are relatively cheap to implement, and the real life experience of testing them at a certain site is a big advantage over testing them in laboratories.

Disadvantage

No control over the environmental parameters being tested, long waiting times until certain cold snaps or icing events occur. Not all wind farm owners are open to this type of testing. Approval needed from OEM's to gain SCADA-data, which is needed to understand certain events.

Challenge

The implemented new technologies must have a high reliability and may not interrupt the availability of the wind turbine since downtime is expensive. A high technology readiness level and proof of laboratory tests will be required to convince park owners.

- EON performs research and test projects in its Bowbeat wind farm located in the UK to benchmark different ice-detection and retrofitted de-icing systems [343] .

- Alstom is working together with the Lappeenranta University of Technology (LUT) in Finland on research and testing at the 21MW Muukko wind farm to understand how wind turbines respond under arctic climate conditions. The goal of this research is to further improve operations, performance and reliability using production experience [344].

- TechnoCentre éolien has a 4MW research wind farm consisting of two 2.05 Senvion MM92 CCV wind turbines [345]. Here they have tested several sensors including different ice detectors, cameras used for ice detection, and anemometers [342].

- Enercon has performed verification tests of its hot air solution de-icing system for rotor blades at several operational wind farms around the world [346] [347].

- BlaikenVind AB is a joint company owned by Skellefteå Kraft and Fortum and will build one of the largest wind farms in Europe between 2011 and 2016 in the Blaiken area of northern Sweden [348]. The site has Nordex turbines equipped with electro thermal anti-icing systems and Dongfang turbines with hybrid hot air and electro thermal anti-icing systems representing the newest generation of active ice protection systems. Several research projects in Blaiken wind farm will start in 2016.

13 Further needs for technology research and innovation in cold climate

"The inventor of the second wheel made the discovery of the first wheel useful."

The priority list presented in this chapter is intended for research organizations and companies working in the field of cold climate wind energy to focus, harmonize, and accelerate joint efforts for research and innovation in the field of cold climate. This list is also intended for national and international funding agencies: please use this list as guidelines for future research and innovation funding for wind energy. In the absence of national and especially international funding programs for cold climate wind energy, almost all research and innovation activities are typically done on national level only dramatically hindering progress in CC. As Beurskens said in his WinterWind 2015 opening speech [349]:

"*Considerable increases to CC R&D budgets are needed!*"

A list of priorities for research and innovation (R&I) will undoubtedly be different for each stakeholder. Investors might not be interested in technical details, but they sure appreciate measures that decrease the uncertainty. Since the start of IEA Task 19 back in 2002 we've known the importance of market studies for the manufacturing industry and we can conclude that the interest in cold climate issues soared after May 2013 when World Market Update 2012, [2], had been published. Consequently, from the wind turbine manufacturers' point of view, market studies ought to be the number one top priority on the list. Here we're, however, aiming at presenting priorities that reflect the R&I needs for the entire cold climate wind energy community. As stated by Beurskens and Thor [350] in WinterWind 2015 closing summary speech:

"*We need a common research agenda. And in a coordinated way!*"

IEA Task 19 heard this call and is willing to take the lead in proposing prioritized research topics for cold climate. The list is based on IEA Wind Task 19 observations from workshops and panels at international conferences and from WinterWind conferences 2015-2016 and at Québec Wind Energy Conference 2014.

The prioritized R&I topics for cold climate are:

1. Standards, certification, and recommended practices
2. Assessment of reduced production prior to deployment, financial risks, and uncertainties
3. Ice protection systems, equipment, and procedures
4. Testing: test sites, field testing, & lab testing incl. subcomponents and ice detection
5. Health, safety, and environment (HSE) incl. ice throw
6. Construction, installation, operation, maintenance, and repairs
7. Market potential and limitations
8. Grid issues
9. Small wind turbines

These priorities ought not to be misinterpreted. Grid issues and making small wind turbines function in cold climates are still important. Utilities might not know all the challenges associated with wind farms in cold climates and they're not overly keen to talk about problems regularly encountered. As a substitute for diesel generators and fuel, which are expensive to transport using helicopters, small wind turbines that are capable of operating in icing conditions would likely prove to be useful and cost-efficient in wind resource assessment. Offshore wind farms in cold climates are not on the priority list but will be important in the future.

According to a WinterWind 2016 pre-conference survey initiated by Lehtomäki, [351], the three groups most keen to master wind energy in cold climates are owners/developers, consultants, and the research community. A lack of interest from government and authorities is either a coincidence or a sign of ignorance. The two most important issues are considered to be assessing the performance of de-/anti-icing systems and ice detection. Finally, Lehtomäki indicates the importance of the forthcoming (forecasted in 2018) release of IEC 61400-15 Ed. 1.0 ”Assessment of site specific wind conditions for wind power stations” and it's importance to realistic resource assessment regarding icing. Vattenfall is the largest utility in Sweden and is 100% owned by the Swedish government. Odemark, [352] p.13 &14, confirms the interest in assessing the performance of iced up wind turbines as well as ice prevention systems and the importance of accurately detecting icing, during the pre-construction phase, by developing sensors in general, and those intended to measure liquid water content in particular as well as improving methods to evaluate photos of iced up objects.

A Swedish R&I strategy for developing wind energy stands on three legs; Swedish conditions, sustainability and involvement, and power grid integration, Rigole, [353] p.8. Swedish conditions of particular interest to master are those found in the forest, at sea, and in cold climates. The Swedish Energy Agency claims: ”Building in cold climate with weather conditions many times more extreme than what the wind turbines are originally designed for is a prerequisite for expansion of wind power in Sweden. … Sweden has no domestic turbine manufacturer. Therefore, efforts are concentrated on a few areas where there is a potential to achieve excellence and to create an innovation cluster”.

References: [2] [350] [351] [352] [353] [354] [231]

13.1 Standards, certification and recommended practices

What: Being a new, albeit big, niche market, wind energy deployment in cold climates has developed rapidly during the past ten years. Many mistakes have been made and the biggest of them all is probably the initial use of standard wind turbines at ice infested locations. Here, potential energy is not being captured, not only due to low temperatures outside the operating range of standard turbines, but also due to iced sensors and blades. Additionally, blade damages due to falling ice are difficult to detect and expensive to repair.

Why: The main reason for initially using standard products at these sites was a shortage of wind turbines, which made the manufacturers unwilling to adapt to these new meteorological conditions.

How: The market is new and all parties involved seem to have realized that standards, certification, and recommended practices are useful tools that can decrease the uncertainties and thereby lower the cost of energy. Lately, different ice protection systems (mainly active de- and ant-icing systems) have been made available from a large number of manufacturers. When investors demand functionality and verification of performance they realize the need for standardized procedures to evaluate both pre-construction plans and measurements as well as the properties of operating wind farms. Funding for the development of standards is by authorities expected to be made available from the industry. In countries without wind turbine manufacturers in which large-scale wind farms are being deployed there’s strangely enough in general no funding available for standardization work.

The following tasks will be carried out during 2016-2018 within IEA RD&D Wind’s Task 19 – Wind Energy in Cold Climates, Lehtomäki, [355] p.16:

a) Market study update for 2016-2020
b) International standard IEC 61400-15 “Site energy yield assessment” CC aspects
c) T19IceLossMethod validation & development
d) Laboratory and full scale testing
e) Ice protection system performance evaluation guidelines
f) Ice mapping
g) Ice sensor classification
h) Development of International ice throw guidelines

All of the above tasks above except a) Market study update for 2016-2020, are targeted towards standardization of various cold climate challenges.

References: [355] [356] [357] [358] [359]

13.2 Assessment of reduced production prior to deployment, financial risks and uncertainties

What: Methods and tools to evaluate the potential reduction of energy yield due to low temperature and icing effects are needed in order to secure the financial feasibility of a planned wind farm project.

Why: Reliable pre-construction assessment of a wind farm's energy yield is key to reducing the risk and thereby the cost of capital. Wind farms will only be built provided there's a possibility to make a profit.

How: Development of international standards are one of the most effective ways to mitigate the "Wild West" type of practices currently used when talking about resource assessment regarding icing and related financing. The new upcoming IEC 61400-15 ed1 standard will provide transparency and guidelines to the cold climate wind community with regard to assessment of reduced production due to cold climates. Sharing of knowledge and experiences plays also a critical role.

The ability to forecast production with respect to iced up blades has improved greatly during the past few years. This is mainly due to the fact that large wind farms have been built at such locations thereby enabling, for the very first time, evaluation of their performance in icing conditions. Newly developed methods and models will, when verified and further developed by correlating present meteorological conditions with actual production, enable historical data to be used to produce reliable icing maps and accurate site assessments.

Solutions to mitigate reduced production and resulting uncertainty to the energy yield are available to lower financial risks and uncertainties. A developer's dream is to be able to inform the bank manager that the ice protection system ordered is able to handle basically any situation if icing turns out to be a more difficult problem than expected.

For sites in Sweden and Finland, the IEA ice classification of operating sites has been compared to the predicted performance based on icing atlases, Karlsson, [360]. As the models and measurements only correlate well on long-term trends, it is concluded that data from multiple sources and from multiple years are required to carry out a representative classification.

The historical average availability of the studied data sets acquired during mast measurements in cold climates is shown to be below 95%. Therefore, Liléo proposes a strategy based on cooperation to achieve 99% data availability by 2020, [361] p. 17.

References: [9] [362] [360] [363] [361] [364] [365] [366] [367] [368] [369] [370] [371] [372] [373] [374] [11] [375] [376] [377] [378]

13.3 Ice protection systems, equipment and procedures

What: Wind turbine blades can be iced up at ice infested locations.

Why: The available wind resource can't be fully used unless the blades are mostly free of ice. Ice on the blades also increases the risk of blade damage, ice throw, stall induced vibrations, and leads to increased noise.

How: Newly developed commercial ice protection systems (mainly active de- and anti-icing systems) are readily available from a large number of wind turbine manufacturers. The next generation of such systems are being developed and tested. The operational strategy of ice protection systems needs to be investigated and optimized and their actual performance verified.

At WinterWind 2015 and 2016, several wind turbine manufacturers have described the present status of their ice protection systems.

References: [155] [162] [151] [379] [153] [380] [381] [382] [383] [384] [385] [386] [387] [181] [171]

13.4 Testing: test sites, field testing, and lab testing including subcomponents and ice detection

What: Wind turbines consist of several mechanical, hydraulic, electrical, and structural components. All of these components have to function in a safe, reliable, and efficient way to ensure optimal performance, especially for cold climate sites [257]. Therefore, validation testing is performed during the overall development process to verify that wind turbines and their components are implemented as designed, and meet their design specifications.

Why: Wind farms were initially built in cold climates using standard wind turbines. The adapted technologies, required to enable a cost-efficient operation of wind turbines in cold climates, have recently been developed or are under development. Consequently, their performance needs to be verified.

How: Testing is carried out on subcomponents, systems, and complete wind turbines. Such tests are performed both in controlled conditions in laboratories and in the field. Full scale field testing is extremely important in order to validate any given products efficiency and reliability, but controlled laboratory testing is also needed prior to outdoor tests.

The test procedures must be standardized for laboratory and field testing if comparisons are to be meaningful. Currently, there are no commercial test stations in cold climates for today's large wind turbines, only individual test sites exist (see more in chapter 12 on testing).

Most researchers consider camera images to be the most accurate means to detect and quantify ice build-up on objects. If not automated, the evaluation of photos can, however, be time consuming and expensive. A summary of properties and evaluation of a large number of ice detection and measurement methods is presented in [388] p.22. Relative humidity is shown to be a poor means of detecting icing conditions with a 75%

positive false alarm rate, whereas wind direction and wind speed sensors seem to provide quite reliable and reasonable results.

References: [277] [389] [388] [390] [391] [392] [393] [394] [395] [396] [397] [398] [399] [400] [401] [402] [403]

13.5 Health, safety and environment (HSE) incl. ice throw

What: Wind energy in cold climates implies low temperatures and icing conditions. Additionally, these wind farms are often, but not always located at remote, high altitude sites in complex terrain. These cold climate conditions can pose special health and safety issues for maintenance personnel as well as the general public that need to be accounted for.

Why: Low temperatures and iced up surfaces on a wind turbine create potential hazards for service personal and the public. Remote locations in complex terrain can cause rescue operations to be delayed.

How: The development of guidelines and technologies for safe and environmentally friendly operation of wind farms are keys to success.

References: [404] [405] [224] [406] [406] [407] [408] [409] [410] [410] [411] [412] [413] [414] [414] [415]

13.6 Construction, installation, operation, maintenance and repairs

What: After all contractual and financial matters have been agreed for a wind farm, the physical development of the actual wind farm can begin.

Why: The climate, complex terrain, and remoteness of wind farms are factors that can make deployment and operation of wind farms at cold climate sites challenging.

How: If the building season is short, using prefabricated foundations is one way to shorten the installation time. A developer's dream is to be able to inform the bank manager that the ice protection system ordered is able to handle basically any situation, even if icing turns out to be a more difficult problem than expected. Passing steep and narrow passages in complex terrain can be accomplished by delivering the wind turbine in smaller and lighter sections or by using special means of transportation. Energy production might be optimized and noise reduced by lowering the power and rotational speed in icing conditions.

