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IEA Wind TCP Task 19

Technical Report

Ice Detection Guidelines
for Wind Energy Applications

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Ice Detection Guidelines for Wind Energy Applications

Prepared for the
International Energy Agency Wind Implementing Agreement

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The International Energy Agency (IEA) is an intergovernmental organization that works to shape a secure and sustainable future for all, through our focus on all fuels and all technologies, and our analysis and policy advice to governments and industry around the world.

The Technology Collaboration Program (TCP) is a multilateral mechanism established by the IEA with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of thousands of experts across government, academia and industry in 55 countries dedicated to advancing common research and the application of specific energy technologies.

Views of the IEA Wind TCP are not those of the IEA.

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Contents

1 Scope

In this document, the IEA Wind TCP Task19 defines guidelines for ice detection methods developed for wind energy applications.

The document provides background information on ice detection and its practical applications in wind energy and proposes a classification of available methods. The objective of this classification is to pave the way for the optimization, standardization and synchronization of ice detection as it is performed by different methods and systems:

- We discuss which ice detection methods appear to be best suited for different applications.
- We propose standardized metrics to evaluate the performance of ice detection systems.
- We review how ice detection systems are currently certified.
- Lastly, we discuss the main risks and challenges associated with ice detection for wind energy applications.

The performance of ice detection methods is not evaluated herein and no specific ice detection system is mentioned.

This paper is intended as a step towards the standardization and synchronization of ice detection for wind energy. By presenting a framework for general considerations, the essence of this document is to be regularly discussed and updated by the various stakeholders of the cold climate community who endeavour to make the best use of all available ice detection methods for wind energy applications.

2 General Introduction

In icing climates, ice detection is fundamental to the optimization of wind turbine operations.

Specifically, ice detection is used in a wide variety of wind turbine applications, e.g. controlling a rotor blade heating system, ensuring safe operation with respect to ice throw, preventing structural damage to the wind turbine due to the presence of ice, predicting production losses for the coming days, quantifying icing-related production losses during the previous winter season, or quantifying the average share of annual production that a future wind turbine will lose due to icing.

Each of the applications listed above requires an ice detection method tailored to its specific needs. For example:

- Some applications require accurate detection of light icing and early accretion, while others need to accurately differentiate between different severe icing loads.
- For some applications, adequate quantification of ice loads is most important, while for others, correct identification of ice growth periods is more relevant.
- Safety-related applications require particularly high reliability and availability, while simplicity and price are important in other cases.
- Some applications require detection of rotor icing, while in other cases instrumental icing is sufficient or even more appropriate.

In addition to the few direct methods of ice detection, for example by measuring the weight of a metal cylinder exposed to ice accumulation or by determining the thickness of ice on structures from webcam images, there exist many indirect methods of ice detection based on a wide variety of measurement principles. Each ice detection method has its own specificity related to the underlying measurement principle and the location of the ice measurement.

Due to the wide variety of ice detection methods and applications mentioned above, prospective users often struggle to determine which ice detection method or system best suits their needs.

The wide variety of existing ice detection methods also makes it difficult to compare them with each other, which prevents a good synchronization of the behaviour of different ice detection systems. Therefore, even when relying on state-of-the-art ice detection systems certified for a particular use, different ice detection methods currently control wind turbines in different ways, as recent field studies have shown (Godreau, 2019) (Froidevaux & Cattin, 2021).

Better standardization and synchronization of the control of wind turbines by different ice detection systems would be particularly beneficial for the management of ice throw risk.

3 Definitions

3.1 Cold Climate

The general cold climate definitions described below are excerpts from the IEA Wind Task 19 Recommended Practices report (IEA Wind TCP Task 19, 2017).

A Cold Climate ("CC") area is defined as an area or region that experiences frequent atmospheric icing or periods with temperatures below the operational limits of standard IEC 61400-1 ed4 wind turbines (IEC, 2005).

