EXPERT GROUP STUDY ON
RECOMMENDED PRACTICES

13. WIND ENERGY PROJECTS IN COLD CLIMATES

2. EDITION 2017

Submitted to the Executive Committee
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for
Research, Development and Deployment on
Wind Energy Conversion Systems

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Photo: A wind farm consisting of Bonus 600 kW wind turbines with electrothermal anti-icing systems installed on Olos fjell, Finland

FOREWORD

The International Energy Agency Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems (IEA Wind TCP) 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.

As a final result of research carried out in the IEA Wind TCP Tasks, Recommended Practices, Best Practices, or Expert Group Reports may be issued. These documents have been developed and reviewed by experts in the specialized area they address. They have been reviewed and approved by participants in the research Task, and they have been reviewed and approved by the IEA Wind TCP Executive Committee as guidelines useful in the development and deployment of wind energy systems. Use of these documents is completely voluntary. However, these documents are often adopted in part or in total by other standards-making bodies.

A Recommended Practices document includes actions and procedures recommended by the experts involved in the research project.

A Best Practices document includes suggested actions and procedures based on good industry practices collected during the research project.

An Experts Group Studies report includes the latest background information on the topic as well as a survey of practices, where possible. The Task 19 Available Technologies – report is an Expert Group Study.

Previously issued IEA Wind TCP Recommended Practices, Best Practices, and Expert Group Reports can be found at www.ieawind.org on the Task 11 web pages.

PREFACE

Numerous cold climate sites around the world offer great wind energy potential in demanding winter climates. Activities have been conducted in a number of countries to master the difficulties that atmospheric icing and low temperatures pose for wind energy technology. The installed cumulative wind capacity in cold climates across Scandinavia, North America, Europe, and Asia, was approximately 127 GW at the end of 2015, with an expected growth rate of approximately 12 GW per year until 2020 [1]. Increased experience, knowledge, and improvements in cold climate technology have enabled the economics of cold climate wind projects to become more competitive in relation to standard wind projects. The internationally accepted procedures for testing and evaluating wind turbines or wind energy conversion systems encompass a variety of aspects. Although there is vast wind energy potential in cold climates, little attention has so far been paid to the environmental impacts of wind projects in these areas.

The large-scale exploitation of cold climate sites has been limited by our lack of knowledge about their special challenges and the lack of proven and economical technological solutions.

The purpose of this report is to provide the best available recommendations on this topic, reduce the risks involved in undertaking projects in cold climates, and accelerate the growth of wind energy production in these areas. This document addresses many special issues that must be considered over the lifetime of a cold climate wind energy project. The importance of site measurements, project design, and system operation is emphasised.

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January 2017

Approved by the Executive Committee of IEA Wind TCP, 1 February 2017.

EXECUTIVE SUMMARY / SUMMARY OF RECOMMENDATIONS

The purpose of this IEA Wind TCP report is to provide the best available information of recommended practices for cold climate (CC) wind projects to developers, owners, and operators of wind projects within CC. The incentive is to reduce the risks and accelerate the growth of wind energy production. This document also provides preparatory information that should benefit manufacturers, banks, and insurance companies.

Cold climate sites around the world offer large wind energy potential in demanding winter climates. National activities have been conducted to master the challenges that atmospheric icing and low temperatures pose for wind energy development. Our lack of knowledge of special CC issues and the lack of proven and economic technological solutions have limited the large-scale exploitation of these sites. For the sake of this document, the concept of CC includes both low temperature and icing environments.

A generic wind energy development best practise guide provides a good starting point for developing a CC site. Those generic practices should be used to the extent possible, even though they do not normally consider CC issues. This report focuses on the additional challenges that are involved in CC wind energy projects that must also be assessed in detail. CC conditions directly affect site access, working conditions, technology selection, turbine loads, noise, health and safety, public safety and energy production.

Prior to any wind farm investment, mapping of all potential risks are keys to success. In order to get some preliminary information regarding atmospheric icing and low temperature conditions worldwide, associated maps provide a good first glance at potential risks (example in Figure 0-1 below and website in [2]). However, icing maps only provide a rough estimate of potential sites atmospheric icing conditions, and should not be used as the only indicator for icing. Similar to wind speed measurements, on-site icing measurements are of crucial importance and can provide more accurate icing information than icing maps for business case analysis. Icing maps can also be used when planning the site icing measurements that will take place during the resource assessment campaign.

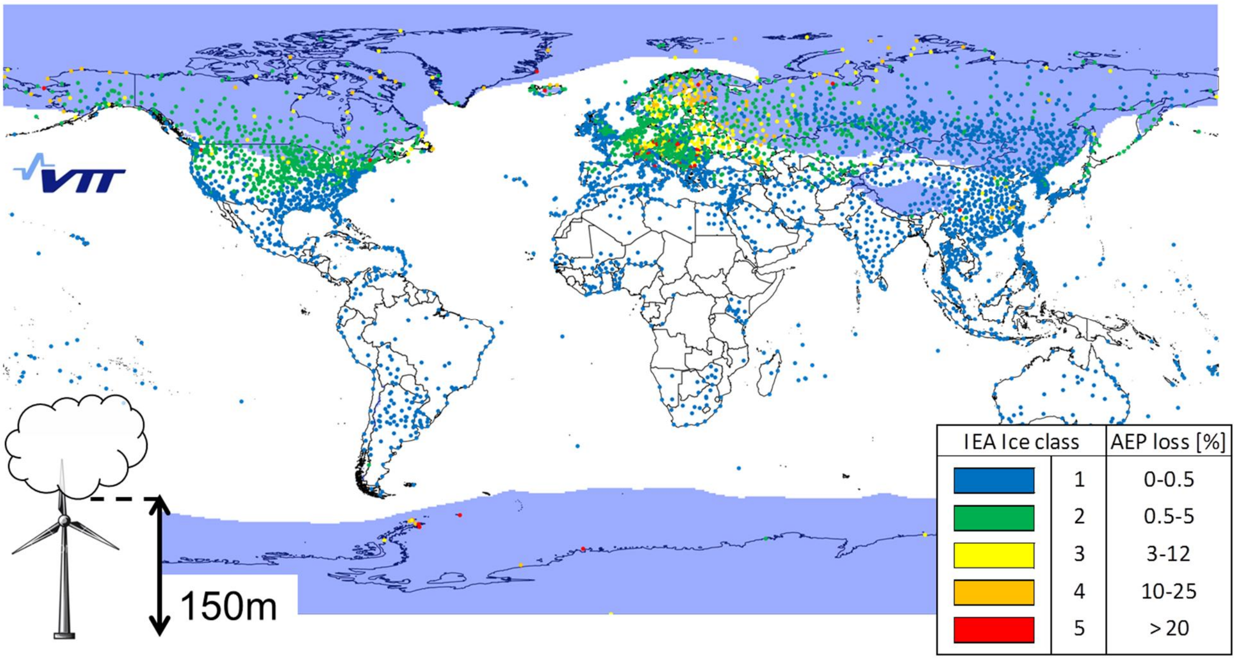


Figure 0-1: Global icing and low temperature (in blue) map [2], [3]

Icing may significantly influence energy production. However, there are no international standards for estimating icing losses in any way. The importance of a thorough site assessment, including the impact of icing, is key in CC conditions, and this report provides recommendations for additional instrumentation that may be beneficial. Site assessment is the most important phase, as other project decisions are based on the site assessment results. A thorough site measurement will include ice measurements for at least one year, and a long-term correction that accounts for the high interannual variability of icing. These measurements should utilize the correct measurement devices and preferably be placed at hub height or higher. The complexity of a measurement program will vary greatly depending on the location, wind farm size and other parameters. A proper measurement campaign also provides valuable information on site access and working conditions.

Instrument and turbine manufacturers may have CC solutions available that decrease production losses due to icing and increase safety. Technological options need to be surveyed for each project, since CC site specific circumstances vary. Commercial and prototype level sensors, blade ice protection (anti-icing and de-icing) systems, and other solutions for icing conditions are available on the market, but only limited information about their effectiveness has been published and different systems may be better suited for different conditions. Solutions for low temperatures are generally more mature because most low temperature technologies have been deployed previously in other fields of engineering. More work is needed, especially in the development of solutions to prevent turbine icing.

CC wind energy projects need to maintain high safety standards, as such projects involve higher risks than undertakings in standard climates. Planners, operators, authorities, insurers, and investors should use an established risk evaluation method to determine the kind of risks a CC wind turbine installation will face, and the measures that have to be taken to avoid or decrease these risks. Although CC projects will bring about additional risks, their assessment will be no different from those of other wind farm development projects. Implementation of projects in

CC will incur additional costs that are related to working conditions, construction, and site access. Some of these costs can be mitigated with careful planning.

A summary of recommendations as addressed in this document are:

- Be aware of the extra risks and costs involved in CC wind energy production at early stages of the project.
- Employ available best practises to the extent possible, even though they generally do not consider CC issues.
- Conduct a survey to nearby land and wind farm owners regarding CC experiences followed by a search on CC technology providers (e.g. see list here [4]) to find solutions on a project by project basis, taking into consideration that CC circumstances vary greatly between different sites. In addition to using icing maps, perform a thorough site assessment measurement campaign for at least one year that includes ice measurements and a long-term adjustment. This phase provides valuable information on site access and working conditions.
- Make the best estimate of icing losses on production based on the results of the site measurements and assessing turbine control strategy in icing conditions with/without a turbine ice protection system
- Be aware that lower availability of wind measurements will increase the uncertainty in energy production estimates.
- During the project planning phase, ensure that CC-related safety aspects, such as low-temperature working conditions and the risk of ice throw are addressed.
- Carry out a risk assessment that includes an assessment of the quality of the selected turbine and the experience and references of the installation companies, contractors, and operators.
- Include the results of the risk assessment as part of the requirements on the turbine, equipment, manufacturing, installation, and operation.
- Consider the possible consequences of increased noise related to iced-up blades and/or cylindrical sound propagation.
- Investigate if turbine manufacturers' CC packages are required as part of the turbine selection and tender process, and invest in blade ice protection systems (anti- or de-icing) if site conditions require them to ensure sufficient system efficiency.
- Consider site specific conditions when determining if an ice protection system may be required, and evaluate different ice protection systems for their site suitability, accounting for the higher uncertainty of unproven technologies.
- Ensure that the selected wind turbines are only operated under the conditions that they have been certified for.

LIST OF ABBREVIATIONS

CC	cold climate
H&S	health & safety
IC	icing climate
IEA	International Energy Agency
IEC	International Electrotechnical Commission
LTC	low temperature climate
HSE	health, safety and environment
WT	wind turbine

CONTENTS

1. INTRODUCTION

Wind turbines in cold climates (CC) are exposed to icing conditions and temperatures below the design limits of standard wind turbines according to IEC 61400-1 ed3 [5]. Sites that have CC have a large potential for wind energy production. Because of the limited number of temperate site locations, and the higher than expected costs of offshore wind development, large wind energy projects in CC have become tempting due to their good wind conditions and low population density. An increase in experience and knowledge, combined with improvements in technology focused on CC conditions, has enabled such projects to become more competitive when compared to onshore projects with low wind resources and offshore projects that are built at higher costs.