References: [405] [416] [417] [418] [419] [420] [418] [421] [422] [423] [424] [133] [235] [234]

13.7 Market potential and limitations

What: Renewable energy in general and such without cost of fuel in particular is destined to replace fossil fuel and other sources of energy with a higher marginal cost.

Why: It is essential for manufacturers' and developers' long-term planning to gain knowledge of future markets. Market studies are regularly being published, but they rarely contain data specific for cold climate sites.

How: Market studies covering wind energy potential at cold climate locations ought to be initiated on a regular basis. According to [425], the wind resource in Mongolia exceeds 8 PWh/year, which equals roughly 40% of the world's annual electricity generation. As HVDC has enabled transfer of electricity over long distances, for example between Norway and Holland (580 km), similar projects are thought of between Mongolia and Japan, and according to Fouquet, also planned for in Europe, [426] p.38.

References: [2] [419] [420]

13.8 Grid issues

"We don't know very much and we're not overly keen to talk about what we do know."

What: Wind energy in cold climates is a young technology and such wind farms are often remotely located, far away from populated areas.

Why: Although utilities and manufacturers are used to operating their equipment in cold climate conditions, new challenges are encountered as the technology is being developed. Icing of power lines seems to be a problem, but utilities, if at all aware, seem not overly happy to talk about it. Hoar frost, which isn't a problem for the wind turbine, can cause significant losses due to the corona effect on power line insulators.

How: A devil's advocate need to challenge the utilities to study the influence on the grid from wind farms at remote locations sharing the grid with, for example, hydro power used to stabilize the grid.

References: [427]

13.9 Small wind turbines

What: Wind resource assessment in general is an expensive business in cold climates, and power supply for remote sites with additional heated instruments remains a challenge. In cold climates it might require transportation of equipment and fuel by means of helicopter.

Why: Provided small wind turbines could cope with icing, their use could decrease or eliminate the need for transporting fuel.

How: Ice protection systems ought to be developed for small wind turbines.

References:

14 Bibliography

[1] C. S. Bidwell and M. G. Potapczuk, "Users Manual for the NASA Lewis Three-Dimensional Ice Accretion Code (LEWICE3D)," NASA TM 105974, 1993.

[2] Navigant Research, "World Market Update 2012," Navigant Research, ISBN: 978-87-994438-4-0, Copenhagen, Denmark, 2013.

[3] IEC, *IEC 61400-1:2005(E) Wind turbines Part 1 - Design Requirements,* Geneva, Switzerland: IEC, 2005.

[4] Ø. Byrkjedal, "Icing Map of Sweden," 2012. [Online]. Available: http://www.vindteknikk.com/services/analyses/wind-power/pre-construction/icing-map. [Accessed 4 03 2016].

[5] B. Tammelin, T. Vihma, E. Atlaskin, J. Badger, C. Fortelius and e. al, "Production of the Finnish Wind Atlas," *Wiley Wind Energy (DOI: 10.1002/we.517),* vol. 16, no. 1, pp. 19-35, 2011.

[6] V. Lehtomäki, T. Karlsson, S. Rissanen, S. Asplund and T. Hilakivi, "Estimating icing in Finnish climate conditions," in *Wind Finland 2015 seminar (http://www.tuulivoimayhdistys.fi/filebank/802-VilleLehtomaki.pdf),* Helsinki, 2015.

[7] K. Hämäläinen and S. Niemelä, "Verification of Icing-model, in Finland," in *IWAIS,* Uppsala, 2015.

[8] Finnish Meteorological Institute, "Finnish Icing Atlas," 2011. [Online]. Available: http://www.tuuliatlas.fi/icingatlas/. [Accessed 2 November 2015].

[9] S. Rissanen and V. Lehtomäki, "Global Wind and icing optimization atlas : case Finland," in *Winterwind,* Åre, Sweden, 2016.

[10] G. A. McKay and H. A. Thompson, "Estimating the Hazard of Ice Accretion in Canada from Climatological Data," *Journal of Applied Meteorology,* vol. 8, no. 6, pp. 927-935, 1969.

[11] S. Lindahl, "Quantification of energy losses caused by blade icing and the development of an Icing Loss Climatology Using SCADA data from Scandinavian wind farms," in *WinterWind,* Piteå, Sweden, 2015.

[12] T. Beckford, "DNV GL's empirical icing map of Sweden and methodology for estimating annual icing losses," in *Winterwind,* Åre, Sweden, 2016.

[13] J. Hošek, “Synoptic icing observations in central Europe and their applicability for icing mapping,” in *13th International Workshop on Atmospheric Icing of Structures*, Andermatt, Switzerland, 2009.

[14] B. Wichura, “The Spatial Distribution of Icing in Germany Estimated by the Analysis of Weather Station Data and of Direct Measurements of Icing,” in *15th International Workshop on Atmospheric Icing of Structures*, St. John's, Newfoundland and Labrador, Canada, 2013.

[15] B. C. Bernstein, L. Makkonen and E. Järvinen, “Eurpoean Icing Frequency Derived From Surface Observations,” in *IWAIS XIII*, Andermatt, Switzerland, 2009.

[16] V. Lehtomäki, T. Karlsson and S. Rissanen, “Wind Power Icing Atlas – tool for financial risk assessment,” in *Winterwind*, Sundsvall, Sweden, 2014.

[17] S. Rissanen and V. Lehtomäki, “Wind Power Icing Atlas (WIceAtlas) & icing map of the world,” in *Winterwind*, Piteå, Sweden, 2015.

[18] F. Lamraoui, G. Fortin, R. Benoit, J. Perron and C. Masson, “Atmospheric icing severity: Quantification and mapping,” *Atmospheric Research*, vol. 128, pp. 57-75, 2013.

[19] A. Manea, I. Ralita, A. Dumitrescu, A. Sommerfeld and B. Wichura, “Analysis of spatial and temporal distribution of freezing rain events in Romania and Germany,” in *13th International Workshop on Atmospheric Icing of Structures*, Andermatt, Switzerland, 2009.

[20] S. Chereshnyuk, L. Timashova and V. Lugovoi, “A new set of climatic loads maps for Russia,” in *15th International Workshop on Atmospheric Icing of Structures*, St. John's, Newfoundland and Labrador, Canada, 2013.

[21] V. Lugovoi, S. Chereshniuk and L. Timashova, “Modern techniques of ice-load assessment and icing maps creation for the design of overhead transmission lines used in the Russian Federation,” in *13th International Workshop on Atmospheric Icing of Structures*, Andermatt, Switzerland, 2009.

[22] K. Harstveit, Ø. Byrkjedal and E. Berge, “Validation of Regional In-Cloud Icing Maps in Norway,” in *13th International Workshop on Atmospheric Icing of Structures*, Andermatt, Switzerland, 2009.

[23] Ø. Byrkjedal, “Estimating wind power production loss due to icing,” in *13th International Workshop on Atmospheric Icing of Structures*, Andermatt, Switzerland, 2009.

[24] Ø. Byrkjedal, “Mapping of icing in Sweden - On the influence from icing on wind energy production,” in *Winterwind*, Skellefteå, Sweden, 2012.

[25] Ø. Byrkjedal, “Vindkart for Norge,” 2009. [Online]. Available: https://www.nve.no/Media/3759/kartbok3a_4143.pdf. [Accessed 4 3 2016].

[26] Ø. Byrkjedal, “Icing Map for Finland,” [Online]. Available: http://www.vindteknikk.com/services/analyses/wind-power/pre-construction/icing-map. [Accessed 4 3 2016].

[27] H. Bergström, P. Thorsson, P. Unden, O. Esbjörn, U. Andrae and S. Söderberg, “Windpower in cold climates – Vindforsk project V313,” in *Winterwind*, Umeå, Sweden, 2011.

[28] G. Ronsten, “Swedens’s bold activities in measurements and mapping of icing and de-icing of wind turbines,” in *14th International Workshop on Atmospheric Icing of Structures*, Chongqing, China, 2011.

[29] B. Wareing and S. M. Fikke, “A UK Probabilistic Wind / Ice Map,” in *14th International Workshop on Atmospheric Icing of Structures*, Chongqing, China, 2011.

[30] B. E. K. Nygaard, I. A. Seierstad, S. M. Fikke, D. Horsman and B. Wareing, “The Development of New Maps for Design Ice Loads for Great Britain,” in *15th International Workshop on Atmospheric Icing of Structures*, St. John's, Newfoundland and Labrador, Canada, 2013.

[31] V. Lehtomäki and M. Wadham-Gagnon, “Low temperature & icing map for Québec,” in *Québec Wind Energy Conference*, Gaspé, Québec, 2014.

[32] B. E. K. Nygaard, I. A. Seierstad and A. T. Veal, “A new snow and ice load map for mechanical design of power lines in Great Britain,” *Elsevier Cold Regions Science and Technology*, vol. 108, pp. 28-35, 2015.

[33] NOAA, “Celebrating 200 years of science, service and stewardship,” 2007. [Online]. Available: http://celebrating200years.noaa.gov/breakthroughs/climate_model/AtmosphericModelSchematic.png. [Accessed 11 03 2016].

[34] B. Tammelin, T. Vihma, E. Atlaskin, J. Badger, C. Fortelius, H. Gregow, M. Horttanainen, R. Hyvönen, J. Kilpinen, J. Latikka, K. Ljungberg, N. G. Mortensen, S. Niemelä, K. Ruosteenoja, K. Salonen and Suomi, “Production of the Finnish Wind Atlas,” *Wind Energy*, vol. 16, no. 1, pp. 19-35, 2013.

[35] S. Söderberg, M. Baltscheffsky, H. Bergström, P. Thorsson, P. Unden and O.

Esbjörn, “Mesoscale modelling of icing climate: Sensitivity to model and model setup,” in *Winterwind*, Östersund, Sweden, 2013.

[36] S. Dierer, R. Cattin, A. Heimo, B. E. Nygaard and K. Santti, “Modelling the risk of icing,” in *European Wind Energy Conference*, Marseille, France, 2009.

[37] S. Dierer, R. Cattin, S. C. Müller, B. E. Nygaard, P. Steiner and B. Calpini, “Modeling the risk of icing in Switzerland,” in *13th International Workshop on Atmospheric Icing of Structures*, Andermatt, Switzerland, 2009.

[38] J. Yang, K. F. Jones, W. Yu and R. Morris, “Simulation of in-cloud icing events on Mount Washington with the GEM-LAM,” *Journal of Geophysical Research: Atmospheres*, vol. 117, no. D17, 2012.

[39] J. Yang, W. Yu, J. Choisnard, A. Forcione and S. Antic, “Coupled Atmospheric–Ice Load Model for Evaluation of Wind Plant Power Loss,” *Journal of Applied Meteorology and Climatology*, vol. 54, no. 6, pp. 1142-1161, 2015.

[40] B. E. Kringlebotn Nygaard, J. E. Kristjánsson and L. Makkonen, “Prediction of In-Cloud Icing Conditions at Ground Level Using the WRF Model,” *Journal of Applied Meteorology and Climatology*, vol. 50, no. 12, pp. 2445-2459, 2011.

[41] N. N. Davis, A. N. Hahmann, N.-E. Clausen and M. Žagar, “Forecast of icing events at a wind farm in Sweden,” *Journal of Applied Meteorology and Climatology*, vol. 53, no. 2, pp. 262-281, 2014.

[42] B. Tammelin, K. Säntti, H. Dobech, M. Dusterwich, H. Ganander, G. Kury, T. Laakso, E. Peltola and G. Ronsten, “Wind Turbines in Icing Environment: Improvement of Tools for Siting, Certification and Operation - NEW ICETOOLS,” Finnish Meteorological Institute, Helsinki, 2005.

[43] G. Fortin, J. Perron and A. Ilinca, “Behaviour and Modeling of Cup Anemometers under Icing Conditions,” in *IWAIS XI*, Montréal, 2005.

[44] T. Pederson and U. Paulsen, “Classification of operational charachteristics of commercial cup-anemometers,” Risoe National Laboratory/Wind Energy and Atmospheric Physics Department, pp 45-49, Denmark, 1999.

[45] B. Tammelin et. al., “Improvement of Severe Weather Measurements and Sensors –EUMETNET SWS II Project,” FMI reports, 2004:3.

[46] Z. Khadiri-Yazami, M. Durstewitz, T. Klaas, L. Peterson and A. Baier, “Performance of LiDAR in icing conditions. Comparison to a 200m mast in complex terrain,” in *Winterwind*, Sundsvall, 2014.

[47] R. Cattin, S. Bourgeois, S. Dierer, M. Mueller and S. Koller, “Wind forecasts in complex terrain. Experiences with SODAR and LIDAR,” in *Ice and Rocks III,* Zadar, 2010.

[48] C. Arbez, M. Boquet and R. Krishnamurthy, “Case study of Lidarin cold climate and complex terrain in Canada,” in *Winterwind,* Sweden, 2014.

[49] ISO, ISO 12494 - Atmospheric icing of structures, Printed in Switzerland: Reference number ISO 12494:2001(E), First edition 2001-08-15.