A Cold Climate area can be either **Low Temperature Climate ("LTC")** and/or **Icing Climate ("IC")**. Areas that have periods with temperatures below the operational limits of standard wind turbines are defined as LTC regions, whereas areas with atmospheric icing are defined as IC regions.

Figure 1 illustrates the definitions for CC, LTC and IC.

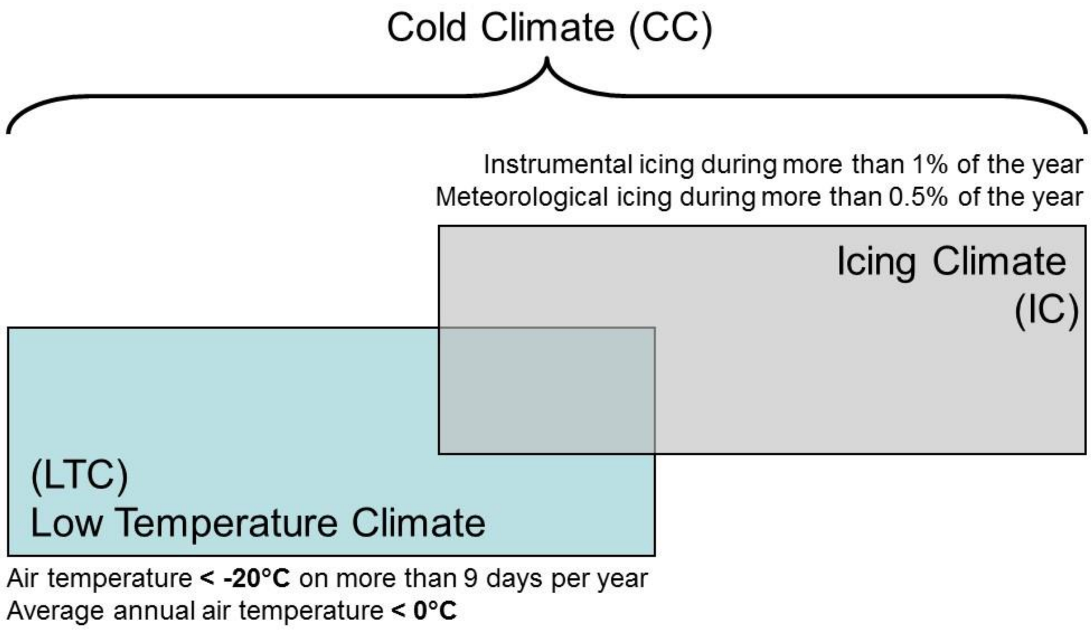

Figure 1: Definition of Cold Climate, Low Temperature Climate and Icing Climate (IEA Wind TCP Task 19, 2017)

3.2 Icing

The following definitions of atmospheric icing (IEA Wind TCP Task 19, 2017) are used:

- For an area to be defined as IC, Instrumental Icing is present more than 1% of the year and/or Meteorological Icing is present more that 0.5% of the year.

- The different types of atmospheric icing that affect wind turbines in IC are in-cloud icing (rime ice or glaze ice) and precipitation icing (freezing rain, freezing drizzle, wet snow). A single icing event can include more than one icing type.
- Within IC areas, the following icing definitions apply:
  ○ **Meteorological Icing**: Period [% of time] during which the meteorological conditions (temperature, wind speed, liquid water content, droplet distribution) allow ice accretion. ○ **Instrumental Icing**: The period [% of time] during which ice is present/visible on a structure and/or a meteorological instrument. ○ **Rotor Icing**: The period [% of time] during which ice is present at the rotor blade of a wind turbine. Due to differences in dimension, shape, flow velocity and vibrations, rotor icing is typically not equivalent to instrumental icing. Typically, incubation and ablation time for rotor icing are shorter than for instrumental icing. Furthermore, the duration of rotor icing strongly differs for a wind turbine at standstill compared to a wind turbine in operation.
- During meteorological icing, the **ice accretion rate** expresses the **intensity** of an icing event in mm/h, kg/h or kg/(m*h).
- During instrumental or rotor icing the **maximum accumulation** of ice expresses the **severity** of an icing event in mm or kg.