The installed cumulative wind capacity in CC across Scandinavia, North America, Europe, and Asia, is about 127 GW as of the end of 2015, with an annual growth rate of 11.7 GW until 2020 [1]. Additionally, icing and low temperature conditions can be found in more temperate and high elevation areas, such as central and southern Europe, Japan, many parts of the United States, and locations in the southern hemisphere such as Australia, New Zealand, and southern South America. Additionally, CC issues are not only tied to onshore wind energy, as turbines installed in the shallow waters off northern Europe and off the coast of New England in the United States, also face icing conditions in the form of drifting sea ice.

The main challenges for standard turbines operating in CC environments are production losses and potentially increased loads due to icing, which in turn could lead to increased risk of premature mechanical failure and financial losses. Additional challenges arise from the potential for increased noise emissions and HSE issues from ice throw.

CC issues are currently being included in recent and near-term IEC international standards. A new CC turbine class is proposed in IEC 61400-1 ed4 and turbine design load cases for iced turbines are defined in [6] and standardized practices for site energy yield assessment regarding icing are being developed in [7]. Additionally, DNV GL is preparing a recommended practices report on iced turbine load assessment [8].

The purpose of this IEA Wind TCP report is to provide the best available information of recommended practices for CC wind projects to developers, owners, and operators of wind projects within CC. The incentive is to reduce the risks and accelerate the growth of wind energy production. This document also provides preparatory information that should benefit manufacturers, banks, and insurance companies.

The document includes chapters on cold climate definitions and terminology, site classification, measurements and monitoring, technology, production, health and safety, project economics, and project design. Each chapter addresses issues that are relevant to wind energy in CC. The document also provides recommendations aiming to bring forth solutions to CC-specific challenges and to reduce the cost of wind energy by lowering their social, technological, and economic risks.

2. COLD CLIMATE

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 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, an Icing Climate, or both, but in all cases they are still denoted as Cold Climate sites. These definitions are further illustrated in Figure 2, with further information about the typical temperature range for atmospheric icing, and a more detailed overview about available LTC definitions and site classification for LTC being provided in chapter 3.1, A site classification for IC is shown in chapter 3.2.

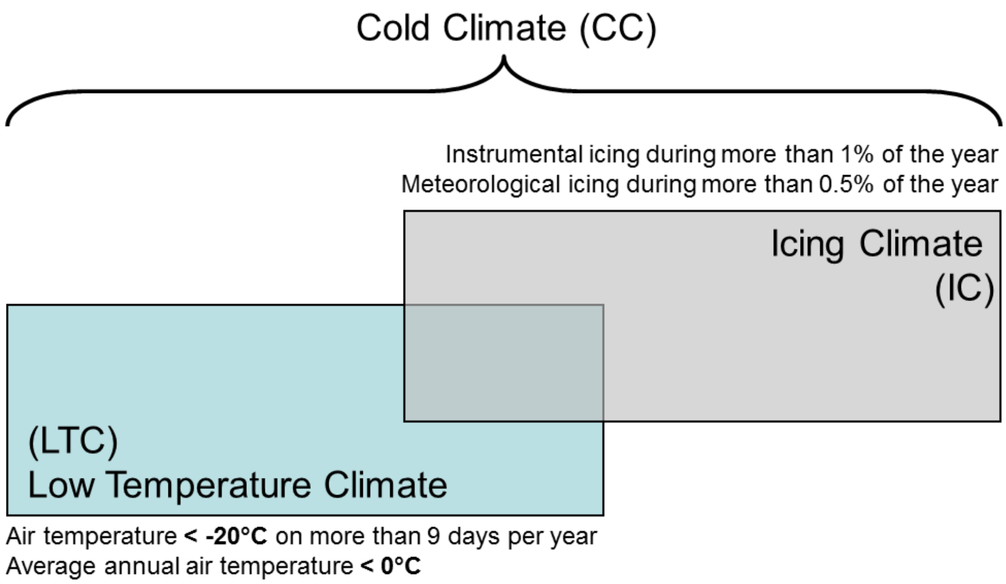


Figure 2. Definition of Cold Climate, Low Temperature Climate and Icing Climate

Standards and best practise guidelines for implementing wind energy projects are available from many national, international, professional, and industrial organisations. It is recommended that these are used as far as possible, even though they do not typically consider CC circumstances.

2.1 Icing climate

Atmospheric icing is defined as the period of time where atmospheric conditions are present for the accretion of ice or snow on structures that are exposed to the atmosphere. 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, and when they hit a surface, they freeze immediately. If the droplets are small, soft rime is formed, but if the droplets are bigger, hard rime is formed. Rime ice growth is asymmetrical, located only on the windward side of a structure, and it can occur at temperatures down to -20°C. Rime ice growth typically occurs at higher temperatures than -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 a higher density than rime ice. Freezing rain or freezing drizzle occurs when warm air melts the snow crystals and forms rain droplets, which then 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.

Atmospheric icing can have the following effects on a wind energy project:

- Icing affects wind measurements, leading to data loss and increased measurement uncertainty.
- Heavy ice loads can cause the collapse of measurement towers that were not dimensioned for the CC site conditions.
- Ice on the wind turbine blades may increases the noise levels of a wind turbine.
- Potential ice throw from the blades of a wind turbine is a safety issue.
- Ice on rotor blades leads to icing related production losses.
- Energy yield calculations for sites where icing condition prevail have a higher uncertainty compared to standard conditions.
- Ice on wind turbine blades can cause aerodynamic and mass imbalances, and with long exposures can increase the loading of components, reducing the turbine's life time.
- The presence of ice may make maintenance and repairs more difficult.

All of the above and more will be addressed in following chapters.

Figure 3 shows the evolution of an icing event, which is the same regardless of the icing type or atmospheric conditions. An icing event can be described with the following terms, applicable to structures, instruments, and wind turbines exposed to atmospheric icing:

- **Meteorological Icing**: The period during which the meteorological conditions (temperature, wind speed, liquid water content, droplet distribution) allow ice accretion.
- **Instrumental Icing:** The period during which ice is present/visible on a structure and/or a meteorological instrument.
- **Rotor Icing**: The period during which ice is present on the rotor blade of a wind turbine. Due to differences in dimension, shape, flow velocity, and vibrations rotor icing is usually not equivalent to instrumental icing. Typically, incubation and ablation times 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**: The time between the start of meteorological icing and the start of instrumental/rotor icing, this depends on the surface and the temperature of the structure.
- **Accretion:** The time when ice is growing (active ice formation).
- **Persistence**: The total time duration when ice remains on a structure (no ice growth).
- **Ablation**: The time when ice is being removed from the structure through natural means. Ablation includes melting, erosion, sublimation, and shedding of ice. This also marks the time between the end of meteorological icing and the end of instrumental/rotor icing.

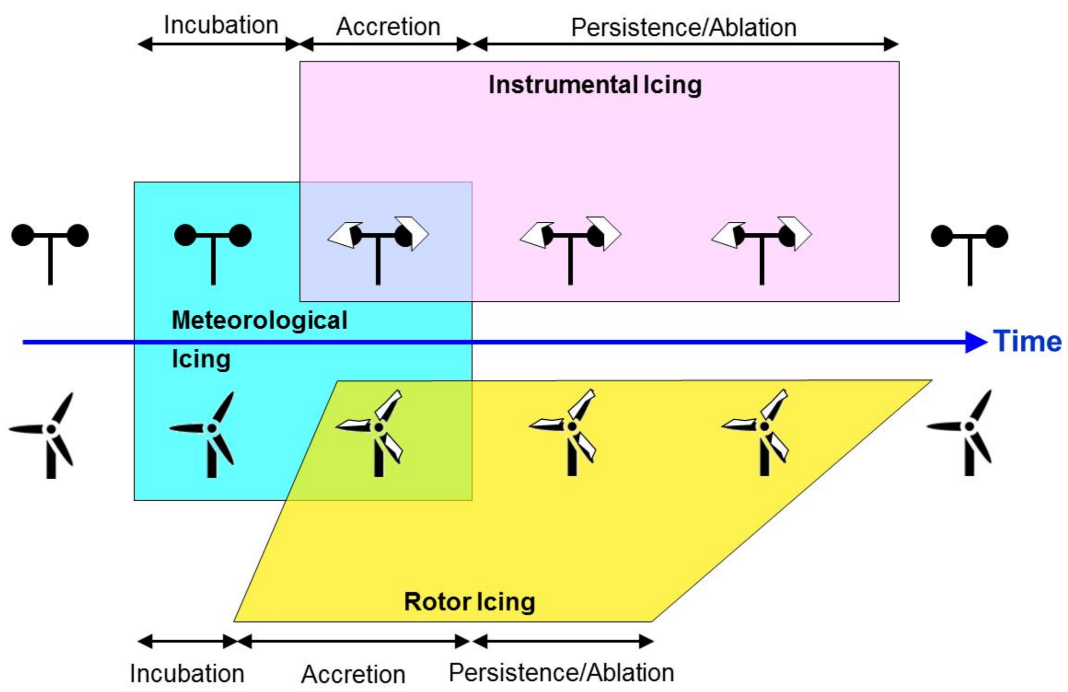


Figure 3. Definition of Meteorological Icing, Instrumental Icing, Rotor Icing, Incubation, Accretion, Persistence, and Ablation

Additional terms that are used to describe the icing conditions at a site in more detail are:

- Icing Intensity: Ice accumulation per time on a structure [cm/hour or g/hour]
- Ice Load: Ice mass accreted on a structure [kg/m]

2.2 Low Temperature Climate

Low temperature climates are most common in polar regions, and are often associated with high pressure systems that lead to clear skies and a corresponding increase in radiation from the surface to the atmosphere. However, they can also be located in areas of high elevation, in the middle latitudes. Most regions that experience very low temperatures are also located either far from coastlines, or along coasts that freeze during the winter.

LTC can lead to the following effects on a wind energy project:

- Materials used in turbines and components can be affected by low temperatures.
- High air density leads to higher energy densities, which needs to be considered in the control of the wind turbine.
- Maintenance work at low temperatures is more time consuming.
- Cold start of a wind turbine can be more difficult at low temperatures.
- Oils and lubricants can lose their viscosity.
- Heating of the components increases a wind farms internal energy use, reducing the energy it can provide to the grid.

All of the above and more will be addressed in following chapters.

3. SITE CLASSIFICATION

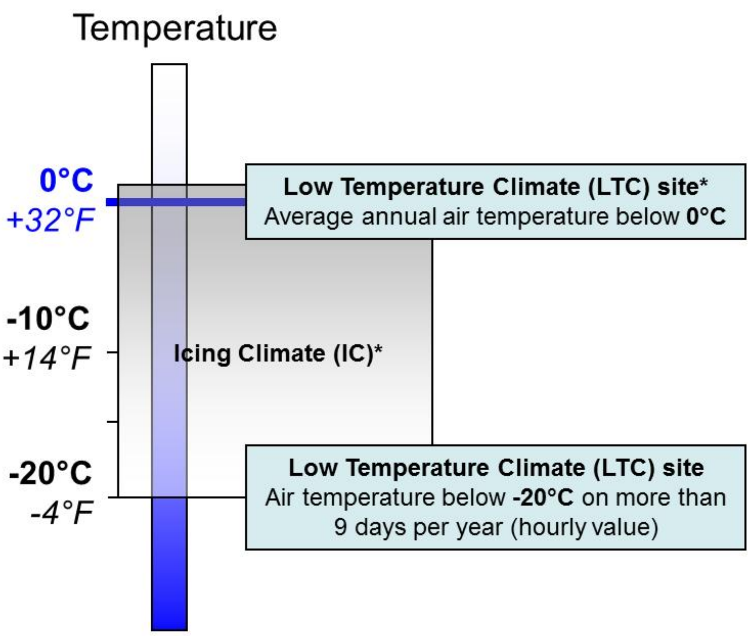
The first step when developing a wind energy project for a potential Cold Climate (CC) site is to check if it is a Low Temperature Climate (LTC) site, an Icing Climate (IC) site or both. If the site is an IC site, there is a further need to define the IEA ice class for this specific site.