[50] A. Krenn, “More Mobile Remote Energy for heated wind measurement systems,” in *Winterwind,* Sweden, 2014.

[51] Krenn, Andreas; Energiewerkstatt, “Intelegent load control for heated wind measurement sensors,” in *Winterwinde, International Wind Energy Conference,* Sweden, 2012.

[52] IEC 61400-12-2:2013 - Power performance measurements of electricity producing wind turbines, 2013.

[53] VAISALA, “Wind Sensors,” [Online]. Available: http://www.vaisala.com/en/products/windsensors/Pages/default.aspx. [Accessed 15 6 2015].

[54] G. Instruments, “WInd sensors,” [Online]. Available: http://gillinstruments.com/products/anemometer/anemometer.htm. [Accessed 22 6 2015].

[55] REMTECH, “DOPPLER SODAR and RASS (Radio Acoustic Sounding System),” [Online]. Available: http://www.remtechinc.com/. [Accessed 22 6 2015].

[56] Leosphere, “Windcube LiDAR,” [Online]. Available: http://www.leosphere.com/en/. [Accessed 22 6 2015].

[57] “efoy Energy for you,” [Online]. Available: http://www.efoy-pro.com/page/wind-measurement. [Accessed 6 2015].

[58] R. Cattin and D. U. Heikkilä, “Evaluation of ice detection systems for wind turbines,” Meteotest, Bern, 2016.

[59] S. Kimura, D. T. Sato, . P. Y. Yamagishi and H. Morikawa, “Evaluation of ice detecting sensors by icing wind tunnel test,” in *IWAIS XIII,* Andermatt, 2009.

[60] D. J. B. Wareing, “Test Site data on icing monitors and conductor ice loads,” in

IWAIS XIII, Andermatt, 2009.

[61] H. Wickman, “Evaluation of field tests of different ice measurement methods for wind power - focusing on their usability for wind farm site assessment and finding production losses,” 2013.

[62] H. Wickman, J.-Å. Dahlberg and P. Krohn, “Experiences of different ice,” 2013.

[63] “User Guide T 40 series of Icing Rate Sensors,” HoloOptics, [Online]. Available: http://holooptics.utrymmet.com/Dokument/651.Userguide%20T40.004.En.pdf. [Accessed 14 01 2016].

[64] J. Rast, R. Cattin and A. Heimo , “Icing Indices: a good solution?,” in *IWAIS XII*, Andermatt, 2009.

[65] M. Wadham-Gagnon, . N. Swytink-Binnema, D. Bolduc, . K. Tété and C. Arbez, “Ice Detection Methods and Measurement of Atmospheric Icing,” in *IWAIS*, Uppsala, 2015.

[66] R. Cattin, S. Kunz, . A. Heimo, M. Russi and . G. Russi, “Two Years of Monitoring of a Wind Turbine under Icing Conditions,” in *DEWEK* , Bremen, 2008.

[67] B. Ollars and P. Jonsson, “Conbitech Ice Detection System,” in *WinterWind conference*, Piteå, 2015.

[68] P. Jonsson, “The ice load surveillance sensor IceMonitor,” Combitech, [Online]. Available: http://www.combitech.se/Documents/Bilder%20och%20filer%20sidor/Tj%C3%A4nster/Environmental%20Solutions/4/IceMonitor_Produktblad_Combitech.pdf . [Accessed 14 01 2016].

[69] J. Šabata, P. Lehký, L. Zeman and P. Vaculík, “Automated Icing Monitoring System on the territory of the Czech and Slovak Republic,” in *IWAIS 2015 - 16th international workshop on atmosperic icing of structures* , Uppsala, 2015.

[70] D. J. B. Wareing and M. J. Sabata, “Testing the PMS Icemeter at Deadwater Fell,” in *IWAIS XIII*, Andermatt, 2009.

[71] J. Sabata, “Studnice Test Station (EGÚ Brno),” in *IWAIS XIII*, Andermatt, 2009.

[72] “EGU Brno,” [Online]. Available: http://www.egubrno.cz/sekce/s002/produkty/s002_produkty_pms.html. [Accessed 19 01 2016].

[73] "LID-3300IP Ice Detector - Installation and Operating Instructions," Labkotec, 19 12 2014. [Online]. Available: http://www.labkotec.fi/sites/default/files/tiedostot/D80186Je.pdf. [Accessed 14 01 2016].

[74] "LID-3300IP - Efficient ice detection brings reliability," Labkotec, [Online]. Available: http://www.labkotec.fi/sites/default/files/tiedostot/LID3300IP_es_ENG_9_15_web_0.pdf. [Accessed 14 01 2016].

[75] R. Cattin, A. Heimo, Y.-A. Roulet and J. Rast , "A test of the Goodrich 0871LH1 ice detector at the Guetsch station," in *IWAS XIII*, Andermatt, 2009.

[76] S. G. Cober, G. A. Isaac and A. V. Korolev, "Assessing the Rosemount Icing Detector with In Situ Measurements," *Journal of Atmospheric and Oceanic Technology*, vol. 18, pp. 515-528, 2001.

[77] "0872F1 Ice Detector - Instruction manual," Goodrich Sensor System (Campbell Scientific), 2014. [Online]. Available: https://s.campbellsci.com/documents/ca/manuals/0872f1_man.pdf. [Accessed 14 01 2016].

[78] "Leine Linde Systems IPMS - Ice prevention for greater safety and higer energy yields," Leine Linde Systems, [Online]. Available: http://www.ll-systems.com/uploads/tx_lliproducts/en_publication_LLS_IPMS.pdf. [Accessed 14 01 2016].

[79] N. N. Davis, Ø. Byrkjedal, A. N. Hahmann, C. Niels-Erik and Ž. Mark, "Ice detection on wind turbines using the observed power curve," *Wind Energy*, vol. 19, no. 6, p. 999–1010, 2016.

[80] E. Hellström, "Development of a model for estimation of wind farm production losses," Uppsala University , Uppsala, 2013.

[81] S. Kolar, "A Comparison of Wind Power Production with Three Different De- and Anti-Icing Systems," Uppsala University , Uppsala, 2015.

[82] "T19IceLossMethod - A standardized method to assess production losses due to icing from wind turbine SCADA data," IEA Task 19 - Wind energy in cold climates, 2015. [Online]. Available: https://www.ieawind.org/task_19/Task19%20Ice%20Loss%20Method.html. [Accessed 16 04 2016].

[83] "BLADEcontrol® Greater output – less risk," Rexroth Bosch Group, [Online]. Available: http://dc-

corp.resource.bosch.com/media/general_use/industries_2/renewable_energies_6/windenergy/products_2/rotor_blade_condition_monitoring_systems_/BLADEcontrol_AE.pdf. [Accessed 14 01 2016].

[84] "fos4x monitoring lightweight structures," fos4x , [Online]. Available: http://www.fos4x.de/produkte/windprodukte/eiserkennung. [Accessed 14 01 2016].

[85] B. Wölfel, "Reliable ice detection for rotor blades to increase availability and yield," in *WinterWind,* Åre, 2016.

[86] "Eologix," [Online]. Available: http://eologix.com/en/product/. [Accessed 19 01 2016].

[87] L. Makkonne, M. Marjaniemi and T. Laakso, "Modeling and prevention pf ice accretion on wind turbines," *Wind Engineering,* vol. 21, no. 1, pp. 3-21, 2001.

[88] M. Homola, T. Wallenius, L. Makkonen, P. Nicklasson and P. Sundsbo, "The relationship between chord length and rime icing on wind turbines," *Wiley Wind Energy,* vol. 13, no. 7, pp. 627-632, 2009.

[89] M. Homola, T. Wallenius, L. Makkonen, P. Nicklasson and P. Sundsbo, "Turbine Size and Temperature Dependence of Icing on Wind Turbine Blades," *Wnd Engineering,* vol. 34, no. 6, pp. 615-628, 2010.

[90] M. Homola, M. Virk, T. Wallenius, P. Nicklasson and P. Sundsbo, "Effect of atmospheric temperature and droplet size variation on ice accretion of wind turbine blades," *Journal of Wind Engineering and Industrial Aerodynamics,* vol. 98, no. 12, pp. 724-729, 2010.

[91] W. Wright, "User manual for the NASA Glenn Ice Accretion code LEWICE version 2.2.2," NASA, Cleveland, Ohio, 2002.

[92] W. Wright, "User's manual for LEWICE version 3.2," NASA, Cleveland, Ohio, 2008.

[93] W. Wright and A. Rutkowski, "Validation Results for LEWICE 2.0," NASA, Cleveland, Ohio, 1999.

[94] W. Wright, "Validation Results for LEWICE 3.0," NASA, AIAA–2005–1243, Reno, Nevada, 2005.

[95] NATO, "Ice Accretion Simulation Evaluation Test," NATO, RTO-TR-038, NEUILLY-SUR-SEINE CEDEX, France, 2001.

[96] R. Colantonio, “Lewice,” NASA Glenn Research Center, [Online]. Available: https://icebox.grc.nasa.gov/design/lewice.html. [Accessed November 2015].

[97] F. Saeed, S. Gouttebroze and I. Paraschivoiu, “Modified CANICE for Improved Prediction of Airfoil Ice Accretion,” in *8th Aerodynamic Symposium, 48th CASI Conference*, 2001.

[98] I. Paraschivoiu and F. Saeed, “Ice Accretion Simulation Code CANICE,” in *International Aerospace Symposium "Carafoli 2001"*, Bucharest, Romania, 2001.

[99] F. Morency, F. Tezok and I. Paraschivoiu, “Anti-Icing System Simulation Using CANICE,” *Journal of Aircraft,* vol. 36, no. 6, 1999.

[100] K. Hasanzadeh, S. Bourgault-Côté, E. Laurendeau, C. Brette and I. Paraschivoiu, “Validation of multi-time steps Lagrangian/Eulerian RANS based icing code CANICE2D-NS,” in *62nd CASI Aeronautics Conference and AGM 3rd GARDN Conference*, 2015.

[101] K. Hasanzadeh, A. Mosahebi, E. Laurendeau and I. Paraschivoiu, “Framework for Multi-Steps Icing Simulation Code CANICE2D-NS,” in *Canadian Aeronautics and Space Institute Conference (CASI),* Toronto, Canada, 2013.

[102] K. Hasanzadeh and E. Laurendeau, “Validation and User Manual of CANICE2D-NS,” Bombardier Co., 2014.

[103] A. Pueyo, C. Brette, S. Vafa and I. Akel, “A Comparison Exercise of Ice Accretion Simulations with 2D and 3D Solvers,” SAE Technical Paper 2007-01-3338, 2007.

[104] K. Hasanzadeh, A. Mosahebi, E. Laurendeau and I. Paraschivoiu, “Validation and Verification of Multi-Steps Icing Calculation Using CANICE2D-NS Code,” in *AIAA Fluid Dynamics and Co-located Conferences and Exhibit*, San Diego, CA, USA, 2013.

[105] R. Gent, “TRAJICE2 - A Combined Water Droplet Trajectory and Ice Accretion Prediction Program for Aerofoils,” RAE-TR-90054, 1990.

[106] W. B. Wright, R. Gent and D. Guffond, “DRA/NASA/ONERA Collaboration on Icing Research Part II - Predictions of Airfoil Ice Accretion,” NASA CR-202349, 1997.

[107] F. Petrosino, G. Mingione and A. Carozza, “Ice Accretion Model on Multi-Element Airfoil,” in *AIAA Atmospheric and Space Environment Conference*, Toronto, Canada, 2010.

[108] F. Petrosino, G. Mingione, A. Carozza, T. Gilardoni and G. D'Agostini, "Ice Accretion Model on Multi-Element Airfoil," *Journal of Aircraft,* vol. 48, no. 6, 2011.

[109] G. Zanazzi, G. Mingione, A. Pagano and A. Visingardi, "Ice Accretion Prediction on Helicopter Rotor Blade in Hover Flight," in *SAE Aircraft & Engine Icing International Conference,* Seville, Spain, 2007.

[110] C. S. Bidwell, "Icing Analysis of the NASA S3 Icing Research Aircraft Using LEWICE3D Version 2," in *SAE Aircraft and Engine Icing International Conference,* 2007.

[111] B. Wiberg, "Large-scale swept-wing ice accretion modeling in the NASA Glenn Icing Research Tunnel using LEWICE3D," University of Illinois, 2014.

[112] R. Colantonio, "LEWICE 3D," NASA Glenn Research Center. [Online]. [Accessed November 2015].

[113] CERTIF-ICE Inc., "CERTIF-ICE - Home," [Online]. Available: http://certifice.com/index.php/en/. [Accessed November 2015].

[114] H. Beaugendre, F. Morency and W. Habashi, "FENSAP-ICE's Three-Dimensional In-Flight Ice Accretion Module: ICE3D," *Journal of Aircraft,* vol. 40, no. 2, pp. 239-247, 2003.

[115] Y. Bourgault, W. Habashi, J. Dompierre and G. Baruzzi, "A finite element method study of Eulerian droplets impingement models," *International Journal for Numerical Method in Fluids,* vol. 29, pp. 429-449, 1999.