The evolution of an icing event is illustrated in Figure 2.

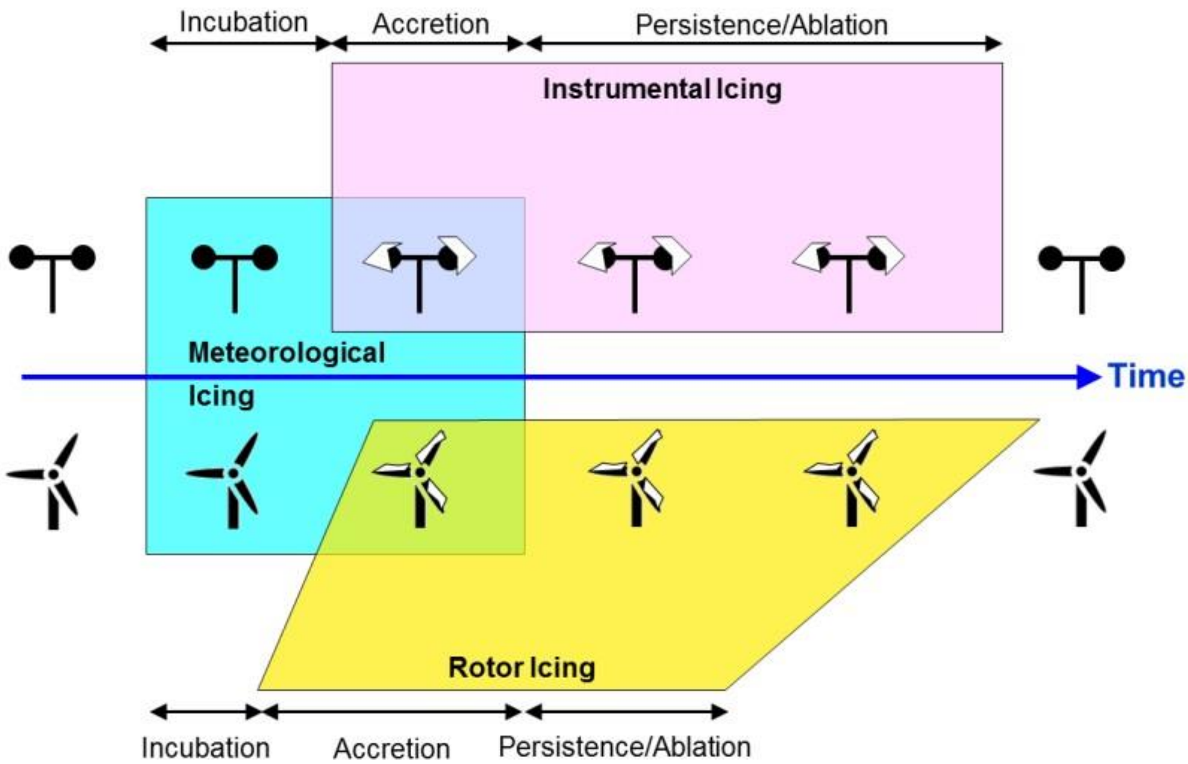

Figure 2: Definition of Meteorological Icing, Instrumental Icing, Rotor Icing, Incubation, Accretion, Persistence, and Ablation (IEA Wind TCP Task 19, 2017)

3.3 Ice Detection Methods

Ice detection methods aim to reliably and automatically detect instrumental, meteorological or rotor icing periods and measure severity (ice load) and intensity (ice growth rate). Ice detection can be used both during the project development phase and during wind farm operation, although some alternative methods, including icing maps and icing forecasts, do exist.

The location, measuring principle and design of the ice detection method determine what kind of icing can be detected. These guidelines only focus on commercially available methods. Ice detection solutions that are not widely deployed commercially are not discussed here. More technologies might become commercially available in the future, and it is recommended that these guidelines be updated accordingly.