3.1 Low Temperature Climate Classification

Figure 3-1 shows the position of LTC and IC sites with respect to ambient temperature. The following definitions apply for a LTC site:

- If minimum temperatures of below -20°C have been observed during long term measurements (preferably ten years or more) on an average of more than nine days a year, the site is defined as a LTC site. The nine-day criteria is fulfilled if the temperature at the site remains below -20°C for one hour or more on the respective days.

- The long term average annual air temperature of the site is below 0°C.



From DNV GL Recommended Practices (2016)
”Extreme temperature conditions for wind turbines”

Figure 3-1: Low temperature and icing climate with respect to ambient temperature.

3.2 IEA Ice Classification

This chapter presents an ice classification for wind energy sites. This classification provides a first indication on the severity of icing and its consequences for a given site. In later phases of the project, it is strongly recommended to carry out more detailed analyses on the site specific icing conditions, and the possible consequences icing may cause on the site under consideration.

The ice classification refers to long term icing conditions, for single years/winters the results may be located outside the classes indicated in the table. The IEA Ice Classification is based on the definitions explained in in Chapter 2 (see also [9]).

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 a fully unheated anemometer or heated camera on a mounting boom

Table 3-1: IEA Ice Classification with Corresponding Recommendations.

IEA Ice class	Meteorological icing	Instrumental icing	Icing loss
	% of year	% of year	% of gross 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

NOTE: When using the IEA Ice Classification there is a chance that a site can end up in two or three different IEA Ice Classes depending on whether the meteorological icing, the instrumental icing or the icing loss is used as input. Variations may also occur depending on the used instrumentation and the chosen measurement period. In such case where variations occur, it is recommended to use the highest class of the two options.

A validation study of the IEA Ice classification using site measurements can be found in [10].

Initial site Ice Classification using icing maps: Meteorological icing can be modelled numerically with mesoscale weather prediction models, or evaluated from long-term observations. If there is an icing map available, these values can be used as a starting point for identifying the sites icing class. However, as when using wind resource maps for screening potential sites, special care is needed when using icing maps. As with wind resource maps, the absolute values coming from icing maps are typically only suitable for rough indications of the icing conditions, and not accurate enough for detailed financial calculations. However, icing maps are well suited for screening larger geographical areas that potentially are influenced by meteorological icing, and for comparing icing severities between different locations within the same icing map. The information format in which the icing maps (list of icing maps here [4]) are presented should be known e.g. in meteorological icing frequency (% of time) when connecting it to the IEA Ice Classification (Table 3-1) for initial site classification. If the initial Ice Classification from an icing map is class 2 or higher, a through ice measurement campaign is recommended (for details see chapter 4.2.2). The use of multiple icing maps per area is advised, to increase confidence in the obtained results. The best way to obtain data for the site classification, however, is to measure the icing directly at the site.

4. SITE MEASUREMENTS

Monitoring the wind resource at a potential site is typically one of the first steps of any wind energy development project. The complexity of a measurement program will vary greatly depending on the location and the parameters that need to be measured. Cold Climate (CC) issues, particularly icing, may complicate matters further. The investment required for CC measurement campaigns, including the potential need for independent power, will be higher than for non-CC sites. However, the potential cost of missing or unreliable data, and the increased maintenance costs due to the use of non-CC equipment warrants an appropriate investment. Issues associated with the implementation of measurement monitoring programs in CCs, including equipment and accessibility, are addressed in this chapter. Prior to all measurement activities, it is recommended to conduct a survey to the planned wind farm land owners and nearby wind farm operators for some initial CC experiences.

4.1 Meteorological Towers

Figure 4-1: A collapsed meteorological tower, likely due to heavy icing.

Ice build-up should be recognised as a selection criterion for the tower if icing is likely at the installation site. The towers must be designed to support heavy ice loads, as is the case in the Canadian Standards Association (CSA) standard on Antennas, Towers and Antenna-Supporting Structures [11]. Heavy ice accumulation on the mast structure and guy-wires can lead to sensor and boom failures (Figure 4-1). In the worst cases, such ice loads can result in critical failure of the mast. When the ice load is combined with high wind speeds ice accumulation can lead to a collapse of the mast. Additionally, the lower ends of tower guy wires (where they are attached to anchors) need to be protected in severe icing climates. This is to protect the cable clamps and anchor rods from ice that may have built-up on the guy wires before sliding down during melting conditions.

Before purchasing and erecting a met mast in a region with ice, a calculation of the highest combination of ice load and wind load the site may experience is recommended. For masts with a long-term installation, the standard ISO 12494 [12] states that a combination of the three (3) year maximum ice load and the fifty (50) year maximum wind speed should be used. For constructions that are designed to be short term in nature, or if the site can be closely monitored, the maximum wind speed and ice loading can be reduced. These types of calculations will usually show that the standard or traditional wind measurement masts may need to be reinforced to make them strong enough for locations with severe icing. Often mast suppliers in regions where CC conditions may occur have CC mast options available. This might increase the cost for non-permanent met masts compared to locations in climates without icing.

In addition to the challenges resulting from ice accretion, standard steel structures may become brittle at low temperatures. A tubular tower may fail, so caution should be applied when planning installations at low temperature sites.

Additionally, details like the quality and strength of all equipment, lightning rods, mounting booms, cable straps, wind vanes, and anemometers must be considered.

4.2 Measurement Sensors

4.2.1 Wind

Wind measurements in CCs can be challenging. Many factors can reduce their quality and availability. Anemometers may stop or slow down, wind vanes might stop, and ice build-up on booms or lightning rods may affect the measurements (Figure 4-2). Furthermore, falling ice may damage the sensors and interrupt measurements altogether.

In an icing environment, ice build-up on mounting booms, guy wires, lightning rods, tower, and other components should be expected. The dimensions of the iced structures and their influence on the measurements need to be considered.

As a rule, fully heated sensors are recommended at sites with potential icing. Various types of heated sensors such as shaft heated and fully heated cup anemometers, and heated ultrasonic anemometers are available.

Figure 4-2: The impact of ice build-up on mounting hardware and sensors must be considered to ensure the accuracy of wind speed and direction measurements. Photo credit: TMV2 Murdochville, TechnoCentre éolien.

The fully heated sensors have varying amounts of heating power output that will dictate the conditions under which they will remain ice free. A shaft heated sensor should not be considered ice free, but is able to keep the bearing at constant temperature, improving readings in LTCs. The readings of shaft heated instruments are difficult to filter with regard to icing, as in many cases, an iced sensor will still rotate, but will record a lower wind speed than normal.

These periods are not able to be identified in the time series, unless there is an unheated sensor available (see example in Figure 4-3). Additionally, no fully heated sensor can stay ice free under all conditions (red circle in Figure 4-3). If grid power is not available, an autonomous power supply is recommended (see Chapter 4.3).

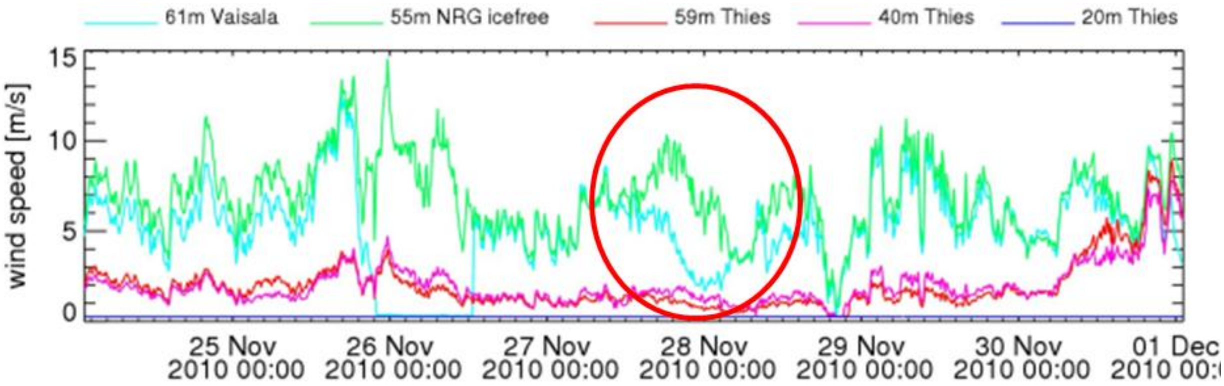


Figure 4-3: Comparison of two fully heated (green, cyan), two shaft heated (red and purple) and an unheated (blue, stand still) anemometer during an icing event.

In general, heated ultrasonic anemometers and fully heated cup anemometers are highly recommended in cold climate and icing conditions, in addition to first class unheated sensors.

When providing power to heated sensors, special attention must be paid to the Joule effect that causes voltage drop over distances, which can reduce the expected heating power of the sensors [13].

The behaviour of icing influenced unheated anemometers depends on the anemometer type. Unheated cup anemometers measure lower wind speeds or stop, providing no measurement (0 m/s). While, unheated ultrasonic anemometers can measure unrealistically high wind speeds when the transducer is influenced by icing.

In general, it is important to note that heated sensors tend to be less accurate than unheated sensors, because they are usually less sensitive to low wind speeds and to changes in wind speed. Some of the heated sensors are also sensitive to flow that is not horizontal [14]. Therefore, conventional cup anemometers that fulfil the IEC requirements are recommended, in addition to the heated sensors. A significant difference in the average wind speed measured by different sensors is a likely indication that the unheated sensor is being impacted by icing. However, under certain conditions, the heated sensors may melt falling snow that will then refreeze on the sensor, leading to self-induced icing.

Attention must also be paid to the positioning of the anemometer and wind vane in ICs. In severe icing conditions, the accuracy gained by using heated sensors can be quickly lost if neighbouring objects, such as booms and masts, are allowed to collect ice. Therefore, surrounding objects need to be heated as well.

Furthermore, falling ice may damage sensors, so it is recommended to avoid having objects, booms or other sensors, directly above each other, and to choose sensors with small exposed surface areas and sufficient heating [13]. It is noted that protecting a sensor from falling ice with an ice shield is generally not recommended, as this would likely affect the wind flow.

If power is not readily available at the mast site, it is possible to install heated sensors on another mast as close as possible to the site where power is available. This approach can be used when the winds at the two locations are expected to be similar. This sensor can then be treated as redundant to the unheated sensors at the site. The relationship between the site and the heated sensor must be established during non-icing periods, to allow the heated sensor to be used when the unheated sensor is not operating. However, when establishing the relationship, the possibility of seasonal variations in the correlation also needs to be taken into account.

At sites where icing occurs less frequently, filtering techniques can be used to remove samples that are affected by icing. For example, a significantly lower standard deviation of the wind vane signal occurs when sensors are iced up. A filter that combines the standard deviation of wind direction and temperature will allow identification and removal of most periods when wind speed measurements are likely to be compromised by icing [1]. In cases where anemometers are used at different heights, a comparison of the data can also help to detect icing on the sensors, when the difference between their measurements diverges from normal. Because the icing process is slow, samples should be removed a number of hours before and after a suspected icing event to ensure data quality. However, these filtering techniques might not be appropriate for all climatic conditions.