[116] Y. Bourgault, Z. Boutanios and W. Habashi, "Three-dimensional Eulerian approach to droplet impingement simulation using FENSAP-ICE, Part 1: model, algorithm, and validation," *Journal of Aircraf,* vol. 37, no. 1, pp. 95-103, 2000.

[117] Y. Bourgault, H. Beaugendre and W. Habashi, "Development of a Shallow-Water Icing Model in FENSAP-ICE," *Journal of Aircraft,* vol. 37, no. 4, pp. 640-646, 2000.

[118] ANSYS, "ANSYS FENSAP-ICE," ANSYS, 2016. [Online]. Available: http://www.ansys.com/Products/Fluids/ANSYS-FENSAP-ICE. [Accessed 24 February 2016].

[119] T. Hedde and D. Guffond, "ONERA Three-Dimensional Icing Model," *AIAA Journal,* vol. 33, no. 6, pp. 1038-1045, 1995.

[120] E. Montreuil, A. Chazottes, D. Guffond, A. Murrone, F. Caminade and S. Catris, "Enhancement of Prediction Capability in Icing Accretion and related

Performance Penalties Part I: Three-dimensional CFD Prediction of the Ice Accretion," in *1st AIAA Atmospheric and Space Environments Conference*, San Antonio, 2009.

[121] N. Davis, Icing Impacts on Wind Energy Prodution - PhD, Denmark: DTU Wind Energy, 2014.

[122] B. E. Kringlebotn Nygaard, H. Ágústsson and K. Somfalvi-Tóth, "Modeling Wet Snow Accretion on Power Lines: Improvements to Previous Methods Using 50 Years of Observations," *Journal of Applied Meteorology and Climatology,* vol. 52, no. 10, pp. 2189-2203, 2013.

[123] L. Makkonen, "Models for the growth of rime, glaze, icicles and wet snow on structures," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* vol. 358, no. 1776, pp. 2913-2939, 2000.

[124] Ø. Byrkjedal, J. Hanss and H. Van der Velde , "Development of operational forecasting for icing and wind power at cold climate sites," in *IWAIS 2015 – 16th International Workshop on Atmospheric Icing of*, Uppsala, Sweden, 2015.

[125] Ø. Byrkjedal, "Icing map of Sweden," in *Winterwind*, Östersund, Sweden, 2013.

[126] N. N. Davis, P. Pinson, A. N. Hahmann, C. Niels-Erik and M. Žagar, "Identifying and characterizing the impact of turbine icing on wind farm power generation," *Wind Energy,* 2015.

[127] K. Finstad, *Numerical and Experimental Studies of Rime Ice Accretion on Cylinders and Airfoils -- PhD*, Edmonton, Alberta, Canada: University of Alberta -- Department of Geography, 1986.

[128] S. Söderberg, *WICE - WeatherTech Production Loss Model*, Uppsala, Sweden: WeatherTech Scandinavia AB, 2015.

[129] S. Soderberg and M. Baltscheffsky, "Long-term estimates and variability of production losses in icing climates," in *Winterwind*, Skellefteå, Sweden, 2012.

[130] M. Baltscheffsky and S. Söderberg, "Estimation of Production Losses Due to Icing – Development of methods for site assessment and forecasting," in *Winterwind*, Östersund, Sweden, 2013.

[131] S. Söderberg and M. Baltscheffsky, "A novel model approach to test de-icing strategies and de-icing efficiency," in *Winterwind*, Sundsvall, Sweden, 2014.

[132] O. Byrkjedal, J. Hansson and H. van der Velde, "Development of operational forecasting for icing and wind power at cold climate sites," in *IWAIS*, Uppsala,

2015.

[133] S. Kaija and J. Dillingh, “A Generic Model for Ice Growth and Ice Decrease Process,” in *Winterwind*, Piteå, Sweden, 2015.

[134] T. T. W. I. B.-G. M. D. R. H. A. L. E. P. G. R. L. T. Laakso, "State-of-the-art of wind energy in cold climates," VTT Working Papers, 2010.

[135] S. Ferguson, “Wind energy development in harsh environments subtopic 3: Design and installation challenges,” in *GL Garrad Hassen Presentation*, 2010.

[136] L. Kokkala, “Icing Studies and ENERCON Rotor Blade Heating System (RBHS),” in *Optimising Wind Farms in COld Climates*, Helsinki, 2014.

[137] Enercon, “ ENERCON rotor blade de-icing system,” *WINDBLATT*, pp. 10-11, January 2011.

[138] J. Quitter, “Wind Power Monthly: Vestas reveals de-icing system,” Wind Power Monthly, 23 October 2013. [Online]. Available: http://www.windpowermonthly.com/article/1217693/vestas-reveals-de-icing-system. [Accessed 6 November 2015].

[139] D. Hautmann, “Electricity that Comes from the Cold,” *H!tech Magazine*, pp. 34-35, 2013.

[140] P. Jordaens, “Why performing climate chamber tests for wind energy applications?,” OWI-Lab, 2014.

[141] N. Vindkraft, “Study of wind turbine foundations in cold climate,” Nordisk Vindkraft, 2012.

[142] M. Gemuend, “Cold climate – test of pitch system,” GL, 2013.

[143] B. C. J. N. R. V. S. P. Jordaens, “Cold start of a 5.5MW offshore transformer,” *Transformer Magazine*, vol. 2, no. 2, pp. 28-35, 2015.

[144] P. J. J. (OWI-Lab) and S. G. (. W. Power), “Extreme cold start-up validation of a wind turbine gearbox by the use of a large climatic test chamber,” in *EWEA 2014*, Barcelona, 2014.

[145] T. O. S. Patel, “Prepare your renewable plant for cold weather operations,” *Power Magazine*, 2014.

[146] O. Parent and I. Adrian, “Anti-icing and de-icing techniques for wind turbines: Critical review,” *Elsevier Cold Regions Science and Technology*, vol. 65, no. 1,

pp. 88-96, 2011.

[147] L. Battisti, Wind Turbines in Cold Climates - Icing Impacts and Mitigation Systems, Springer, 2015.

[148] S. Kolar, “A Comparison of Three Different Anti- and De-Icing Techniques Based on SCADA-Data,” in *IWAIS*, Uppsala, 2015.

[149] Deutsche WindGuard, “Summary of a Technical Validation of ENERCON's Rotor Blade De-Icing System,” Deutsche WindGuard Consulting Gmbh, Varel, 2011.

[150] R. Cattin, “Performance of Enercon wind turbines under icing conditions in Europe,” in *WinterWind*, Sundsvall, 2014.

[151] E. Sjögren, “Wind Energy in Cold Climate - experiences from Sweden and the world,” in *WinterWind*, Pitea, 2015.

[152] B. D. Nielsen, “Vestas de-icing system,” in *WinterWind*, Sundsvall, 2014.

[153] B. Nielsen, “Vestas De-icing System,” in *WinterWind*, Pitea, 2015.

[154] Vestas, “Vestas Cold Climate solutions brochure,” Vestas, 2015. [Online]. Available: https://www.vestas.com/en/products_and_services/options_and_solutions#!vestas-cold-climate-solutions. [Accessed 6 November 2015].

[155] J. Birkemeyer, “Anti-icing System on Nordex wind turbines - lightning protection and operation experience,” in *WinterWind*, Pitea, 2015.

[156] F. D. Madsen, “Siemens Wind Power Blade De-Icing,” in *WinterWind 2014*, Sundsvall, 2014.

[157] Wicetec, “Wicetec Ice Prevention Systems,” [Online]. Available: http://wicetec.com/. [Accessed 23 October 2015].

[158] Wicetec, “Wicetec Ice Prevention System brochure,” 2015. [Online]. Available: http://wicetec.com/wp-content/uploads/2015/09/Wicetec_IPS_description_A4_v1_5_compr.pdf. [Accessed 23 October 2015].

[159] P. Antikainen, “Ice Prevention Systems for wind turbines,” in *Wind Power Monthly: Optimizing Wind Farms in Cold Climates*, Helsinki, 2015.

[160] Nordex, “Anti-Icing - Higher Yields in Icy Conditions,” [Online]. Available: http://www.nordex-

online.com/fileadmin/MEDIA/Produktinfos/EN/Nordex_Anti-Icing_en.pdf. [Accessed 23 October 2015].

[161] Nordex, “Anti Icing brochure,” [Online]. Available: http://www.blaikenvind.se/wp-content/uploads/2013/01/Nordex_Anti-Icing_en.pdf. [Accessed 23 October 2015].

[162] B. Birkemose, “Siemense Wind Power Blade De-icing - 20 years of experience with blade de-icing,” in *WinterWind*, Pitea, 2015.

[163] Siemens AB, “Robust and proven technology for de-icing,” Siemens AB, January 2013. [Online]. Available: http://w3.siemens.se/home/se/sv/energy/energiproduktion/vindkraft/documents/produktblad%20wind%20power_2013wp_001a_webb.pdf. [Accessed 13 October 2015].

[164] F. D. Madsen, “Siemens Blade De-icing,” in *NordVind Seminar"Vindkraft i kaldt klima"*, Copenhagen, 01.12.2011.

[165] Siemens AG, “Onshore Wind Customer Event,” in *Onshore Wind Customer Event, http://w5.siemens.com/belux/web/en/energy/events/Documents/Siemens_Customer_Event%201492015.pdf*, Beveren Waas, 2015.

[166] E. Peltola, M. Marjaniemi, H. Stiesdal and J. Järvelä, “An IcePrevention System for the Wind Turbine Blades,” in *European Wind Energy Conference*, Nice, 1999.

[167] Gamesa, “Gamesa technological solutions for regions with icy conditions,” September 2014. [Online]. Available: http://www.gamesacorp.com/recursos/doc/productos-servicios/aerogeneradores/technological-solutions-for-regions-with-icy-conditions.pdf. [Accessed 16 October 2015].

[168] K. Johansson, “Anti-icing and Deicing of Wind Turbines using Microwave Technology,” in *WinterWind 2014*, Sundsvall, 2014.

[169] J. Karthäuser, “Deicing of Wind Turbines using Microwave Technology,” in *WinterWind conference*, Piteå, 2015.

[170] P. Laaksonen, “Using De-Icing and Anti-Icing Systems to tackle production loss,” in *Wind Power Monthly's Optimizing Wind Farms in Cold Climates forum*, Helsinki, 2014.

[171] H. Gedda, “Airborne de-icing solution for wind turbines,” in *WinterWind*, Åre,

2016.

[172] L. Makkonen, “Back to the basics: Wettability, icing and ice adhesion,” in *IWAIS,* Uppsala, 2015.

[173] S. Chemyy, M. Jäm, K. Shimizu, A. Swerin, S. U. Pedersen, K. Daasbjerg, L. Makkonen, P. Claesson and J. Iruthayaraj, “Superhydrophilic Polyelectrolyte Brush Layers with Imparted Anti-Icing Properties: Effect of Counter ions,” *ACS Appl. Mater. Interfaces,* vol. 6, no. 9, pp. 6487-6496, 2014.

[174] G. Heydari, E. Thormann, M. Jäm, E. Tyrode and P. Claesson, “Hydrophobic Surfaces: Topography Effects on Wetting by Supercooled Water and Freezing Delay,” *The Journal of Physical Chemistry,* vol. 117, no. 42, pp. 21752-21762, 2013.

[175] L. Makkonen, “Ice Adhesion —Theory, Measurements and Countermeasures,” *Journal of Adhesion Science and Technology,* vol. 26, no. 4-5, pp. 413-445, 2012.

[176] C. Laforte, C. Blackburn and J. Perron, “A Review of Icephobic Coating Performances over the Last Decade,” in *SAE 2015 International Conference on Icing of Aircraft, Engines, and Structures*, Prague, 2015.

[177] F. Arianpour, M. Farzaneh and R. Jafari, “Hydrophobic and anti-ice properties of homogeneous and heterogeneous nanoparticle coatings on Al 6061 substrates,” in *IWAIS*, Uppsala, 2015.

[178] H. Koivuluoto, C. Stenroos, R. Ruohomaa, G. Bolelli, L. Lusvarghi and P. Vuoristo, “Research on icing behavior and ice adhesion testing of icephobic surfaces,” in *IWAIS*, Uppsala, 2015.

[179] TopNano, “TopNANO - Top-level nanoscale coatings and surface treatment to prevent and combat condensation of water, ice formation, ice growth and adhesion with applications in aircraft, wind turbines and heat exchangers for improved energy efficiency,” Internal final reprot, 2014.

[180] H. Endo, S. Kimura and I. Nakane, “Behavior of a Small Water Droplet on a Superhydrophobic Coating in a Cold Environment,” in *IWAIS,* St. Johns, 2013.

[181] A. Swerin, “Breaking the ice using passive anti-icing coatings – Lessons learned from the Nordic TopNANO research project,” in *WinterWind conferece,* Piteå, 2015.

[182] HYDROBOND, “HYDROBOND EU FP7 project (2009-2013),” [Online]. Available: http://hydro-bond.eu/. [Accessed 12 May 2016].

[183] WALiD, “WALiD EU FP7 project (2013-2017),” [Online]. Available: http://www.eu-walid.com/. [Accessed 12 May 2016].