Some ice detection methods rely on a dedicated piece of equipment, referred to as an ice detector, while others rely on standard metrics measured on a modern wind turbine (double anemometry, power curve degradation). The different ice detection methods will be detailed in Section 4.

Considering the variety of available methods and measuring principles, two main categories can be defined based on the location of the ice measurement:

- Ice detectors placed on met masts and wind turbine nacelles to measure instrumental icing; or
- Ice detectors placed on – or inside – rotor blades to measure rotor icing.

In addition, some ice detection methods with sufficient sensitivity and resolution can measure meteorological icing where they are installed. A high sensitivity, or in other terms a high accuracy at low icing severity, is necessary for the detection of early ice accretion. A high resolution is necessary for the detection of ice growth.

Heated sensors that regularly melt the ice accreted on their structure are particularly suitable to measure meteorological icing since new ice accretion can be measured repeatedly as long as meteorological icing conditions prevail. Periods of meteorological icing can also be derived from ice detectors capable of distinguishing short and small variations of ice loads.

3.4 Hazards Related to Ice Fall and Ice Throw from Wind Turbines

Given their size and characteristics, the deployment, operation and maintenance of wind turbines in CC requires special considerations. Icing on wind turbines can cause serious harm to humans and/or objects in the vicinity and thus requires that the hazards and associated risk of ice fall and ice throw be assessed (Canadian Renewable Energy Association, 2020). Icing can also potentially lead to wind turbine failure due to loss of structural integrity (F2E Fluid & Energy Engineering, n.d.).

The hazard depends mainly on icing severity, icing type, wind conditions, rotor speed and other environmental conditions, e.g. temperature, which impacts the ice shedding process.

The CanREA report on Best Practices for Wind Farm Icing and Cold Climate Health and Safety (Canadian Renewable Energy Association, 2020) describes the phenomena that lead to icing and the different types of ice that can accrete on wind turbines and other structures of a wind farm, including met masts.

Mathematical models used to define ensuing hazards, including the modelling of ice fragments and throw trajectories, are detailed in Section 2 of the IEA Wind TCP Task 19 report on International recommendations for Ice Fall and Ice Throw Risks Assessments (IEA Wind TCP Task 19, 2018b).

According to Bredesen (Bredesen, 2017), an impact with a kinetic energy of more than 40 J is considered fatal. This corresponds to a 0.2 kg ice fragment with a density of 500 kg/m^3 falling from an elevation of 30 to 50 metres.

In the IEA Wind TCP Task 19 International recommendations for Ice Fall and Ice Throw Risks Assessments (IEA Wind TCP Task 19, 2018b), it is suggested that the likelihood of fatality shall be assessed using the probit function with ice fragment mass ranging from 0.1 to 4.5 kg.

3.5 Risks Related to Ice Fall and Ice Throw from Wind Turbines

For clarity, the definitions of “risk” and “hazard” herein will be that of the International Organization for Standardization (International Organization for Standardization, 2009): “A hazard is any source of potential harm” and a risk is the “effect of uncertainty on objectives.” In the context of this document, the objective is safety. These terms apply to persons, objects, structures and the environment.

Whether it relates to the handling of hazardous materials, heavy machinery or operating wind turbines in cold climate, a risk can be expressed as:

Risk = Likelihood (probability of occurrence) x Consequence (impact of occurrence)

The latter formula and other principles of risk assessment are detailed in Section 4 of the IEA Wind TCP Task 19 report on International recommendations for Ice Fall and Ice Throw Risks Assessments (IEA Wind TCP Task 19, 2018b).

Figure 3 is an exemplary probability map that divides the surroundings of a wind turbine into safety zones by iso-risk contours. The actual contours and dimensions of the safety zones are sitespecific. Such a map can be used by any given jurisdiction based on the latter’s risk acceptance criteria and risk communication strategies for the assessment of a specific site as well as for the selection of appropriate risk-reducing measures if necessary.