The use of redundant and heated anemometers will not guarantee accurate wind resource data collection. Other parameters such as outside air temperature, ice accumulation and ice duration should also be measured. This information will allow for an accurate assessment of potential turbine availability based on conditions outside of the turbine's normal operating regime. The additional information is also useful in evaluating different mitigation options, such as cold weather packages and ice protection systems (see Chapter 7).

Remote sensing techniques, such as SODAR and LIDAR, have been used in CC for wind measurements. The advantage of these technologies is that they have no exposed moving parts, but snow accumulation may hinder their operation. However, there is often a low atmospheric aerosol count at very low temperatures and clear skies, which can impact the performance of LIDARs. Previous measurement campaigns using LIDARs in low temperature conditions found that they had significantly lower data availability when measuring high above ground level. In contrast, fog or low clouds also influence the data availability of remote sensing devices [15] [16].

SODARs have also been used in cold climate conditions, but few evaluation studies have been published at this time.

Supplying power for SODAR and LIDAR devices can often be a challenge when grid power is not available. Additionally, these sensors are typically not designed for CC conditions, and therefore, may require modifications to the housing, sensors, and instrument.

4.2.2 Ice

It is important to assess the site-specific characteristics of atmospheric icing in relation to wind energy development. The key characteristics include the intensity, duration, and frequency of icing events, as well as the maximum ice load and type of ice as described in Chapter 2.1. It is recommended that each of these parameters is either measured directly, or estimated based on other measurements. The measurement of site specific icing characteristics allows for an assessment of the potential icing loss and the requirements for ice protection systems. The interannual variation of icing is typically much larger than that of annual average wind speed [17], [3], making long-term correlations to short term site icing measurements extremely important.

In general, the frequency of meteorological in-cloud icing conditions increases as turbine blades get larger or are placed on taller towers. This is due to the higher probability of the blades being inside clouds, and due to the decrease in temperature with altitude. Therefore, to properly estimate atmospheric icing impacts on the turbine, a representative height above ground level, for the wind turbine rotor, is required. This representative height, the rotor icing height [6], is defined as:

$$\text{Rotor icing height} = z\_hub + 1/3\ D,$$

where z_hub is the hub height of the wind turbine [m], and D is the rotor diameter [m].

Figure 4-4 illustrates the definition of rotor icing height. For cloud heights below the rotor icing height, it may be assumed that the remaining part of the rotor above this height is in cloud or influenced similarly by icing.

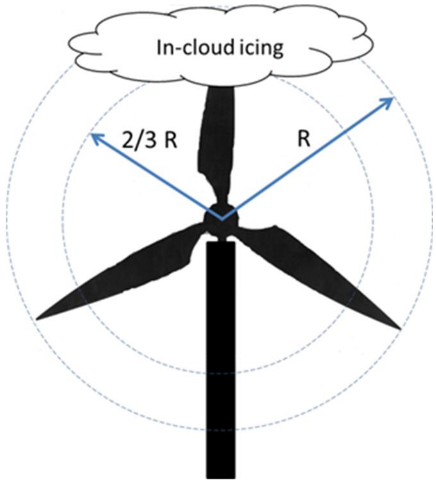


Figure 4-4: Representative ice affected rotor area as defined by rotor icing height [6]

If the site icing assessment is performed below the rotor icing height, this information needs to be taken into account in the analysis.

As minimum requirements when building a site in likely icing conditions one should:

- Assess the frequency of meteorological or instrumental icing at or above hub height.
- Instrumental icing: Install one properly heated and one unheated anemometer (or one unheated wind vane) or
- Meteorological icing: Include a measurement device to assess the frequency of meteorological icing. It is recommended that a camera system be used, but other validated direct or in-direct methods are also applicable.
- Evaluate if vertical extrapolation from measurement height to rotor icing height is required.
- Correlate the measured icing frequency to long-term site specific data[1], preferably 10 years or more, to assess the interannual variability of icing.

As recommended practices in addition to the minimum requirements mentioned above

- Assess both meteorological and instrumental icing.

[1] Either using cloud base height and temperature measurements, relative humidity and temperature as indirect methods or mesoscale weather models

- Use a camera or other validated system to define the frequency of meteorological icing, instrumental icing, maximum ice load, type of ice and icing rate. Camera images can also be used to filter out ice affected wind speed measurements.
- Use multiple, parallel ice detection methods for increased availability and reliability

In addition to using heated and unheated wind sensors to detect icing, ice may also be detected using specialized devices. There are a number of instruments currently available for this purpose, although no single instrument can be used to detect all phases of icing events. Only a few, if any, of the ice sensors are well tested and proven. For this reason, many other approaches using common meteorological sensors have been used to assess the icing environment. This includes the use of sensors such as, visibility sensors, ceilometers, and dew point detectors. Acquiring information such as cloud base height from the nearest airport and comparing that with site measurements is also advisable. For locations in flat terrain, these methods are likely to give a fairly good assessment of the frequency of icing at your site.

Estimating atmospheric icing using a combination of air temperatures below 0°C and high relative humidity (RH) is **not recommended,** as it significantly overestimates the frequency of icing [18] [19] (Figure 4-5). Icing is mainly driven by air temperature, wind speed, liquid water content of the air, and the droplet size distribution. Small water droplets tend to be transported around a structure without hitting it, and thus, not producing any ice despite there being a high RH when they are present. Unfortunately, there is no instrument that is currently capable of automatically measuring the liquid water content and the droplet size distribution automatically under icing conditions. In addition to RH being a poor proxy for icing, unheated RH sensors can become iced, resulting in the capture of humid air within the instrument, which leads to the overestimation of the icing event. Finally, measurements of RH are typically performed according to WMO/CIMO standards, which require that saturation water vapour pressure is always calculated with respect to water. Below 0°C, saturation cannot be reached using this procedure (Figure 4-6). While RH and temperature cannot be used to identify icing periods, it can be used to exclude the occurrence of icing. It can be carefully assumed that there is no icing accretion when RH is below 80 percent at the sensor level [18].

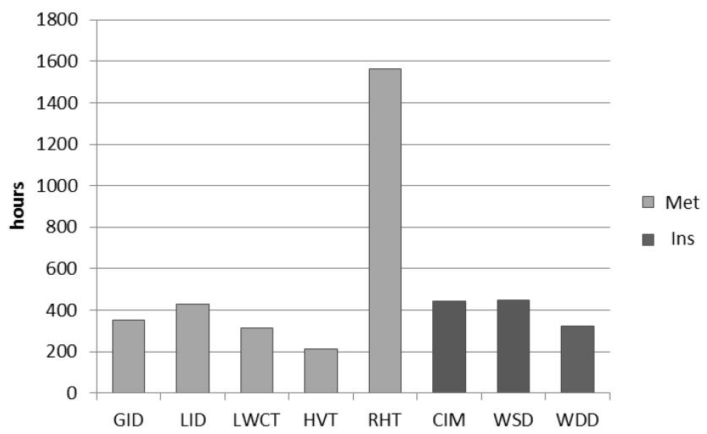


Figure 4-5: Icing hours from various ice detection methods showing the relative humidity and temperature method significantly over-estimates icing duration compared to all other methods tested [19].

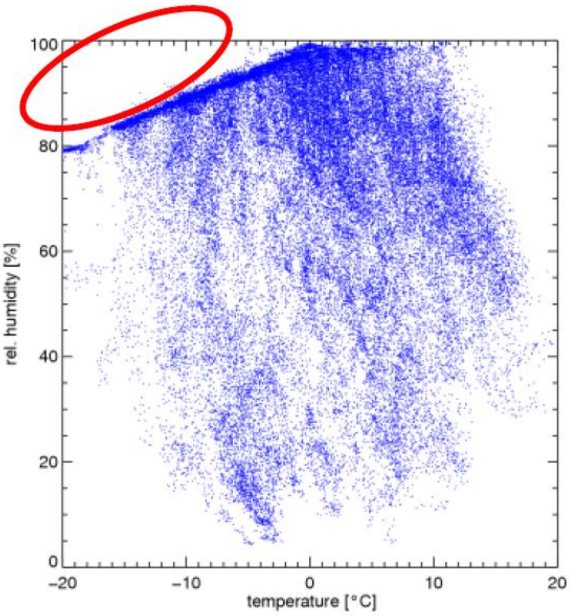


Figure 4-6: Relative humidity measured according WMO/CIMO standards does not reach saturation anymore at temperatures below 0°C (red area).

Relative humidity and temperature may be used carefully as an in-direct indicator of icing at low elevations, when the relative humidity sensor is not directly in icing conditions. If site relative humidity measurements correlate with nearby meteorological station measurements, long-term correction of site measurements can be performed using the longer historical meteorological station measurements.

4.2.3 Temperature

Radiation shields around temperature sensors need ventilation to work properly. The ventilation in conventional small shields with lids may become filled with ice or encased in snow, and provide false readings. The use of high power heating and/or large housings such as those used on meteorological stations may be necessary.

4.2.4 Atmospheric Pressure

Measuring pressure in an icing environment is similar to measuring pressure at a conventional site. However, care should be taken to ensure that the pressure sensor is being exposed to the surrounding atmospheric pressure, by keeping air intakes ice-free, to prevent false readings.

4.3 Site Power Supply

Monitoring systems implemented in arctic and icing climates have larger power requirements than at conventional sites, due to the need to use of heated sensors and other equipment. This may greatly increase the installation requirements and cost. Power for heated sensors can often be a challenge when grid power is not available. Depending on the type of sensor, up to 250 W (for a heated Ultrasonic) may be required to keep the sensor ice-free. Small wind turbines, photovoltaics, diesel engines, fuel cells, and hybrid power systems are options when a grid connection is not available. Remote monitoring should be implemented to allow for early warning of power system problems. The design and implementation of remote power systems are non-trivial tasks. Therefore, organizations that are well acquainted with remote power systems in harsh environments should be employed.

Figure 4-7: Accessing a power system in a remote location. The entire 2.5-meter high container, apart from the air inlet to the engine, has been buried. Photo credit: Lars Tallhaug, Norway

4.4 Setup and Operation & Maintenance of Measurements

4.4.1 Installation

Meteorological monitoring installations should be set up during warm weather for improved safety and to increase the quality of measurements. Winter installation is possible, but should be generally discouraged (Figure 4-8). Ground conditions, such as permafrost or seasonal changes in soil conditions must also be considered.

Figure 4-8: Winter meteorological tower installation in Alaska. Photo: Doug Vought, USA

4.4.2 Accessibility and Site Communication

Site communication at remote CC sites can be challenging. Since conditions are frequently quite harsh, redundant measurements and expanded data logging capabilities are recommended to ensure a high percentage of data capture. Limited site accessibility also justifies extended data retention policies, and the use of multiple sensors for high-priority signals, such as wind speed and temperature. Since an additional effort is required for any CC measurement program, adding these small incremental costs to improve reliability is quite appropriate. At CC sites, it is important that measurement data is checked regularly, since the quality of the data depends on the reliability of subsystems, and ultimately how well supervision can be arranged. Covers and locks for all equipment should be selected to ensure that they can be used with winter gloves, and that they are not likely to be impacted by ice and snow.