[184] SANAD, “SANAD EU FP7 project (2013-2017),” [Online]. Available: http://www.sanadproject.eu/. [Accessed 12 May 2016].

[185] TOPNANO, “TOPNANO Nordic Energy Research project (2010-2014),” [Online]. Available: http://www.topnano.se/en/Sidor/default.aspx. [Accessed 12 May 2016].

[186] T. Wogan, “Best icephobic coating ever created gives ice the slip,” [Online]. Available: http://www.rsc.org/chemistryworld/2016/03/icephobic-coating-polymer. [Accessed 12 May 2016].

[187] A. Camion, “Wind Turbine Operation Optimization under icing and cold climate,” in *8th Quebec Wind Energy Conference,* Gaspé, 2014.

[188] T. Léger, “Operational Strategies in Cold and Harsh Climates,” in *CANWEA O&M Summit,* Toronto, 2015.

[189] J. Nelson, “L'expérience de TransAlta avec le givrage des pales,” in *Quebec's 6th Wind Energy Conference,* Carleton-sur-Mer, 2012.

[190] J. Nelson, “TransAlta's Experience with Blade Icing,” in *WinterWind,* Sundsvall, 2014.

[191] D. Bolduc, “A look at wind turbine performance in Canadian icing climate,” in *WinterWind,* Åre, 2016.

[192] Repower, “Operational experience of REpower MM-CCV under icing conditions,” in *WinterWind,* Skellefteå, 2012.

[193] L. A. Karlberg, *New de-icing systems go live,* Pitea: WinterWind Conference Program Book, 2015.

[194] H. Winkelmeier, “WF Moschkogel in the Austrian Alps,” in *Ice & Rocks III conference,* Zadar, Croatia, 2010.

[195] TÜV Nord, “For assessment of the functionality of ice detection systems to prevent ice throw at ENERCON wind energy converters. Ice detection system based on the ENERCON power curve method,” Hamburg, 2014.

[196] R. Lemoine, “Using operational data to overcome the challenges of icing variability - Enercon Gries Project,” in *WindPower Monthly's Optimising Wind Farms in Cold Climates forum,* Helsinki, 2014.

[197] T. Burchart, "Operational Experiences and Challenges during Icing Conditions," in *IQPC Anti-Icing for Wind Turbines conference*, Hamburg, 2015.

[198] R. Lemoine, "Operating Wind turbines in extreme icing conditions: lessons learned from the Gries project," in *IQPC Anti-Icing for Wind Turbines conference*, Hamburg, 2015.

[199] K. Roloff, "Enercons experiences in operating wind turbines under icy conditions," in *IQPC Anti-Icing for Wind Turbines conference*, Hamburg, 2015.

[200] K. Roloff, "Performance of ENERCON turbines under icing conditions of different severity," in *WindPower Monthly's Optimising Wind Farms in Cold Climates forum*, Helsinki, 2015.

[201] Lagerwey, "Lagerwey," Lagerwey, 2015. [Online]. Available: http://www.lagerwey.com/. [Accessed 4 March 2016].

[202] J. Birkemeyer, "Anti-Icing System on Nordex wind turbines - qualification with focus on lightning protection," in *Wind Turbine Blade manufacturer conference*, Düsseldorf, 2014.

[203] N. Lehming, "NORDEX OPERATION EXPERIENCE IN COLD CLIMATE," in *Windpower Monthly's Optimizing Wind Farms in Cold Climates forum*, Helsinki, 2015.

[204] B. Radowitz, "Recharged IN DEPTH: The cold-climate market is hotting up," February 2016. [Online]. Available: http://www.rechargenews.com/wind/1422120/in-depth-the-cold-climate-market-is-hotting-up. [Accessed 4 May 2016].

[205] Northern Power Systems, "NPS 100C turbine model," Northern Power Systems, [Online]. Available: http://www.northernpower.com/products/nps100/. [Accessed 8 March 2016].

[206] A. Camion, "Wind turbine operation optimization under icing and cold climate," in *Wind optimization, maintenance and repair summit, Wind Energy Update*, Toronto, 2014.

[207] C. Bolduc, "Cold Climate Operation," in *CanWEA Operation & Maintenance Summit*, Toronto, 2015.

[208] Senvion, "Senvion launches 3.2M114 for Canadian market," 30 October 2014. [Online]. Available: https://www.senvion.com/global/en/press-media/press-releases/detail/repower-installs-worlds-largest-wind-turbine-in-brunsbuettel-schleswig-holstein-1/. [Accessed 16 October 2015].

[209] Siemens, "Analysis of Siemens de-icing system (report no: KVT/HS/2013/R04) [available upon request]," 2013.

[210] D. Shymanski, "Anti-Icing/de-icing solution developments," in *WinterWind*, Umeå, 2011.

[211] Kelly Aerospace Thermal Systems, "Wind Turbine Ice Protection System," 2011. [Online]. Available: http://www.kellyaerospace.com/wind_turbine_deice.html http://www.kellyaerospace.com/thermalsystems/wind_turbine_ice_protection.html. [Accessed 23 October 2015].

[212] E. Pederson and H. Gedda, "Wind Turbine Ice Protection System (WTIPS)," in *WinterWind*, Norrköping, 2008.

[213] E. Pederson and H. Gedda, "Wind Turbine Ice Protection System (WTIPS)," in *IWAIS*, Andermatt, 2009.

[214] G. Ronsted, "The rapidly growing interest in wind energy in cold climates," in *VindKraftNet*, Malmö, 2011.

[215] ADIOS Patent Gmbh, "ADIOS Patent Anti- and de-ice Operating System," [Online]. Available: http://www.adios-patent.de/index.php/en/home-2. [Accessed 24 February 2016].

[216] ADIOS Patent Gmbh, "ADIOS brochure," http://www.adios-patent.de/pdf/ADIOS-Product_Datasheet_EN.pdf, Hamburg, 2015.

[217] R. Cattin, S. Kunz, A. Heimo, G. Russi, M. Russi and M. Tiefgraber, "Wind Turbine Ice Throw Studies in the Swiss Alps," EWEC 2007, 7 to 10 April, Milano, Italy, 2007.

[218] R. Cattin, "Ice throw studies, Gütsch and St. Brais," 8. Februar 2012. [Online]. Available: http://winterwind.se/2012/download/6b_winterwind_icethrow_cattin.pdf.

[219] A. Krenn and et al, "Risk of Icefall in the international context," Sundsvall, Sweden, 2014.

[220] M. Wadham-Gagnon and e. al, "IEA task 19 - Ice throw guidelines," in *WinterWind conference*, Piteå, 2015.

[221] H. Seifert, A. Westerhellweg and J. Kröning, "Risk analysis of ice throw from wind turbines," BOREAS VI, 9 to 11 April 2003, 2003.

[222] B. Tammelin, M. Cavaliere, H. Holtinnen, C. Morgan, H. Seifert and K. Säntti, "Wind Energy in Cold Climate," Final Report WECO Finnish Meteorological Institute, Helsinki, Finland, February 2000., 2000.

[223] A. Franks, R. Whitehead, P. Crossthwaite and L. Smail, "Application of QRA in operational safty issues," Crown copyright, Norwich NR3 1BQ, 2002.

[224] A. Krenn and et al, "IEA Task19, Standardized methodology for the elaboration of the ice throw risk assessments," in *Winterwind 2016*, Are, Sweden.

[225] R. Cattin, S. Koller and U. Heikkilä, "ICING AT ST. BRAIS AND MONT CROSIN," in *Executive summary for Swiss Federal Office of Energy SFOE*, Bern, 2016.

[226] C. Morgan, "Assessement of safety risks arising from wind turbine icing," in *EWEC*, Dublin, 1997.

[227] C. Morgan, E. Bossanyi and H. Seifert, "Assessement of safety risks arising from wind turbine icing," in *Boreas IV*, 1998.

[228] H. Seifert and A. Westerhellweg, "Risk Analysis of Ice throw from wind turbines," in *Boreas*, Pyhätunturi, 2003 (A).

[229] R. Bredesen and H. Refsum, "Methods for evaluating risk caused by ice throw and ice fall from wind turbines and other tall structures," in *IWAIS conference*, Uppsala, 2015.

[230] R. Bredesen, "Ice risk forecast system for operational wind farms," in *WinterWind*, Åre, 2016.

[231] B. Göransson and D. Haaheim, "Swedish Wind Energy Associations view on wind energy in cold climates," in *WinterWind*, Åre, 2016.

[232] B. Boucher, "Access to Wind Turbines During Winter Months," in *Wind Energy Update Operation and Maintenance Summit*, Toronto, 2014.

[233] R. Roy, "Caribou Wind Parc (CWP) Ice Mitigation R&D Overview," in *Wind Optimization, Maintenance and Repair Summit*, Toronto, 2014.

[234] B. Brailey, "Validation of New Model for Short-Term Forecasting of Turbine Icing - Using SCADA data from Scandinavian wind farms," in *Winterwind*, Piteå, Sweden, 2015.

[235] J. Persson, H. Körnich, B. Stensen, E. Olsson, H. Bergström and A. Sjöblom, "Probabilistic forecasting of icing and production losses," in *Winterwind*, Piteå,

2015.

[236] N. Davis, A. Hahmann, N. Clausen, M. Žagar and P. Pinson, "Forecasting Production Losses by Applying the Makkonen Icing Model to Wind Turbine Blades," in *The 15th International Workshop on Atmospheric Icing of Structures*, St. John's, Newfoundland and Labrador, Canada, 2013.

[237] J. Yang, W. Yu, J. Choisnard, A. Forcione and S. Antic, "Forecast of icing events at a wind farm in Sweden," *Journal of Applied Meteorology and Climatology*, pp. 262-281. http://doi.org/10.1175/JAMC-D-13-09.1, 2014.

[238] Schipper, Jarno ;, "Icing forecast for wind turbine - Vereisungsvorhersage für Windenergieanlagen," DNV GL, 2015.

[239] Ø. Byrkjedal, R. E. Bredesen and A. Line Løvholm, "Operational forecasting of icing and wind power at cold climate sites," in *Winterwind*, Sundsvall, 2014.

[240] Ø. Byrkjedal , "Icing forecast," Kjeller Vindteknikk, [Online]. Available: http://www.vindteknikk.com/services/analyses/wind-power/post-construction/icing-forecast. [Accessed 01 12 2015].

[241] T. Karlsson, V. Turkia, T. Wallenius and J. Miettinen, "Production Loss estimation for wind power forecasting," in *Winterwind*, Sundsvall, Sweden, 2014.

[242] R. Oechslin, "Wind power forecasting considering icing," Institute of meteorology and geophysics university of Innsbruch, Austria, 2011.

[243] E. Gregow, B. Bernstein, I. Wittmeyer and J. Hirvonen, "LAPS–LOWICE: A Real-Time System for the Assessment of Low-Level Icing Conditions and Their Effect on Wind Power," *J. Atmos. Oceanic Technol., 32,* pp. 1447–1463. doi: http://dx.doi.org/10.1175/JTECH-D-14-00151.1 , 2015.

[244] B. Bernstein, E. Gregow and I. Wittmeyer, "Innovations in F-LOWICE Real-Time Forecasts of Wind Power and Icing Effects," in *IWAIS,* Uppsala, 2015.

[245] "Services to Wind Power sector - Icing," Finnish meteorological intitute , [Online]. Available: http://en.ilmatieteenlaitos.fi/wind-energy. [Accessed 01 12 2015].

[246] "Icing forecast for wind turbine now possible," Swedish meteorological and hydrological institute, [Online]. Available: http://www.smhi.se/en/research/research-news/icing-forecasts-for-wind-turbines-now-possible-1.85372. [Accessed 01 12 2015].

[247] “Icing,” VORTEX, [Online]. Available: http://www.vortexfdc.com/solutions/icing.html. [Accessed 01 12 2015].

[248] “Icing,” WeatherTech, [Online]. Available: http://www.s1106835.crystone.net/?q=en/node/11. [Accessed 01 12 2015].

[249] “Wind Turbine Weather,” Leading Edge Atmospherics, [Online]. Available: http://icingweather.com/whatwedo/windturbine. [Accessed 01 12 2015].

[250] IEC, “IEC 61400-3:2005 (ed1) Wind turbines - Part 3: Design requirements for offshore turbines,” IEC, 2005.

[251] G. Lloyd, “GL Wind-Technical Note 067: Certification of Wind Turbines for Extreme Temperatures (here: Cold Climate),” Germanischer Lloyd, Hamburg, 2011.

[252] G. Lloyd, “Guideline for the Certification of Wind Turbines,” Germanischer Lloyd, Hamburg, 2004.

[253] Germanischer Lloyd, Guideline for the certification of wind turbines, 2010 ed., Hamburg: Germanischer Lloyd Industrial Services GmbH, Renewables certification, 2010.

[254] SAE International, “SAE AIR 5666: Icing Wind Tunnel Interfacility Comparison Tests,” SAE, 2012.

[255] CSA (Canadian Standards Association), “CSA-S37-01 "Antennas, Towers, and Antenna-Supporting Structures,” CSA, Toronto, 2001.

[256] DIBt (Deutche Institut fur Bautechnik), “Richtlinie für Windenergieanlagen Einwirkungen und Standsicherheitsnachweise,” DIBt, Berlin, 2012.