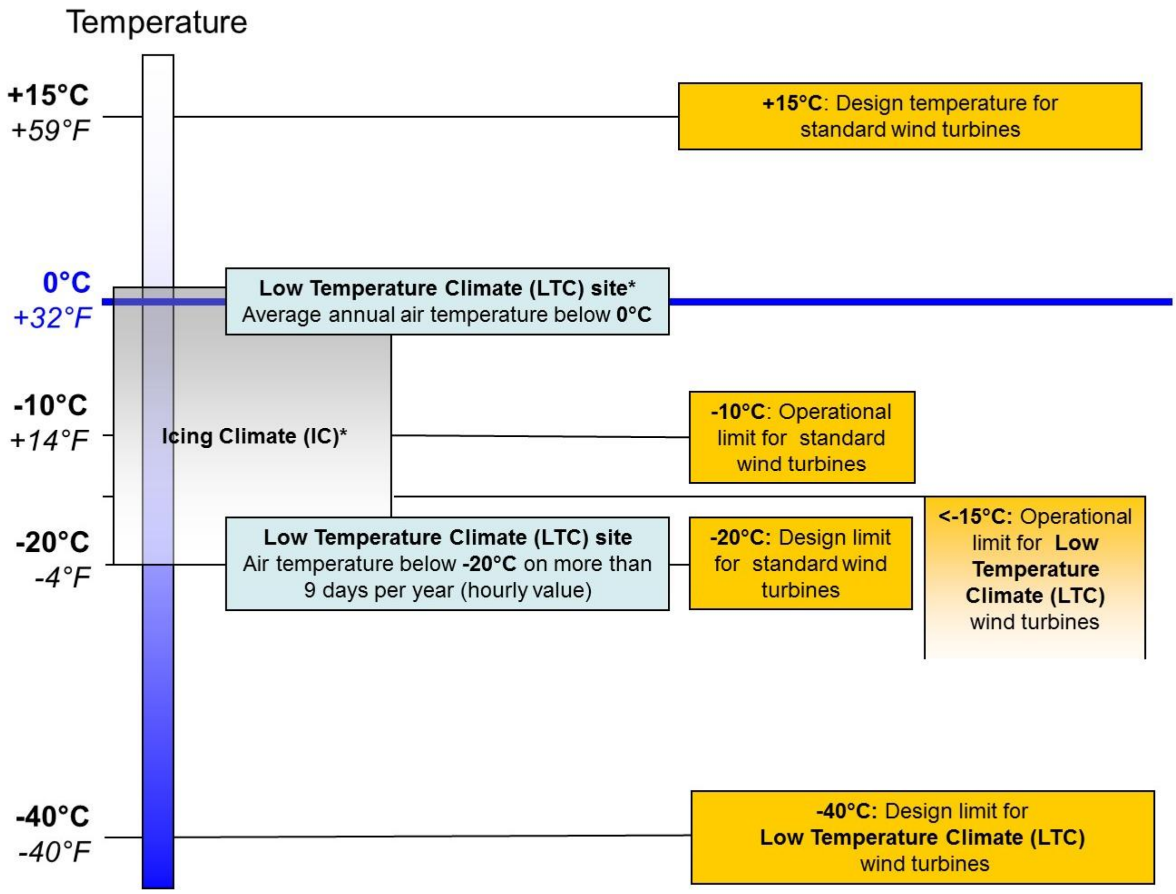
4.5 Checklist of Key Issues for Site Measurements

Checklist of Key Issues

- Conduct a survey to the planned wind farm land owners and nearby wind farm operators for some initial CC experiences
- Measurement mast designed for the local wind and ice conditions
- Remote sensing can be considered viable for CC conditions, be aware of potential low data availability issues with LIDAR technology
- Strong and good quality equipment and materials are being used
- At least the minimum level of ice measurements is conducted: measure meteorological or instrumental icing duration at hub height or higher for one year and perform long-term correction.
- Sufficient data filtering to remove ice influenced data
- Year-round measurement site accessibility ensured
- Power supply ensured for wintertime
- Robust and tested remote communication and data transfer in place
- Devices should be designed and installed to allow service during cold and inclement weather

5. TECHNOLOGY FOR COLD CLIMATE WIND ENERGY

Low temperatures and atmospheric icing pose additional challenges for wind turbines, when compared to conditions at standard sites. Thus, special technologies are recommended for CC sites, these include: materials that can withstand low temperatures, control systems and procedures that are adapted to low temperature operation, and rotor blade ice protection systems. Figure 5-1 illustrates when CC adaptations for wind turbines may be needed.



From DNV GL Recommended Practices (2016) ”Extreme temperature conditions for wind turbines”

Figure 5-1: Low Temperature Climate (LTC) and Icing Climate (IC) with respect to ambient temperature and wind turbine design.

In order to decide if a site is an LTC site or not, IEA recommends the use of the DNV GL definition which is described in Table 5-1 and in the draft standard IEC 61400-1 ed4 [6]. In addition, standard IEC 60721-3-3 defines the limits, related to climatic conditions, for electrical equipment, such as transformers and switch gears, used in wind farms.

Table 5-1: Typical and Recommended Temperature Limits for Wind Turbines.

Limits	for standard turbines according to IEC(1)	typical for LTC(2) turbines
Operational temperature limits	-10 ºC	-30 ºC
Survival temperature (stand still)	-20 ºC	-40 ºC

(1) IEC 61400-1 ed3

(2) Low Temperature Climate turbines are turbines that have low temperature modifications provided by the turbine suppliers, as defined in draft standard IEC 61400-1 ed4 [6] and DNV GL [20]

Wind turbines with technologies adapted for operating in low temperatures and/or icing conditions typically cost more than standard wind turbines. Depending on the climatic site conditions and requirements of local authorities, these extra investments may be mandatory to improve the energy yields, safety, lower maintenance costs, or simply a prerequisite for permit approval.

It is recommended to use wind turbines designed for low temperatures if the annual average temperature is below 0°C or if the temperature at the site remains below -20°C for one hour or more for more than nine days a year. These criteria for low temperatures are from DNV GL [20] and draft standard IEC 61400-1 ed4 [6].

5.1 Technologies for Low Temperatures and Icing Conditions

Wind turbine manufacturers offer readily available wind turbines for use in LTCs, typically denoted as Cold Climate Packages. The following modifications and items are typically included in a cold climate package, although these vary based on the turbine manufacturer:

- Materials and components adapted for low temperature applications such as low temperature alloys and special elastomers instead of standard rubber.
- All welding procedures completed with special low temperature flux.
- Lubricants (grease and oils) and hydraulic fluids suitable for low temperature.
- Heaters for components and lubricants e.g. for generator, gearbox, yaw and pitch systems, control boxes, converters and transformers.
- Cooling system suitable for low temperature operation to avoid icing of condensers or other systems.
- Control system designed with low temperature features, such as preheating of components and subsystems during cold start after a grid failure.
- Appropriate measurement systems including heated sensors. Although not typically included, it is recommended that the measurement system support structures, such as mounting booms, are also heated.
- Nacelle heating to allow a reasonably safe and comfortable working environment for turbine maintenance.
- Ice detection systems to safeguard nearby personnel and infrastructure from ice throw, and to safeguard the wind turbine against rotor unbalances and potential damage to the turbine.

- Blade ice protection technology to prevent down-time, mitigate ice throw risks, decreased iced blade noise emissions and reduce potential increased turbine loading due to icing.
- Blade ice protection system requirements and selection for the site-specific conditions. Simultaneous wind speed and temperature assessment during and after meteorological icing conditions are typically needed for assessing ice protection system site suitability.

A more extensive list of typical low temperature package options here [4]. Above all it is important to determine the level of experience the manufacturers have in turbine installation and operation in cold climates. Additionally, it is recommended to negotiate icing as a factor in the turbine availability guarantee, and to consider ice protection technologies.

Atmospheric and precipitation icing cause ice accretion on rotor blades, which leads to reduced aerodynamic performance of the rotor blades and consequently icing losses, possibly increased fatigue loads [21], [22], and an increased risk of ice throw. These adverse effects can be reduced by means of ice protection systems. An ice protection system can be a requirement to get building permission for wind turbines in some countries because of the safety issues. Such systems exist, although the industry is not yet mature; currently there are many different technologies under development. The most promising technologies are based on heating the blade surfaces actively either by electro-thermal heating foils on the blade surface or warm air circulation inside the blades. For more information about available turbine technologies, please see list of turbine suppliers here [4].

Well documented information or data is not available from the different technologies, making the comparison of the technologies is difficult. Typically, the energy consumption of blade heating is 2% or less of annual energy production. In moderate or severe icing conditions, the payback time of proven ice protection system can be less than a year, and sometimes only a couple of months.

The recommendation is to use ice protection systems for improved energy production, safety, and reduced fatigue loads, if economically beneficial or if local regulations require them to be installed.

Table 3-1 can be used as a guideline for whether ice protection systems are needed, but the need for ice protection systems is always case- and site-sensitive, especially for site classes 1 and 2.

5.2 Ice Detection

Ice detectors are typically located at the top of nacelle of a wind turbine, but some are mounted directly on the blade. These ice detectors can be used to detect icing conditions and to predict the conditions of the rotor blades.

Some turbine manufacturers use the change in a turbine's operating performance to detect ice build-up on rotor blades. This method is based on the sensitivity of rotor blade profiles to changes in the shape and surface roughness of the profile, which are changed when ice forms on the blade. The disadvantages of this method are that ice cannot be detected during standstill of the rotor and that the reduced power output can be the result of other phenomenon, such as yaw misalignment.

IEA Wind TCP Task 19 has developed a free and open source program called the T19IceLossMethod, to provide a standardized method for assessing production losses due to icing using wind turbine SCADA data [23]. This software uses the turbines operating performance as an ice detector to calculate the icing losses. The software can be downloaded from Task 19 website here.

Ice build-up on the rotor blades can change the blade's eigenfrequency and this change in blade eigenfrequency can also be used to indirectly detect ice build-up on the rotor blades. An advantage of this technology is that ice can be detected when the turbines are standing still, but the technology must be tuned in such a way that the effect of temperature changes is eliminated in the eigenfrequency and damping calculations, so that it is sensitive enough for ice detection.

An advantage of these approaches, detecting ice from power or the eigenfrequencies of the blades, is that ice formation can be detected even when nacelle based ice detectors are cloud free, but the blades are rotating through clouds further aloft.

5.3 Foundations

The presence of permafrost can add another challenge when developing wind energy sites in cold climates. It is recommended that a soil analysis is undertaken, and to take actions to mitigate the effects of permafrost, if it exists.

Installing a wind turbine foundation in permafrost may require substantial changes to its design. For example, freeze-back pylons (see Figure 5-2), rock anchors, or other proven construction techniques may be necessary since soil changes can change the dynamic behaviour of the wind turbine tower, blades and other components. If there is a risk of significant soil changes over the lifetime of the wind turbine, it is recommended to utilize a structural health monitoring system (SHM) that can identify changes to the structural dynamics of the foundation and other structures.