[257] P. Jordaens, “Cold climate issues for wind turbine machinery,” *Windtech International magazine*, vol. 2, no. 1, pp. 17-19, 2015.

[258] Deutsche WindGuard Wind Tunnel Services GmbH, “Wind Tunnel Centre Services,” Deutsche WindGuard Engineering GmbH, [Online]. Available: http://www.windtunnelcentre.com/services.html#none. [Accessed 1 March 2016].

[259] Deutsche WindGuard Engineering GmbH, “Contact,” Deutsche WindGuard Engineering GmbH, 2 3 2016. [Online]. Available: http://www.windtunnelcentre.com/service/contact.html. [Accessed 2 3 2016].

[260] Deutsche WindGuard GmbH, “Sensor Testing Under Icing Conditions,” Deutsche WindGuard GmbH, 2 3 2016. [Online]. Available:

http://www.windguard.com/services/wind-tunnel-centre/sensor-testing-under-icing-conditions.html. [Accessed 2 3 2016].

[261] RTA, “Vienna Climatic Wind Tunnel,” Rail Tec Arsenal Fahrzeugversuchsanlage GmbH (RTA), 2 3 2016. [Online]. Available: http://www.rta.eu/en/facility/customer-area. [Accessed 2 3 2016].

[262] RTA, “Vienna Climatic Wind Tunnel - Contacts,” Rail Tec Arsenal Fahrzeugversuchsanlage GmbH (RTA), 2 3 2016. [Online]. Available: http://www.rta.eu/en/about-us/contact/management. [Accessed 2 3 2016].

[263] RTA, “General Information and Guide for Customers - Climatic / Icing Wind Tunnel Vienna (ver. 2.3 PDF),” Rail Tec Arsenal Fahrzeugversuchsanlage GmbH (RTA), Vienna, 2015.

[264] NRC, “3 m x 6 m icing wind tunnel,” National Research Council Canada, 2 3 2016. [Online]. Available: http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/wind_tunnel/3x6_metre.html. [Accessed 2 3 2016].

[265] D. Orchard, C. Clark and M. Oleskiw, “Development of a Supercooled Large Droplet Environment within the NRC Altitude Icing Wind Tunnel (2015-01-2092),” in *SAE 2015 International Conference on Icing of Aircraft, Engines and Structures,* Prague, 2015.

[266] D. Fuleki, J. Chalmers and B. Galeote, “Technique for Ice Crystal Particle Size Measurements and Results for the National Research Council of Canada Altitude Ice Crystal Test System (2015-01-2125),” in *SAE 2015 International Conference on Icing of Aircraft, Engines and Structures,* Prague, 2015.

[267] P. Struk, T. Bartkus, J. Tsao, T. Currie and D. Fuleki, “Ice Accretion Measurements on an Airfoil and Wedge in Mixed-Phase Conditions,” in *SAE 2015 International Conference on Icing of Aircraft, Engines and Structures,* Prague, 2015.

[268] T. Currie, D. Fuleki and C. Davison, “Simulation of Ice Particle Melting in the NRC RATFac Mixed-Phase Icing Tunnel (2015-01-2107),” in *SAE 2015 International Conference on Icing of Aircraft, Engines and Structures,* Prague, 2015.

[269] C. Clark and D. Orchard, “Design and Calibration of a New High-Speed Insert for the NRC Altitude Icing Wind Tunnel,” in *SAE 2015 International Conference on Icing of Aircraft, Engines and Structures,* Prague, 2015.

[270] NRC, “Altitude icing wind tunnel,” National Research Council Canada, 2 3

2016. [Online]. Available: http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/wind_tunnel/altitude_icing.html. [Accessed 2 3 2016].

[271] X. Wang, E. L. Bibeau and G. F. Naterer, "Experimental Investigation of Energy Losses due to Icing of a Wind Turbine," in *International Conference on Power Engineering - 2007 (23-27.10.2007 China),* Hangzhou, 2007.

[272] A. G. Kraj and E. Bibeau, "Icing characteristics and mitigation strategies for wind turbines in cold climates: accumulation rate," in *Renewable Energy 2006 Makuhari - Japan,* Chiba, 2006.

[273] University of Manitoba, "Renewable energy research," University of Manitoba, Canada - Mechanical and Manufacturing Engineering Department, 2 3 2016. [Online]. Available: http://home.cc.umanitoba.ca/~bibeauel/index.php?pg=Research. [Accessed 2 3 2016].

[274] A. G. Kraj, "ndex of /~bibeauel/research/thesis," 3 2007. [Online]. Available: http://home.cc.umanitoba.ca/~bibeauel/research/thesis/2007_Andrea.pdf. [Accessed 15 03 2016].

[275] "Anti-icing Materials International Laboratory (AMIL)," University of Chicoutimi, 2012. [Online]. Available: http://www.uqac.ca/amil/en/. [Accessed 8 April 2016].

[276] L. Makkonen, "Ice Adhesion - Theory, Measurements and Countermeasures," *Journal of Adhesion Science and Technology,* vol. 26, no. Ice adhesion, pp. 413 - 445, 2012.

[277] M. Tiihonen, T. Jokela, L. Makkonen and G.-J. Bluemink, "VTT Icing Wind Tunnel 2.0," in *Winterwind International Wind Energy Conference 2016,* Åre - Sweden, 2016.

[278] V. &. L. Oy, "Labkotec Pre-Certificate," 22 6 2011. [Online]. Available: http://www.labkotec.fi/sites/default/files/Labkotec_pre_certificate.pdf. [Accessed 15 3 2016].

[279] T. Jokela, "Brochure - VTT Icing Wind Tunnel 2.0," 15 03 2016. [Online]. Available: http://www.vttresearch.com/Documents/Low%20Carbon%20Energy/Wind%20energy/Icing_Wind_Tunnel_02022016.pdf. [Accessed 15 03 2016].

[280] VTT Ltd - Finland;, "Coating Tests," 15 03 2016. [Online]. Available: http://www.vttresearch.com/Documents/Low%20Carbon%20Energy/Wind%20e

nergy/Coating_Tests_02022016.pdf. [Accessed 15 03 2016].

[281] C. Stenroos, “PROPERTIES OF ICEPHOBIC SURFACES IN DIFFERENT ICING CONDITIONS,” Tampere University of Technology, MSc thesis, Tampere, 2015.

[282] H. Koivuluoto, C. Stenroos, R. Ruohomaa, G. Bolelli, L. Lusvarghi and P. Vuoristo, “Research on icing behavior and ice adhesion testing of icephobic surfaces,” in *IWAIS*, Uppsala, 2015.

[283] Fraunhofer IFAM, “Icing Laboratory With Integrated Wind Tunnel,” 01 2016. [Online]. Available: http://www.ifam.fraunhofer.de/content/dam/ifam/en/documents/Adhesive_Bonding_Surfaces/Paint_Lacquer_Technology/ice_lab_en_fraunhofer_ifam.pdf. [Accessed 15 03 2016].

[284] Fraunhofer Institute for Mnufacturing Technology and Advanced Materials IFAM, “Icing Laboratory With Integrated Wind Tunnel,” [Online]. Available: http://www.ifam.fraunhofer.de/content/dam/ifam/en/documents/Adhesive_Bonding_Surfaces/Paint_Lacquer_Technology/ice_lab_en_fraunhofer_ifam.pdf. [Accessed 16 03 2016].

[285] CARDC, “0.3mx0.2m Icing Wind Tunnel,” China Aerodynamics Research and Development Center, 27 1 2015. [Online]. Available: http://www.cardc.cn:88/html/Facility/f6/107.html. [Accessed 15 03 2016].

[286] H. H. Koss, H. Gjelstrup and C. T. Georgakis, “Experimental study of ice accretion on circular cylinders at moderate low temperatures,” *Journal of Wind Engineering and Industrial Aerodynamics,* vol. 12, no. Ice accretion, pp. 104-106, 540-546, 2012.

[287] C. Demartino, H. H. Koss and F. Ricciardelli, “Experimental study of the effect of icing on the aerodynamics of circular cylinders – Part I: Cross flow,” in *Proceedings of the 6th European and African Wind Engineering Conference,* Cambridge, UK, 2013.

[288] A. Hudecz, H. Koss and M. O. Hansen, “Accretion on Wind Turbine Blades,” in *Proceedings of IWAIS XV*, St. John’s, Newfoundland and Labrador, Canada, 2013.

[289] E. Mattiello, “Aerodynamic forces on a NACA 0015 airfoil section model,” in *Proceedings of the 13th Conference of the Italian Association for Wind Engineering*, Genova, Italy, 2014.

[290] M. B. Eriksen, E. Mattiello and S. . V. Larsen, “The Climatic wind tunnel:

Research activities and developments," in *Symposium on the Dynamics and Aerodynamics of Cables (SDAC)*, Copenhagen, Denmark, 2014.

[291] E. Mattiello, T. Ingvorsen and S. V. Larsen, "Experimental and Numerical Simulations of In-Cloud Icing on an Airfoil," in *ICWE 14: 14th International conference on wind engineering*, Porto Alegre, Brazil, 2015.

[292] M. B. Eriksen and S. V. Larsen, "Wind Tunnel Testing of Structural Cables: Climatic Effects Including Ice Accretion," in *SEWC 2015: 5th Structural Engineers World Congress*, Singapore, 2015.

[293] N. Davis and N.-E. Clausen, "Simulated Ice Growth on a Blade Profile and Representative Cylinders," in *WinterWind 2015*, Piteå, 2015 (2).

[294] FORCE Technology, "Wind Tunnels," FORCE Technology, [Online]. Available: http://forcetechnology.com/en/all-industry-facilities/wind-tunnel-facility. [Accessed 15 3 2016].

[295] D. T. C. E. &. A. A. g. (CEAero), "Climatic Wind Tunnel," DTU , 07 May 2014. [Online]. Available: http://www.windengineering.byg.dtu.dk/Research/Climatic_Wind_Tunnel. [Accessed 21 September 2015].

[296] Technology, Force, "Wind Tunnels," Force Technology, 2014. [Online]. Available: http://forcetechnology.com/en/all-industry-facilities/wind-tunnel-facility. [Accessed 16 03 2016].

[297] B. Matteo, "Cloud Characterization in CIRA Icing Wind Tunnel," 2007. [Online]. Available: http://www.fedoa.unina.it/1473/1/Bellucci_Ingegneria_Aerospaziale_Navale_e_della_Qualita.pdf. [Accessed 15 03 2016].

[298] I. A. R. C. -. CIRA, "IWT - Icing Wind Tunnel," CIRA, [Online]. Available: http://www.cira.it/en/impianti-en/iwt-icing-wind-tunnel. [Accessed 15 03 2016].

[299] R. Waldman and H. Hu, "High-Speed Imaging to Quantify the Transient Ice Accretion Process on a NACA 0012 Airfoil," *Journal of Aircraft,* vol. DOI: 10.2514/1.C033367, no. Ice accretion process, p. 9, 2015.

[300] K. Zhang, W. Tian and H. Hu, "An Experimental Investigation on the Surface Water Transport Process over an Airfoil by using a Digital Image Projection Technique," *Experiments in Fluids,* vol. 56:173, no. DOI: 10.1007/s00348-015-2046-z, p. 16 pages, 2015.

[301] H. Hu and Z. Jin, "An Icing Physics Study by using Lifetime-based Molecular

Tagging Thermometry Technique," *International Journal of Multiphase Flow,* Vols. Vol. 36, No.8, no. DOI:10.1016/j.ijmultiphaseflow.2010.04.001, p. 672–681, 2010.

[302] H. Hu and D. Huang, "Simultaneous Measurements of Droplet Size and Transient Temperature within Surface Water Droplets," *AIAA Journal,* Vols. Vol.47, No.4, no. http://arc.aiaa.org/doi/pdf/10.2514/1.37158, pp. 813-820, 2009.

[303] H. Li, R. Waldeman and H. Hu, "An Experimental Investigation on Unsteady Heat Transfer and Transient Icing Process upon Impingement of Water Droplets," in *AIAA Science and Technology Forum and Exposition (SciTech2016),* San Diego, California, US, 2016.

[304] H. Li, R. Waldman and H. Hu, "An Experimental Investigation on Unsteady Heat Transfer and Transient Icing Process upon Impingement of Water Droplets," in *AIAA Science and Technology Forum and Exposition (SciTech2016),* San Diego, California, US, 2016.

[305] Iowa State University - US, "Aircraft Icing Physics and Anti-/De-icing Technology Laboratory," College of Engineering | Department of Aerospace Engineering, [Online]. Available: http://www.aere.iastate.edu/icing/. [Accessed 15 03 2016].

[306] I. S. University, "Advanced Flow Diagnostics and Experimental Aerodynamics," College of Engineering / Department of Aerospace Engineering, [Online]. Available: http://www.aere.iastate.edu/~huhui/. [Accessed 15 03 2016].

[307] Iowa State University - News Service, "Iowa State's icing wind tunnel blows cold and hard to study ice on wings, turbine blades - See more at: http://www.news.iastate.edu/news/2014/02/11/icingtunnel#sthash.SWLcFBai.dpuf," Iowa State University, US, [Online]. Available: http://www.news.iastate.edu/news/2014/02/11/icingtunnel. [Accessed 16 03 2016].

[308] National Aeronautics and Space Administration, "NASA´s Aeronautics Test Pogram - Icing Research Tunnel," 05 2009. [Online]. Available: http://facilities.grc.nasa.gov/documents/TOPS/TopIRT.pdf. [Accessed 15 03 2016].

[309] National Aeronautics and Space Administration, "Icing Research Tunnel (IRT)," NASA, 30 11 2011. [Online]. Available: http://facilities.grc.nasa.gov/irt/index.html. [Accessed 15 03 2016].

[310] National Aeronautics and Space Administration, “Icing Research Tunnel,” NASA, 25 03 2011. [Online]. Available: http://facilities.grc.nasa.gov/irt/contact.html. [Accessed 15 03 2016].

[311] PennState, “Adverse Environment Rotor Test Stand,” [Online]. Available: http://www.aero.psu.edu/Facilities/AERTS/. [Accessed 7 April 2016].

[312] S. Gonzalez Ruiz, “Calibration of the VKI Cold Wind Tunnel by Interferometric Laser Imaging,” in *SAE 2015 International, Conference on Icing of Aircraft, Engines and Structures*, Prague, Czech Republic, 2015.

[313] The Von Karman Institute, “Low Speed Wind Tunnels - Cold Wind Tunnel CWT-1,” VKI, 2009. [Online]. Available: https://www.vki.ac.be/index.php/research-consulting-mainmenu-107/facilities-other-menu-148/low-speed-wt-other-menu-151/63-cold-wind-tunnel-cwt-1. [Accessed 16 03 2016].

[314] The Von Karman Institute, “Home,” VKI, 2009. [Online]. Available: https://www.vki.ac.be/. [Accessed 16 03 2016].

[315] D. Hammond, “The Cranfield University Icing Tunnel,” in *41st Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meeting (http://dx.doi.org/10.2514/6.2003-901),* Reno, Nevada, US, 2003.

[316] Cranfield University, UK, “Icing Tunnel,” Cranfield University, 2016. [Online]. Available: https://www.cranfield.ac.uk/About/People-and-Resources/resources/facilities/soe/Icing-Tunnel. [Accessed 16 03 2016].

[317] Cranfield University, “Icing Tunnel - Overview of Icing Tunnel (PDF, Link),” 2016. [Online]. Available: https://www.cranfield.ac.uk/About/People-and-Resources/resources/facilities/soe/Icing-Tunnel. [Accessed 16 03 2016].

[318] K. Shigeo, Y. Yamagishi, H. Morikawa, K. Tetsuya, S. Tekeshi, T. Aaltio, H. Valo and J. Hietanen, “De-Icing Testing and Development of Ultrasonic Windsensor For Cold Climate,” in *Winterwind 2013 International Wind Energy Conference*, Östersund, Sweden, 2013.

[319] S. Kimura, T. Sato, Y. Yamagishi and A. Heimo, “Calibration of the off-the-shelf ice detectors by icing wind tunnel test,” in *COST727 Action*, Prague, 2008.

[320] S. Kimura, A. Sakabe, T. Sato and Y. Yamagishi, “Icephobic coating for prevention of secondary icing,” in *Winterwind International Conference,* Norrkoping, Sweden, 2008.

[321] S. Kimura, T. Sato, Y. Yamagishi and H. Morikawa, “Evaluation of ice detecting

sensors by icing wind tunnel test," in *Proceedings of 13th International Workshop on Atmospheric Icing on Structures*, Andermatt, Switzerland, 2009.

[322] S. Kimura, A. Sakabe and H. Sakaue, "A Note on Icing Wind Tunnel Test," in *Proceedings of the 49th Aircraft Symposium, The Japan Society for Aeronautical and Space Sciences JSASS-2011-5166,*, Kanazawa, Japan, 2011.

[323] K. Morita, K. Okamoto, S. Kimura and H. Sakaue, "Hydrophobic Coating Study for Anti-icing Aircraft," in *SAE 2011 International Conference on Aircraft and Engine Icing and Ground Deicing, SAE International, 2011-38-0010,* Chicago, US , 2011.

[324] H. Endo, S. Kimura, Y. Yamagishi and I. Nakane, "Behavior of a small water droplet on superhydrophobic coating in a cold environment," in *15th International Workshop on Atmospheric Icing of Structures*, New Foundland, Canada, 2013.

[325] H. Endo, S. Kimura, M. Hasegawa, Y. Yamagishi and T. Tanaka, "Analysis of minute water droplet's freezing process on coated surface," *SAE International Journal of Aerospace,* Vols. Vol.6, No.2, pp. pp.465-474, 2013.

[326] M. Hasegawa, T. Hyugaji, Y. Yamagishi, S. Kimura, T. Tanaka, K. Morita and H. Sakaue, "Experimental Investigation of a Single Droplet on a Superhydrophobic Coating in Icing Wind Tunnel for the Development of Ice-Protection System," in *The American Institute of Aeronautics and Astronautics (AIAA),* 2014.

[327] Kanazawa University, Japan, "Researcher Information," Kanazawa University, Japan, [Online]. Available: http://ridb.kanazawa-u.ac.jp/public/detail_en.php?id=2332. [Accessed 16 03 2016].

[328] T. Saito, S. Kimura, K. Sato, H. Morikawa, T. Kojima, H. Endo, Y. Yamagishi, S. Mochizuki and J. Hietanen, "Combined effect of the heating and the superhydrophhobic coating on the de-icing capability of the ultrasonic wind sensor," in *Winterwind 2016 International Wind Energy Conference*, Åre, Sweden, 2016.

[329] Zarges, "New CCV lift for wind turbines works down to -40°C," Zarges, 15 April 2014. [Online]. Available: http://www.zarges.com/en/company/news/press/news-detail/?tx_news_pi1%5Bnews%5D=10611&cHash=ef2df801c5bb003c51102012e2313ad8. [Accessed 21 September 2015].

[330] A. Mikhails, "Clipper Wind Turbines Receive GL Certification for Cold Climate

Operation," *Renewable Energy World Magazine,* 2007.

[331] OWI-Lab, "Testing 80 ton of steel to ensure reliable wind power production in all harsh conditions," OWI-Lab, [Online]. Available: http://www.owi-lab.be/content/testing-80-ton-steel-ensure-reliable-wind-power-production-all-harsh-conditions. [Accessed 09 November 2015].

[332] Nordex, "Nordex submitting turbine components to extended quality testing," Nordex, 25 June 2013. [Online]. Available: http://www.nordex-online.com/index.php?id=53&L=2&tx_ttnews%5Btt_news%5D=2406&tx_ttnews%5BbackPid%5D=46&cHash=f2f2a83661. [Accessed 14 December 2014].

[333] Ishibashi, "Gearbox lab with good usability," Ishibashi, 2015. [Online]. Available: http://www.ishibashi-mfg.com/en/feature/index.html.

[334] Fraunhofer, "Climate chamber," Fraunhofer, [Online]. Available: http://www.windenergie.iwes.fraunhofer.de/en/test_centers_laboratories/climate-chamber.html.

[335] VTT, "Concrete materials for the built environment," VTT, [Online]. Available: http://www.vtt.fi/files/research/ama/newmaterials/VTT_concreteA4_2012.pdf. [Accessed 09 November 2015].

[336] Gamesa, "Gamesa's climate chamber for testing wind turbines named one of the '100 best ideas of the year," Gamesa, March 27 2013. [Online]. Available: http://www.gamesacorp.com/en/cargarAplicacionNoticia.do?idCategoria=72&identificador=969&urlAmigable=gamesas-climate-chamber-for-testing-wind-turbines-named-one-of-the-100-best-ideas-of-the-year.html. [Accessed 21 September 2015].

[337] Advanced composites & structures center - OFFSHORE WIND LABORATORY , "DESIGN, FABRICATE, AND TEST UNDER ONE ROOF," [Online]. Available: http://composites.umaine.edu/files/2015/05/UMCompositesCenter_WindBladeTesting_rev2-9.pdf. [Accessed 09 November 2015].

[338] DTU, "Østerild - National Test Centre for Large Wind Turbines," DTU, [Online]. Available: http://www.vindenergi.dtu.dk/English/About/Oesterild.aspx. [Accessed 09 November 2015].

[339] CENER, "Cener experimental wind farm Alaiz," CENER, [Online]. Available: http://www.cener.com/en/wind-energy/wind-experimental-wind-farm-alaiz.asp. [Accessed 09 November 2015].

[340] ECN, “ECN Wind Turbine Test Site Wieringermeer,” ECN, [Online]. Available: https://www.ecn.nl/fileadmin/ecn/units/wind/docs/EWTW/EWTW_b-08-014_br.pdf. [Accessed 09 November 2015].

[341] Ecofys, “Test Site Lelystad,” Ecofys, [Online]. Available: http://www.ecofys.com/nl/project/test-site-lelystad/. [Accessed 09 November 2015].

[342] F. Technologies, “FT Wind Sensor: Winter testing,” FT Technologies, [Online]. Available: http://www.fttech.co.uk/ufiles/file/Articles/FT_at_Technocentre_Winter_2013_Web.pdf. [Accessed 2015 November 09].

[343] M. Lindholm, “Comparing Ice-Detector Systems Through Data Analysis: Moulded On Blades Versus Static Systems,” in *Wind Power Monthly Event: Optimising wind farms in cold climate*, Helsinki , 2014.

[344] Alstom, “Alstom announces an exclusive R&D cooperation with Lappeenranta University of Technology in Finland at the inauguration of its first wind farm in the Nordic region,” Alstom, [Online]. Available: http://www.alstom.com/press-centre/2013/8/alstom-announces-an-exclusive-rd-cooperation-with-lappeenranta-university-of-technology-in-finland-at-the-inauguration-of-its-first-wind-farm-in-the-nordic-region/. [Accessed 2015 November 09].

[345] “4 MW wind farm,” TechnoCentre éolien, [Online]. Available: https://www.eolien.qc.ca/en/infrastructures-en/repower-wind-turbines.html. [Accessed 09 Novemner 2015].

[346] Enercon , “Wind energy in cold climate: experience in Sweden and the world !,” in *Winterwind*, Piteä, 2015.

[347] D. S. D. R. G. M. M. S. K. R. C. Dr. Ulla Heikkilä, “Performance of Enercon wind turbines under icing conditions in Europe,” in *EWEA* , Paris, 2015.

[348] Blaiken Vind, [Online]. Available: http://www.blaikenvind.se/?lang=en. [Accessed 12 May 2016].

[349] J. Beurskens, “R&D as a prerequisite for successfully utilising the cold climate wind energy market oppotunities,” in *WinterWind conference*, Piteå, 2015.

[350] J. Beurskens and S.-E. Thor, “Summary WinteWind 2015,” in *WinterWind conference*, Piteå, 2015.

[351] V. Lehtomäki, “Web-survey results & Panel,” in *Winterwind 2016*, Åre, 2016.

[352] Y. Odemark, “An overview of Vattenfalls research within turbine icing - Yesterday and tomorrow,” in *Winterwind 2016*, Åre, 2016.

[353] P.-J. Rigole, “The Swedish Energy Agency strategy within wind energy,” in *Winterwind 2016*, Åre, 2016.

[354] D. Fouquet and D. Gustafsson, “Summary of Winterwind 2106,” in *Winterwind 2016*, Åre, 2016.

[355] V. Lehtomäki, “Overview of IEA wind Task19 results from 2013-2015,” in *Winterwind 2016*, Åre, 2016.

[356] R. Cattin, “Validation of the IEA Task 19 ice site classification,” in *Winterwind 2016*, Åre, 2016.

[357] J. Hansson, J. Lindvall and U. Turkyilmaz, “Methods for estimation of occurred icing losses in operational wind farms - measurements and modeling,” in *Winterwind 2016*, Åre, 2016.

[358] S. Rissanen and J. Heinonen, “Simulations of drifting sea ice loads on offshore wind turbine support structures,” in *Winterwind 2016*, Åre, 2016.

[359] V. Lehtomäki, S. Rissanen, D. Bolduc, N. Davis, R. Klintström, S. Dierer, R. Gugerli and U. Heikkilä, “Standardized method to evaluate production losses due to icing using only SCADA data “T19IceLossMethod”,” in *WinterWind conference*, Piteå, 2015.

[360] T. Karlsson, “Validation of icing atlases based on SCADA data,” in *Winterwind 2016*, Åre, Åre.

[361] S. Liléo, “Mast measurements in cold climates- Challenges and recommendations,” in *Winterwind 2016*, Åre, 2016.

[362] T. Beckford, “Update of DNV GLs empirical icing map of Sweden and methodology of estimating icing losses using further Nordic wind farm data,” in *Winterwind 2016*, Åre, 2016.

[363] L. Johansson, “Frozen anemometers and bias in the wind resource,” in *Winterwind 2016*, Åre, 2016.

[364] M. Baltscheffsky, S. Söderberg, M. Wadham Gagnon and N. Swytink-Binnema, “Towards validation of microphysics schemes in numerical weather prediction models for icing applications,” in *Winterwind 2016*, Åre, 2016.