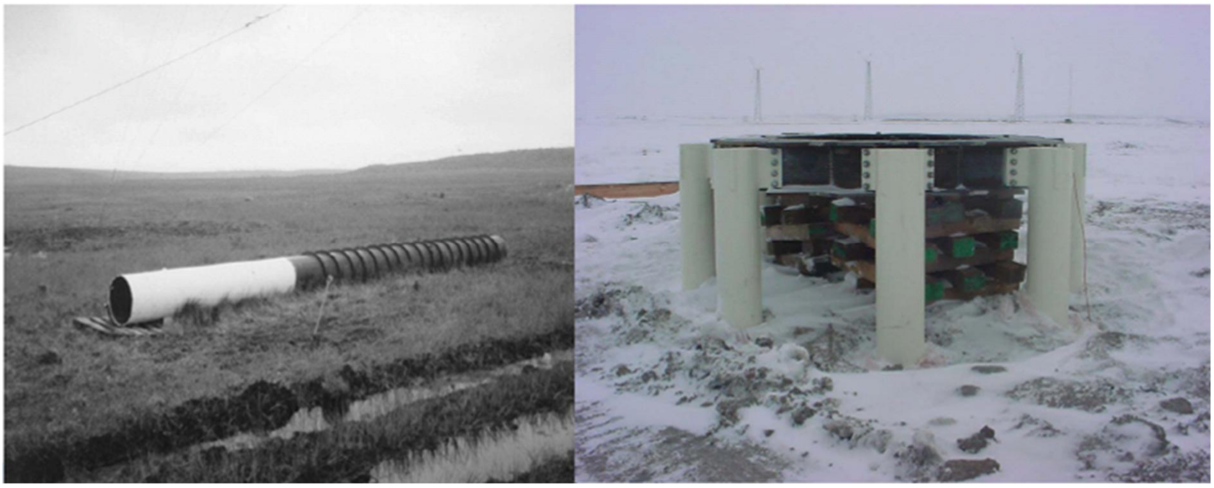


Figure 5-2: Freeze-back pylons used for turbine (and other) foundations in permafrost areas. Photo credit, Northern Power Systems, USA

5.4 Grid Connection

Permafrost or solid rock limits the use of buried cable, both because of the expense of trenching and the dynamic behaviour of the permafrost soil, which can rupture conduits and damage cables. While, overhead cables can be damaged by ice, and permafrost freezing cycles can impact power poles. Instead, a cable can usually be laid on the ground and affixed to concrete blocks or other ground ties. If an armoured cable is needed to protect against animals or other mechanical hazards, simple wooden structures or steel conduits can be used.

5.5 Turbine Certification

Current national and international standards for wind turbines, for example IEC standards, do not typically address low temperature operation or icing conditions, but the IEC 61400-1 ed4, which is currently under review, has proposals for a cold climate turbine class parallel to wind and turbulence classes. These would include iced turbine design load cases [6]. Additionally, current performance and maintenance contracts contain a statement that operation outside of "normal" conditions can impact many of the terms. This makes it difficult to find turbines that have certification for low temperatures and/or icing conditions.

DNV GL has developed a certification criteria for turbines operating in low temperatures [20]. The low temperatures influence the loads, safety, sensors, materials, and operation. Because the scope of the DNV GL certification is low temperatures, icing is not dealt with. The certification simply requires ice detection, either through sensors or indirect methods to shut down the turbine during instrumental icing. This procedure may not be applicable, or desired, for turbines operating at sites with frequent meteorological icing, especially at icing class 3 or higher, due to the significant impact this would have on energy production.

However, a new recommended practices document on iced turbine load assessment is being prepared at DNV GL [8], to be published in 2017. This recommendation plans to use the new IEC 61400-1 ed4 as baseline, and to provide more detailed guidelines for fatigue load assessment of iced turbines.

5.6 Testing

Different test centres, research institutes and universities have set-up testing infrastructure that comply with cold climate certification standards and best practices. Similar to milder "normal" climate technology solutions, it is recommended to always test products or solutions for cold climates in relevant controlled environments, for example a laboratory or a test site, prior to using them in an operational environment. More information on this topic can be found in the Task 19 Available Technologies report [4]. DNV-GL's recommended practices with respect to 'extreme temperature conditions for wind turbines' [20] also recommends that critical components, such as brakes, pitch and yaw systems, gearboxes, and liquid filled transformers are tested at low temperatures to assess their safety and reliability. A critical event for a wind turbine at a CC site is cold start-up. There this process is quite often included in the scope of the testing and validation program of a wind turbine.

5.7 Turbine Warranty in cold climates

It is recommended that extra attention is paid during the contract negotiations when buying turbines to be installed at sites with low temperatures and/or icing conditions. When negotiating the availability guarantee, ideally, icing will be included. Additionally, the exact site conditions and turbine specifications should be investigated in consultation with the wind turbine manufactures and project engineers. Based on the site conditions, a decision must be made on the installation of a cold climate weather package to avoid downtime and long start-up times in wintertime when potential production revenue is at its best, or to not include one and take the risk of lost periods of production.

Wind farm performance in ICs is reliant on a high performance and commercially warranted ice protection systems to mitigate the icing characteristics expected at a site, both from the permit and business perspectives.

Without an ice protection system, project icing losses can potentially be a large percentage of the expected Annual Energy Production (AEP). Therefore, a limitation of these icing losses is required to make the wind farm profitable. Additionally, the performance of the installed ice protection system needs to be sufficiently warranted.

Although there is, currently, no standardised method of tracking the efficiency and reliability of ice protection systems, there are several possible methods that could work. It is recommended that any ice protection system should include at least:

a) a system performance specification,
b) a method for follow up testing and evaluating the performance, and
c) warranted levels of performance that take the operational conditions into consideration.

Warranties are normally provided for turbine functionality and the ice protection system warranty should be included in these warranties.

IEA Wind TCP Task 19 will be working on "Ice protection system performance evaluation guidelines" together with industry participants, and these guidelines will be published in 2017-2018.

5.8 Checklist of Key Issues for Cold Climate Technology

Checklist of Key Issues

- Check latest international standards and certification practices for CC solutions, make sure that technology providers follow them
- Use site temperature and wind speed data to determine if LTC adaptations are needed
- Use ice maps and site ice measurements to determine if ice protection systems (anti- or de-icing) should be applied, assess ice protection system site suitability
- Special foundations may be required due to permafrost
- Review test reports of certain critical solutions from a laboratory or test stands before placing them in the field
- Review local regulations if ice protection systems are required for permitting purposes
- Consider the experience of the turbine supplier and the technology track record in CC
- Contents of the turbine suppliers Cold Climate Package should be considered
- Try to negotiate icing to be included in the availability/production guarantee
- Construction, service, and maintenance in CC might take relatively longer time compared to standard climates

6. OPERATION AND MAINTENANCE

6.1 Operation and Maintenance

At cold climate sites, low temperatures and the icing of wind turbine blades make the operation and maintenance of turbines more demanding than at standard sites.

Turbine operation must be adapted to low temperatures, including more frequent cold starts, heated sensors, heating and cooling configurations, special lubrications and greases, and low temperature materials. Normally these issues are taken into account if the turbine is equipped with a low temperature package, but the level of low temperature adaption varies with the turbine supplier. It is particularly import to avoid the freezing of components, since extended downtime can lead to damage of some mechanical components, e.g. standstill marks on geared machinery.

Icing affects the turbine operation by decreasing the production and by potentially increasing vibrations, noise, and the risk of ice throw (for more information on ice throw, see chapter 8.1). Icing also affects the nacelle wind speed measurements. The direct influence of icing on operation, unless equipped with an icing protection system and heated wind sensors, will be an increased number of "lower than expected power" stops, stops due to high vibration amplitude, and stops due to faulty wind measurements. Also, the available ice protection systems and heated sensors don't always guarantee 100% fault free operation in icing conditions. The indirect consequences of icing on operation include a reduced technical lifetime, bodily injuries and material damages caused by falling ice, and an increased noise level.

Local rules and regulations must be considered, for example in certain regions and countries, such as Germany and Belgium, a wind turbine with iced blades cannot be operated due to ice throw safety reasons. Additionally, some rules and regulations require that icing or vibration alarms cannot legally be reset without a visual observation of the conditions of the rotor blades. In some areas, indirect observations including remote sensing, web based or direct video cameras, and other relevant sensors can be used to enable a legal remote restart procedure of the turbine. In other countries, adequate warning signs and marked safety zones may allow turbine operation in icing conditions (read more in Chapter 8).

The operator or owner of a WT should learn the operational behaviour of his/her turbine in CC by studying the turbine owner's manual. Operators should monitor the turbine behaviour and investigate all abnormal situations, so that the life-time of turbine is not decreased due to faulty operation.

To help the operation and maintenance in CC, a SCADA system (*Supervisory Control and Data Acquisition*) can be fitted with ice detection and condition monitoring, both working condition and turbine condition. Additional information that can aid in operating a site in CC includes ambient temperature, visibility at the site, web camera photos of the rotor blades, turbine wind sensors, and met mast data. An assessment of the local conditions will likely indicate which specific level of monitoring and remote communication is most appropriate. However, erring on the conservative side will often pay off greatly over the lifetime of the project.

Maintenance of turbines should preferably be scheduled to avoid harsh conditions (read more about working conditions in Chapter 8).

The impact of icing on production forecasts can also lead to risks on the SPOT market. It is recommended to investigate the use of short-term icing forecasts to lower these uncertainties, and provide a better forecast of the day-ahead production.

6.2 Accessibility

During the winter, icing and snow drifts can make vehicle access to cold climate sites difficult or impossible without snowmobiles or other over snow transport. Additionally, many CC sites experience swampy conditions or flooding during the spring and summer, which has to be accounted for when planning site access. Typical snow depths, flood frequencies, and high stream levels must also be studied to allow for the design of adequate road surfaces, culverts, fords, bridges, and road marking poles that will keep the site accessible and road visible.

The logistics of turbine installation must be planned according to seasonal conditions. Seasonal limitations on accessibility may cause project construction to be implemented over more than one season.

Adverse conditions may prevent evacuation for medical or work related emergencies, therefore contingency planning, for such occurrences, must be undertaken early in the implementation process.

Site accessibility can impact the overall economics of a project, and must therefore be carefully analysed in the early stages of the project.

6.3 Checklist of Key Issues for Operation and Maintenance

Checklist of Key Issues

- Check if LTC turbine operation is permitted by the manufacturer in order to avoid damages due to cold start up or frozen machinery
- Check if IC turbine operation is permitted, plan preventive measures for ice throw if needed. Check for the risk of ice throw on the O&M crew and implement HSE procedures to limit the risk during turbine access
- Check if maintenance scheduling addresses the harsh conditions
- Consider icing forecasts for increased accuracy of production forecasts
- Consider wintertime site access limitations
- Consider additional monitoring systems such as ice-detection, webcams etc.

7. ENERGY YIELD CALCULATIONS

7.1 Low Temperature Effects

Temperatures below the operational limit of the wind turbine will prevent it from operating and thus impact turbine availability. However, even before reaching this limit, the turbine will be down rated from its nominal capacity to protect the various systems that are impacted by the low temperatures. Additionally, the low temperature adaptations to turbines can lead to extra energy usage by the turbine itself, reducing the amount of power provided to the grid.

When calculating energy output, one should identify the correlation between wind speed and temperature. In many areas, very low temperatures are associated with high-pressure systems, and therefore, weak winds. For areas with cold temperatures, an analysis should be conducted to calculate the loss of energy production, using measurements of both wind speed and temperature, when temperatures are below the operational threshold defined by the turbine manufacturer. A statistical analysis can be conducted based on long term diurnal and seasonal temperatures and wind speed distributions, to provide a reasonably accurate assessment of energy production losses due to low temperatures.

While, there is potential overlap between periods with production losses related to low temperatures and those related to icing, simultaneous periods with extremely low temperatures and active icing events are rare.

7.2 Ice Effects

Ice build-up on the blades usually reduces lift and increases drag, which results in reduced power output and potentially turbine shutdown. An example of an large ice layer on a turbine blade is presented in Figure 7-1.

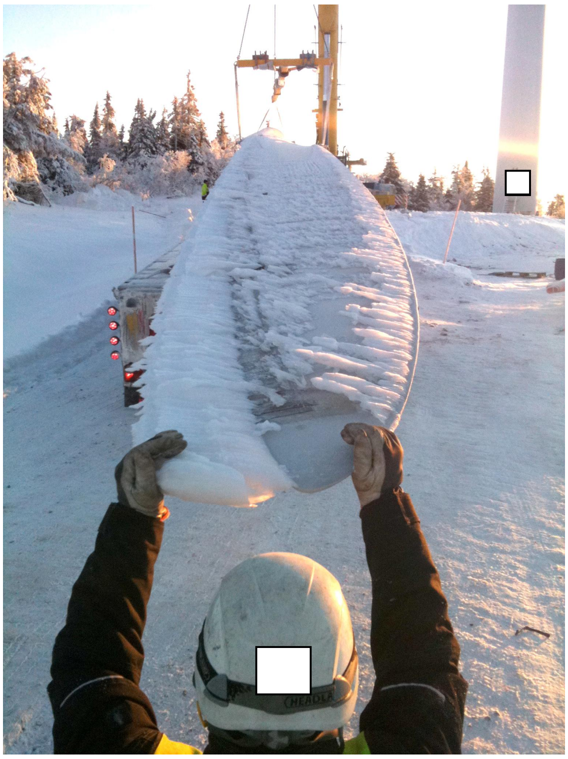


Figure 7-1: An iced-up wind turbine blade. Photo credit: Göran Ronsten

Atmospheric icing reduces the aerodynamic performance of a wind turbine rotor significantly, since the blade aerodynamics are sensitive to the increase in surface roughness and the shape alterations caused by the ice growth [24]. The most important parameters for estimating ice induced energy production losses are intensity, duration, type, and frequency of icing with respect to the wind conditions. It is also necessary to know how these parameters correlate as a function of time. Icing has been shown to have larger interannual variability than average wind speed [3], [17] and therefore, there will be larger interannual energy production variability. This adds additional complexity to the calculation of production uncertainty, which impacts the calculation of P50 and P90 values. Other factors that impact the energy production of a turbine under icing are ice protection systems, the configuration of turbine control systems under icing conditions, and local regulations that can determine if the turbine can continue to operate or must shut down. <u>It should be noted that turbine operation and control strategy in icing</u>

conditions may significantly impact the energy production, some sites have seen a factor of 5 impact on the production loss, e.g. for turbines that shutdown immediately in icing conditions versus continuing operations normally or having an ice operation mode that behaves similar to curtailment operation.

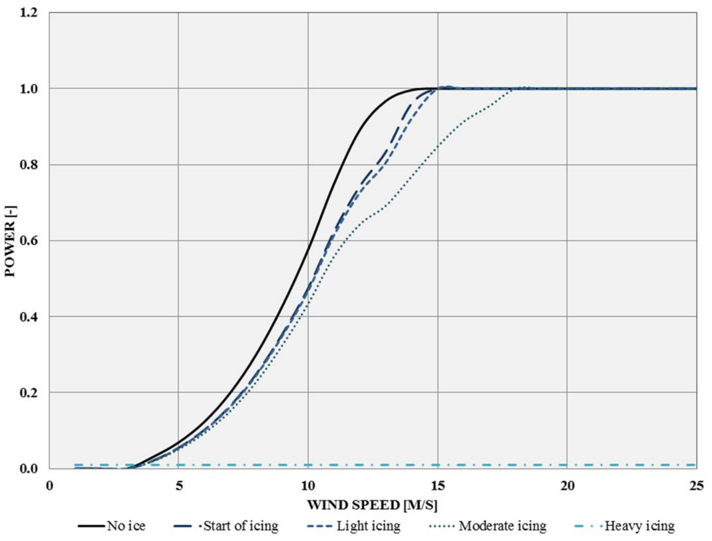


Figure 7-2: The impact of ice on the power curves of a 3MW wind turbine that was used in creating the Finnish icing atlas [25]

The performance of modern pitch regulated wind turbines will be impacted even in light icing conditions, and may even shutdown entirely, which is a turbine specific issue. Examples of simulated power curves for iced up wind turbines can be found in [25]. The new proposed IEC 61400-1 ed4 also has a calculation method for iced airfoil lift and drag coefficients [6].

Regardless of the uncertainty in estimating the aerodynamic properties of an iced-up blade, it is recommended that time-series of wind, ice accumulation, and temperature be produced. The time-series of ice accumulation and temperature can be obtained from a mesoscale model or measurements, but the wind series should be obtained from measurements. By utilizing concurrent wind and icing data, different cases can be analysed, depending on the turbine operating strategy. Examples of these are:

1. No production during meteorological and instrumental icing
2. No production during meteorological icing followed by the de-icing procedure
3. Reduced production or shutdown during meteorological and instrumental icing

In examples 1 and 2, it should be noted that regulatory requirements may increase the icing losses, as turbine inspections may be required before restart. In example 3, the icing losses are defined based on turbine specific power performance curves that include the impact of icing, as illustrated in Figure 7-3.

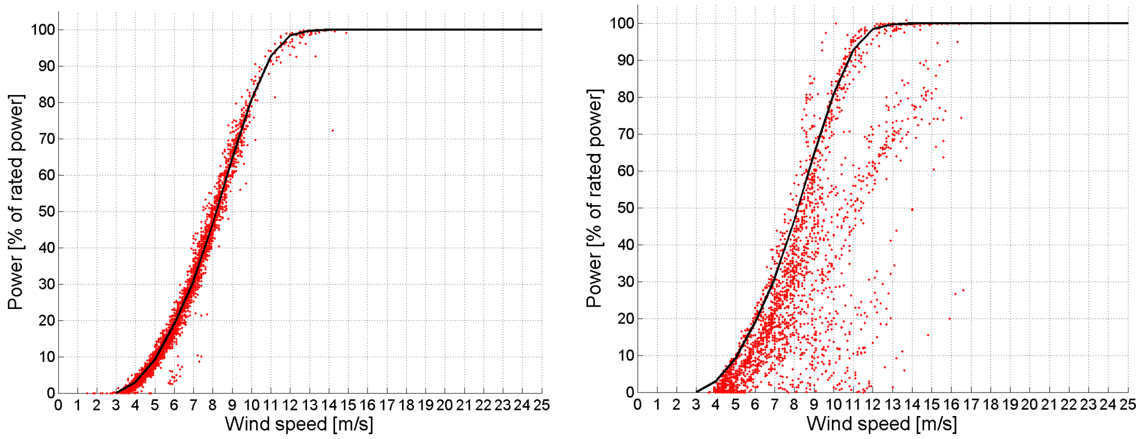


Figure 7-3: Power (% of rated power) as a function of wind speed in two cases. On the left: A power curve registered in May 2010. On the right: An ice-impacted power curve registered in November 2009.

Typical levels of icing losses to be expected in different icing climates, and can be related to the sites ice class that was presented in Table 3-1. However, these should not be used over site specific assessments of potential turbine specific icing losses.

7.3 Checklist of Key Issues for Energy Yield Calculations

Checklist of Key Issues

- An assessment of AEP impacts due to CC issues should be undertaken. This should include the impact of CC conditions on measurement data
- Lower turbine availability/production should be assumed due to CC conditions
- Additional uncertainties due to CC conditions need to be incorporated in AEP calculations
- Request turbine specific performance analyses in IC using the latest standards and best practices, with a particular focus on the turbine control strategy

8. HEALTH, SAFETY AND ENVIRONMENT

8.1 Planning for H&S by Assessing the Risk of Ice Throw and Ice Fall

The risk of injury caused by falling ice from high buildings, wind turbines, masts, and towers should always be treated seriously. There is a risk of serious injury and property damage within the maximum ice throw distance for a rotating turbine represented by the Seifert Formula (**Equation 1**).

During project development, the following process order is recommended (further details are in [26]):

1) Carry out site specific ice assessment to determine if icing will occur at your site,
2) Screening turbine surroundings for ice throw with Seifert Formula,
3) Perform ice throw simulations providing strikes/year/m^2,
4) Determine acceptable risk levels, and
5) Apply risk mitigation strategies.

Figure 8.1 describes the recommended ice throw analysis process.

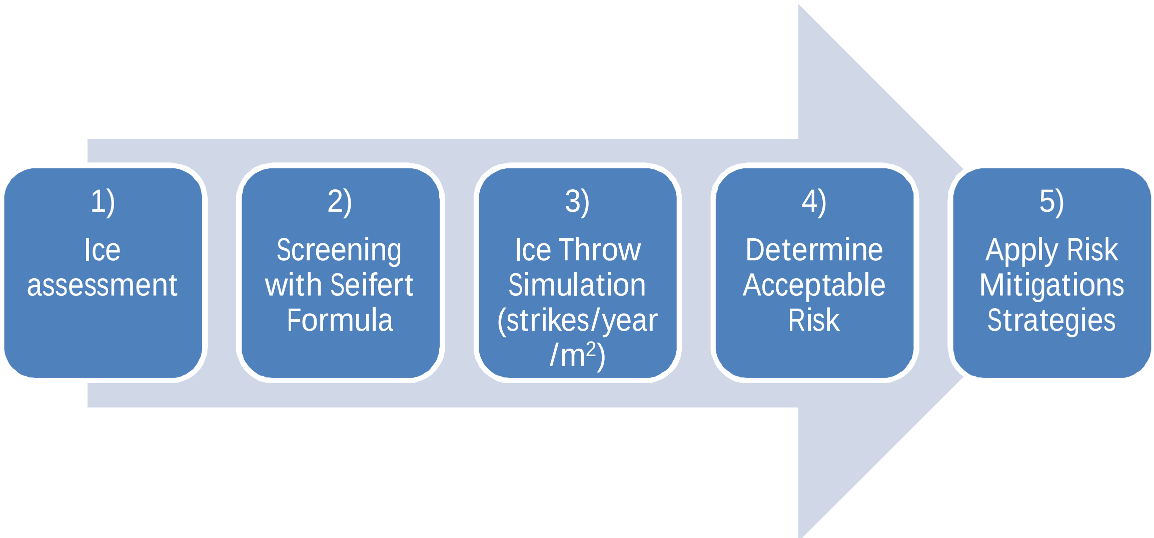


Figure 8.1: A flowchart for managing the risk of ice throw during the project development stage (incl. ice fall).

8.1.1 Site-specific ice assessment

If there is no risk of ice throw, no further measures are required. For rime ice, an initial assessment of the frequency of ice accretion can be made by mapping simultaneous occurrences of clouds and sub-zero temperatures or by using weather models. Similar procedures can be used to assess the occurrences of clear ice and freezing wet snow. If significant icing is expected based on the ice map analysis, icing measurements should always be carried out to capture the site-specific icing assessment (see chapter 4.2.2), and used for site classification (see chapter 3.2).

8.1.2 Screening with Seifert Formula

The maximum distance for ice throw from a rotating wind turbine can be estimated by the following rule of thumb, in flat terrain [27].

$$d = 1.5(D + H), \qquad \textbf{Equation 1}$$

where d is the maximum throwing distance of ice (m), D is the rotor diameter (m), and H is the hub height (m).

Example: *For a wind turbine located in flat terrain with a 100-m diameter rotor and a 100-m tall tower, the initial conservative maximum ice throw radius is 300 m.*

Seifert et. al., [27], suggest that $d = 1.5(D + H)$, **Equation 1** is conservative and that it shall be used only as an initial estimate. Therefore, more detailed calculations, including risk assessment (see chapter 8.1.4), should be carried out.