[365] E. Olsson, H. Körnich, J. Persson Söderman, B. Stensen, P. Undén and H. Bergström, “Uncertainty quantification for wind power forecasts in cold

climates," in *Winterwind 2016*, Åre, 2016.

[366] B. Martinez and P. J. Trombe, "Benchmark study of icing forecasts - Do they really add a value," in *Winterwind 2016*, Åre, 2016.

[367] L. Makkonen, "Models for the growth of rime, glaze, icicles and wet snow on structures," *Ice and Snow Accretion on Structures*, vol. 358, no. 1776, pp. 2913-2939, November 2000.

[368] M. C. Pedersen, M. W. Gagnon, H. Sørensen and B. Martinez, "On-site measurement from cold climate - possibilities and applications towards validation of CDF model," in *Winterwind 2016*, Åre, 2016.

[369] B. Messinger, "Equilibrium temperature of an unheated icing surface as a function of air speed," *Lockheed Aircraft Corporation, I.A.S., Los Angeles, USA,* 1953.

[370] W. Habashi and G. McClure, "Cross-fertilizing the technologies of atmospheric icing on structures and in-flight structural icing," in *IWAIS 2011*, Chongqing, China, 2011.

[371] H. Bergström and G. Bergström, "Doing a meso-scale re-analysis using the WRF-model - does it matter for the resulting icing climatology which version of WRF you use?," in *Winterwind 2016*, Åre, 2016.

[372] T. Saito, S. Kimura, K. Sato, H. Morikawa, T. Kojima, H. Endo, Y. Yamagishi, S. Mochizuki and J. Hietanen, "Combinded effect of the heating and the superhydrophobic coating on the deicing capability of the ultrasonic wind sensor," in *Winterwind 2016*, Åre, 2016.

[373] E. Lindblom, "In Situ Instrument AB - your overall partner when it comes to measuring wind in any environment," in *Winterwind 2016*, Åre, 2016.

[374] P. Jonsson and B. Ollars, "Monitoring systems for harsh climate," in *Winterwind 2016*, Åre, 2016.

[375] T. Beckford, "ESTIMATING ENERGY LOSSES CAUSED BY BLADE ICING FROM PRE-CONSTRUCTION WIND DATA," in *WinterWind conference*, Piteå, 2015.

[376] J. Miettinen, "On the influences of icing on regional forecast errors," in *WinterWind conference*, Piteå, 2015 (2).

[377] S. Söderberg and M. Baltscheffsky, "Analysis of spatial and temporal variability in icing conditions and production losses due to icing using a new long-term

icing climate database," in *WinterWnd 2015*, Piteå, 2015 (2).

[378] T. Karlsson, "Lidar as ice detector," in *WinterWind 2015,* Piteå, 2015.

[379] E. Aslund, "GAMESA solutions for Cold Climate Conditions," in *WinterWind 2015,* Pitea, 2015.

[380] M. Galbiati, "Prediction of production losses in cold climates and ice protection system de- sign by computational fluid dynamics," in *Winterwind 2016,* Åre, 2016.

[381] N. Rehfeld, "Assessment of de-icingandanti-icing technologies in ice wind tunnel," in *Winterwind 2016,* Åre, 2016.

[382] A. M. Nodeland, "ENERCON experiences with wind energy turbines in icing conditions," in *Winterwind 2016,* Åre, 2016.

[383] B. D. Nielsen, "Vestas cold climate offerings to cope with icing conditions," in *Winterwind 2016,* Åre, 2016.

[384] A. Skovgaard Sørensen, "Improving output in harsh conditions," in *Winterwind 2016,* Åre, 2016.

[385] A. Beyer, "Nordex Anti-Icing System on N131 wind turbines - development and validation," in *Winterwind 2016,* Åre, 2016.

[386] H. Zhong, "Dongfang experience in low temperature wind turbine de-icing," in *Winterwind 2016*, Åre, 2016.

[387] J. Van den Broecke, "An experimental study on the use of nanosecond pulsed dielectric barrier discharge plasma actuators for de-icing of aerospace structure," in *Winterwind 2016,* Åre, 2016.

[388] M. Wadham Gagnon, N. Swytink-Binnema, C. Arbez, D. Bolduc and C. Godrea, "Ice detection methods and measurements," in *Winterwind 2016,* Åre, 2016.

[389] K. Satoh, S. Kimura, T. Saito, H. Morikawa, T. Kojima and H. Endo, "Wet-snow production and snowing wind tunnel test for snow accretion and prevention," in *Winterwind 2016,* Åre, 2016.

[390] S. Shoja, V. Berbyuk and A. Boström, "An approach in using guided waves for ice detection on wind turbines," in *Winterwind 2016,* Åre, 2016.

[391] D. Futter, "Wind turbine ice detection systems testing," in *Winterwind 2016,* Åre, 2016.

[392] M. Moser and T. Schlegl, "Real-world icing distribution analysis based on data from surface sensors," in *Winterwind 2016,* Åre, 2016.

[393] M. Tiihonen, V. Lehtomäki and P. Suopajärvi, "Ice detection via advanced infrared image analysis," in *Winterwind 2016,* Åre, 2016.

[394] T. Muukkonen, "Recent development on blade mounted and nacelle mounted ice detectors," in *Winterwind 2016*, Åre, 2016.

[395] Z. Khadiri-Yazami, C. Scholz, A. Baier, T. Tang and M. Durstewitz, "Classification based approach for icing detection," in *Winterwind 2016,* Åre, 2016.

[396] Ø. Byrkjedal, B. E. K. Nygaard, Ø. Welgaard and Ø. Byrkjedal, "New advances in icing measurements and icing predictions," in *Winterwind 2016,* Åre, 2016.

[397] T. Muukkonen, "Experiences from blade-mounted Ice detector development," in *WinterWind conference,* Piteå, 2015.

[398] L. K. Eppanapelli, J. Casselgren and S. Rosendahl, "Detection of different phases of water on a wind turbine blade using a NIR camera and three IR wavelengths," in *WinterWind conference,* Piteå, 2015.

[399] D. Brenner, "1,500 operational Years of Icing on Wind Turbines –A Long Term Study," in *WinterWind conference*, Piteå, 2015.

[400] D. Bolduc, M. Wadham-Gagnon, J. Petersen, H. Friedrich and A. Camion, "Ice Monitoring for R&D projects," in *WinterWind conference,* Piteå, 2015.

[401] M. Moser, T. Schlegl and H. Zangk, "On the variability of temperature and icing status over the blades of a wind turbine," in *WinterWind conference*, Piteå, 2015.

[402] S. Rydholm, "Measuring Air Liquid Water Content by Shadowgraph Image Analysis for Wind Turbine Icing Detection," in *WinterWind conference,* Piteå, 2015.

[403] K. Hynynen, I. Romero, S. Afanasyeva, J. Armet and O. Pyrhönen, "Perfomance of two nacelle-mounted ice detectors a case study," in *Winterwind 2016,* Åre, 2016.

[404] A. Sandve and T. Nielsen, "Integrated approach to saftey and asset performance in cold climates," in *Winterwind 2016,* Åre, 2016.

[405] S. Meyer, "North Asia driving the wind industry," in *Winterwind 2016,* Åre, 2016.

[406] A. Krenn, N. Clausen, N. Davis, M. Wadham-Gagnon, V. Lehtomäki, R. Cattin, G. Ronsten, H. Wickman, R. Klintström, Z. Khadiri and P. Jordaens, "IEA Task19 standardized methodology for the elaboration of the ice throw risk assessments," in *Winterwind 2016,* Åre, 2016.

[407] R. E. Bredesen, "Ice risk forecast system for operational wind farms," in *Winterwind 2016,* Åre, 2016.

[408] N. Lawal, "Cost effective system for ice throw detection," in *Winterwind 2016,* Åre, 2016.

[409] D. Brenner, "Determination of the actual ice mass on wind turbine blades Measurments and methods for avoiding excessive icing loads threads," in *Winterwind 2016*, Åre, 2016.

[410] R. Hann, "Applications of iced wind turbines noise simulations," in *Winterwind 2016,* Åre, 2016.

[411] L. Aldén and A. Barney, "Decommissioning of wind farms - ensuring low environmental impact," in *Winterwind 2016*, Åre, 2016.

[412] H. A. Refsum and R. Bredesen, "Methods for evaluating risk caused by ice throw from wind turbines," in *WinterWind conference*, Piteå, 2015.

[413] F. Storck, "Influence of wind conditions under icing conditions on the result of a risk assessment," in *WinterWind,* Piteå, 2015.

[414] R. Cattin, "Operation of wind parks under icing conditions," in *WinterWind conference*, Piteå, 2015.

[415] CCOHS, "Cold Environments - Working in the Cold," 11 April 2016. [Online]. Available: http://www.ccohs.ca/oshanswers/phys_agents/cold_working.html.

[416] R. Buils, "Urbano Quantifying the impact of ice accretion on turbine life for typical Scandinavian sites using numerical modelling," in *Winterwind 2016*, Åre, 2016.

[417] D. Bolduc, M. Wadham-Gagnon, C. Godreau, N. Swytink-Binnema, C. Golombek and H. Friedrich, "A look at wind turbine performance in Canadian icing climate," in *Winterwind 2016,* Åre, 2016.

[418] G. Nilsson, "Blade heat system repair part II," in *Winterwind 2016,* Åre, 2016.

[419] D. Gustafsson, "Moving forward in a frosty market," in *Winterwind 2016*, 2016.

[420] H. MacDonald, M. Stack and D. Nash, "Assessing the likelihood of hail impact damage on wind turbine blades," in *Winterwind 2016,* Åre, 2016.

[421] A. Leskinen, "WIND PARK DEVELOPMENT - Long-term on-line sound monitoring," in *WinterWind conference,* Piteå, 2015.

[422] R. Hann, "Simulating Iced Wind Turbine Noise," in *WinterWind conference,* Piteå, 2015.

[423] M. Muckermann, "Benchmark of ice noise modelling," in *WinterWind conference,* 2015, 2015.

[424] E. Olsson, "High resolution forecast maps of production loss due to icing," in *WinterWind 2015,* Piteå, 2015.

[425] Newcom Group (presented by Meyer, Sebastian), "Salkhit Wind Farm Background," in *Winterwind 2016,* Åre, 2016.

[426] D. Fouquet, "The European Commissions Winter Package and the latest developments regarding cooperation and market integration of renewable energy," in *Winterwind 2016,* Åre, 2016.

[427] S. Uski and S. Niskanen, "Temperature and wind influence on power transmission capability of power lines in the vicinity of cold climate wind farms - case studies in Finland," in *WinterWind conference,* Östersund, 2013.

[428] H. E. Addy, "Ice accretions and icing effects for modern airfoils, NASA/TP-2000-210031, DOT/FAA/AR–99/89," NASA, Cleveland, Ohio, 2000.

[429] J. Miettinen, H. Holttinen, T. Karlsson, Ø. Byrkjedal and M. Kiudulas, "On the influences of icing on regional forecast errors," in *Winterwind,* Piteå, 2015.

[430] Ø. Byrkjedal and S. Lileo, "Icing forecast," Kjeller Vindteknikk, [Online]. Available: http://www.vindteknikk.com/services/analyses/wind-power/post-construction/icing-forecast. [Accessed 06 2015].

[431] L. Battisti, "Optimizing wind turbine design for operation in cold climates," *Wind Energy Systems,* pp. 388-460, 2011.

[432] L. Battisti, R. Fedrizzi, M. Rialti and S. Dal Savio, "A model for the design of hot-air based wind turbine ice prevention system," in *WREC05,* Aberdeen, UK, 2005.

[433] "Infralytic," Infralytic, [Online]. Available: http://www.infralytic.de/. [Accessed 14 01 2016].

[434] N. Davis, N.-E. Clausen, A. Hahmann, P. Pinson, M. Žagar, Ø. Byrkjedal, T. Karlsson, T. Wallenius, V. Turkia, S. Söderberg and M. Baltscheffsky, "IceWind Inter-comparison of Icing Production Loss Models," in *Winterwind*, Sundsvall, Sweden., 2014.

[435] N. Davis, N. Pinson, A. Hahmann, N. Clausen and M. Žagar, "Identifying and characterizing the impact of turbine icing on wind farm power generation," *Wind Energy*, p. n/a–n/a. http://doi.org/10.1002/we.1933, 2015.

[436] M. Baltscheffsky, "Modelling of production losses due to icing for individual turbines in a wind farm - development of techniques for forecasting and site assessment.," in *Winterwind*, Östersund, Sweden, 2013.

[437] Ø. Byrkjedal, "The benefits of forecasting icing on wind energy production," in *Winterwind*, Skellefteå, Sweden, 2012.

[438] N. Davis, A. Hahmann, N. Clausen and M. Žagar, "Forecast of icing events at a wind farm in Sweden," *Journal of Applied Meteorology and Climatolo*, pp. 262–281. http://doi.org/10.1175/JAMC-D-13-09.1, 2014.

[439] B. Göransson and D. Haaheim, "Swedish Wind Energy Associations view on wind energy in cold climates," in *Winterwind 2016*, Åre, 2016.