Ice throw from a WT blade typically occurs downstream of the rotor plane. The maximum observed ice throw distance known to IEA Wind Task 19 is roughly 2/3 of the Seifert Formula [28]. If there is an overheight, dZ, between the turbine location and the surrounding terrain, the formula can be extended by adding dZ to H for screening purposes [28]. The Seifert Formula for a rotating wind turbine includes ice fall (shed) from a wind turbine at standstill.

8.1.3 Ice throw simulations

Within the maximum distance calculated using the Seifert Formula, there is a decreasing probability of ice throw with increasing distance from the turbine. Ice will be thrown in directions and to distances determined by factors including, but not limited to, the size, density, roughness, and shape of the piece of ice thrown, as well as by the wind speed, wind shear, wind direction, hub height, rotor radius, and the RPM of the turbine. Using these inputs, the spatially distributed number of strikes/year/m^2 can be calculated by means of ice throw simulations. An example of the results from such a calculation is shown in [29].

8.1.4 Acceptable risk level

An international standard for acceptable risk levels from ice throw is yet to be developed. Consequently, the acceptable risk levels for different activities differs from country to country. The risk associated with the spatial distribution of calculated ice throws in 8.1.3 can be analysed using Localized Individual Risk per Annum (LIRA) and ALARP (As Low As Reasonably Practicable) principles. For more details on different risk assessment methods and principles, see [30].

8.1.5 Risk mitigation strategies

For an extended checklist of possible risk mitigating strategies related to ice throw and ice fall including strategies on internal and external communication, turbine specific ice-mapping, turbine technical measures, and operational strategies, see [31].

IEA Wind's Task 19 working group is currently (2016-2018) developing international guidelines for ice throw and ice fall risk assessments [32] that will be published in 2018. The guidelines will be based on work presented in [4] [28] [29] [33] [30], and make use of contributions from external partners.

8.2 Public Safety

Figure 8-2-1: Ice falling or being thrown off a wind turbine poses a safety threat to turbine maintenance staff and, depending on turbine siting, the general public. Photo credit: Jeroen Van Dam, USA

Iced up WT blades and towers can pose a safety hazard for wind farm visitors and staff. See Figure 8-2-1 for an example of falling ice fragments. The fact that no serious accidents caused by ice throw have been reported is no reason to think otherwise. Special technical solutions may need to be implemented to prevent accidents on CC sites accessible to the public.

Ice, particularly clear ice, on a WT blade can be very difficult to see from the ground. Ice can also fall from places that are not visible from the ground, such as from the nacelle and the blade roots. A dangerously thick layer of clear ice can form on top of the nacelle if heat from the nacelle is allowed to melt accumulated snow. Ice seldom melts completely, it either sublimates or falls from the structure.

Turbine operation with iced up blades may not be permitted in certain high population density countries, due to HSE concerns. Since visibility can be extremely poor during active icing conditions, warning signs should be closely spaced, unless the area is accessible only via specific posted entry points.

The areas of potential ice throw should be calculated, and the proximity of developed areas, roads, and tourist infrastructure, such as ski slopes, lifts, footpaths, and parking areas must be taken into account when placing the turbines.

The potential ice throw zones should be clearly marked in the terrain by means of reasonably located and designed warning signs. However, warnings signs indicating the ice throw zone might not be sufficient, if used as the only means of risk mitigation for ice throw. Flashing lights, horns, or other active attention devices that warn of falling ice after icing events can be implemented before turbine start-up to help ensure public safety (see examples in Figure 8-2-2). Flashing lights at the park entrances during periods with risk of ice throw is also an option.

In many cases, the area around the turbine will be accessible to the public either intentionally or because fencing is buried under snow. Warning signs and assistance to visitors who could possibly be injured while touring the turbines should be utilized. General alarm and security measures need to be incorporated into the project design. Insurance coverage should be planned, and the necessary analyses done to estimate visitor frequency for planning mitigation measures. In order to address the issues above in a formal manner, an assessment of mitigation options that limit the risks associated with wind farm deployment at specific sites, should be carried out.

Figure 8-2-2: Warning signs for falling ice. Photo credit Lars Tallhaug, Norway.

8.3 Labour Safety

Working in cold conditions poses particular challenges in terms of labour safety. Outdoor activities should generally be avoided when temperatures are very low. People's capability to focus on safety and problem solving quickly decreases in adverse conditions, such as low temperatures, high winds, and during precipitation. Thus, apart from being costlier due to the extra time and equipment requirements, low temperatures may also pose significant safety hazards. Even limited exposure to extremely cold conditions can lead to frostbite and other injuries. In addition, the wind chill must be considered as well, since this can be particularly significant on wind farms as sites tend to be located in areas with high winds.

Figure 8-3: Work in extreme and cold climates requires special equipment, increased focus on personnel safety and expanded planning. Photo credit: Lars Tallhaug, Norway

Heated accommodations, proper clothing, proper training, shelter, survival equipment, and machine design that allow service and maintenance to be carried out during extremely cold or adverse weather should be implemented. Extended ice and snow storms deteriorate access roads and can isolate construction sites. Emergency response and evacuation procedures need to be implemented and tested on a regular interval.

Routine maintenance visits should be scheduled during periods of best accessibility, but if they must be made during more uncertain climatic conditions, the time to carry out the service is likely to be longer. Special vehicles such as snow mobiles, snow cats, and tracked vehicles may be required, and additional equipment may be required, such as wearing a helmet and using special gear and tools. Finally, it is recommended that certain procedures are put in place and adhered to such as remotely stopping the wind turbine prior to access.

8.4 Environmental Considerations

Chemicals – At standard sites, manufacturers will install WTs during winter conditions. However, these sites may still experience below freezing temperatures, therefore, liquid salt solutions are sometimes used on the ground to keep components free of ice before they are installed. Metal surfaces exposed to this mixture might corrode. Therefore, it is important to obtain approval from the local authorities to use such mixtures and to remove all traces of salt before installing the components.

Noise – Iced up WT blades can cause additional noise levels which may violate the original assumptions made in the building- and environmental permits [34], [35]. Any ice accumulated on the leading edge of a WT blade will, in most cases, cause a transition from laminar to a turbulent airflow, which in turn will increase the noise generated by the blade. Additionally, sound tends to propagate further in stable atmospheric conditions. The use of an ice protection systems may be the only option to stopping the operation of a WT if neighbours are affected by the additional ice-induced noise in a non-acceptable way.

8.5 Checklist of Key Issues for HSE

Checklist of Key Issues

- Carry out site specific ice assessment
- Screen the maximum ice throw distance using Seifert Formula
- Perform ice throw simulations to determine strikes/year/m^2
- Determine acceptable risk levels
- Apply risk mitigation strategies
- Take appropriate actions for public and labour safety for LTC and IC
- Consider potential increased iced turbine noise in IC sites

9. PROJECT ECONOMY

Independent of the climate, a multitude of economic risks are associated with developing and operating wind farms. However, a wind energy project in CC and CC-like sites have additional risks that must be assessed in order to determine if the project is economically feasible, and what mitigation measures are necessary. This chapter provides a framework for evaluating the economic risks related to operating turbines in CC.

9.1 Estimating Financial Losses Due to Climate Conditions

Financial losses result from a combination of several issues: 1) Lost energy production related to ice build-up or low temperatures, 2) increased financial costs due to higher uncertainties in energy yield predictions, 3) expenses for risk mitigation measures, and 4) the costs of more demanding maintenance. Further examples of CC-specific economic risks are listed below:

- Increased initial project costs due to limited installation schedules and higher equipment and installation costs. For example, foundations might need to be installed one season before the turbines are erected.
- Increased downtime or icing losses over seasons reducing expected income. Additionally, there can be more market based penalties in forecasted spot markets if a storm results in an un-expected icing event.
- Increased cost of finances if overall uncertainties, for example energy yield assessment, are higher due to icing losses and other cold climate effects.
- Increased downtime and liability due to concerns for public safety related to ice throw from turbine blades or the tower.
- Long duration of rime ice, which may increase turbine loading and cause premature failures.
- Increased maintenance costs due to low temperatures and the likely higher than average downtime between repairs caused by turbine inaccessibility.

Financial losses should take the effects of CC conditions on project development and energy production (as described in Chapter 7) into account. It should be noted, however, that power losses due to both low temperatures and icing events may occur simultaneously.

Calculated estimates for financial losses due to CC should be assessed and weighed against the additional cost of applying relevant counter measures. Examples of mitigation measures include cold climate packages or ice protection systems that are available from some turbine manufacturers. The energy consumption of the adapted technology should also be included in the calculations, using the best information available from the manufacturer. The reduced availability caused by remote site locations and other accessibility limitations should be determined during the project planning phase. It is clear that the economic uncertainty associated with CC projects is higher than at conventional sites but this uncertainty can be managed with proper planning and using current recommended practices. An increased uncertainty lowers the 75% and 90% production probability (typically referred to as P75 and P90) of the wind energy project.

There are no specific guidelines for assessing the economic impacts and risks associated with projects in CC climates other than this IEA Wind TCP Recommended Practices report. It is expected, however, that this understanding will increase as more projects are developed and implemented. At the same time, continuous progress can be expected with respect to the maturity level of specific CC technologies, such as ice sensors and rotor blade ice protection systems. In addition, the high wind potential, the availability of land for project installation, and the need for clean and renewable energy all lead to a market that will increasingly favour wind projects in CC areas. However, it is certainly important to pay attention to the recommended practices when designing and implementing a project.

9.2 Checklist of Key Issues for Project Economy

Checklist of Key Issues

- Higher project development costs at CC sites
- Thorough assessment of the effect of low temperatures and icing on energy production
- Assessment of CC induced uncertainty in energy production
- Assessment and quantification of CC related technology risk
- Additional O&M costs need to be properly addressed
- Mitigation of CC related technological and O&M risks during contracting
- Address the increased overall uncertainty of CC projects
- Conservative financial analysis

10. PROJECT CHECKLIST

Many additional issues need to be considered in a typical CC wind energy project then in a conventional project that is developed and constructed in a mild climate. This chapter provides a simple check list that can be used to determine if certain CC specific and the most crucial issues have been considered during project development.

	Considered/Applied [Yes/No]		**Comments**
	Yes	No	
A. SITE CONSIDERATIONS			
Low temperatures (< -20) do exist	X		
Atmospheric icing occurs annually	X		
Icing maps addressed	X		Use of multiple icing maps advised, if any icing map indicates IEA Ice Classification ≥ 2, measure ice at site
Clear understanding on site conditions	X		
…			
B. PROJECT DEVELOPMENT PHASE			
Cold climate compatible measurement system deployed to the site	X		
Icing measurements included	X		Both meteorological and instrumental. Long-term adjustment.
Heated wind sensors applied in measurement system met mast	X		
Ice throw issue addressed and risk zones calculated	X		If not, is an issue regarding permitting?
Icing and low temperature addressed during the Energy yield calculations	X		
Ice protection systems considered	X		Check ice protection system site suitability
Limited site accessibility due to low temperature, snow and ice considered in cost estimates	X		
Cold climate turbines selected for the project	X		Review turbine control strategy in icing conditions
…			
C. CONSTRUCTION AND OPERATIONAL PHASE			
Cold climate considered in HSE procedures	X		
Ice detectors/detecting methods in use during winter operation	X		
Ice fall zones marked with warning signs	X		
…			

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