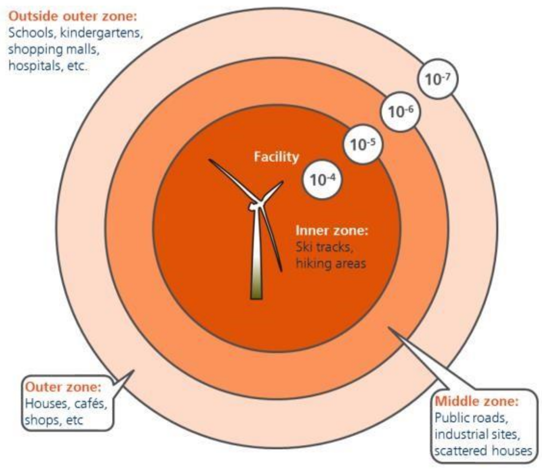

Figure 3: Suggested safety zones around installation that may cause risk of ice throw or ice fall. The numbers indicate the iso-risk contours for localized individual risk (LIRA). The numbers indicate the probability

that an average unprotected person, permanently present at a specified location, is killed during one year due to ice fall of throw from the facility. (Source: courtesy of Lloyds Register / Kjeller Vindteknikk)

3.6 Regulations Related to Icing on Wind Turbines

A search for regulations aimed at mitigating the risk of operating wind turbines in cold climates revealed that many countries have not yet defined clear regulations. A 2016 review of the regulatory framework for wind energy in European Union countries (González & LacalArántegui, 2016) makes no mention of cold climate or icing. In a 2018 article of the *Oxford Journal of Legal Studies* (Fisher, 2018) on the legal challenges pertinent to wind energy, no mention of cold climate considerations can be found.

In Norway for example, wind turbine operation in cold weather is a country-wide reality during the winter months. Yet there is no specific regulatory framework that governs ice fall and ice throw risk. Damage caused by these CC phenomena are handled in accordance with the general principles of compensation. In addition to potential liability for the licensee, wind farm operators may also be subject to corporate penalties and criminal liabilities (Bredesen et al., 2017).

Examples of regulations specifically aimed at mitigating ice throw are still very rare worldwide. Bredesen (Bredesen et al., 2017) makes the very telling ascertainment that "…a lack of understanding of the ice throw phenomenon among authorities […] has led to the fact that there is no coherence in the applied ice throw mitigation policies in various countries…"

In a 2019 survey conducted by the IEA Task 19, respondents from 6 countries out of the 12 represented mentioned being aware of permitting restrictions related to ice throw mitigation in their country. However, specific references are difficult to find. In most instances, the restrictions relative to the mitigation of ice fall and ice throw risks are implemented at the permitting stage and seem to be dictated by the interpretation of more general laws about the safety of infrastructures.

For example, in Germany, the suggested minimum distance between a wind turbine and people or objects is set by the WECO report recommendation of 1.5 * (hub height + rotor diameter) (Hahm & Stoffels, 2016). This criterion has become part of the *Muster-Liste der technischen Baubestimmungen*, a list of technical rules of the German building code. Consequently, if a wind turbine does not comply with this minimum distance and is located in a region with a high risk of icing, additional measures have to be taken. A site-specific risk assessment report is needed, mostly based on regional icing frequency, supplemented by an assessment report of ice detecting capabilities of the wind turbine. Additional guidance for site assessment in icing climates is available in other Task 19 references (IEA Wind TCP Task 19, 2018a)(IEA Wind TCP Task 19, 2017).

Another example is Sweden, where the recommended minimum distance of 1.5 * (hub height + rotor diameter) from the WECO report was reviewed by the Swedish Energy Agency through its ICETHROWER project (Swedish Energy Agency, 2017). This study concluded that the minimum distance can be reduced to 1.0 * (hub height + rotor diameter), since the probability for an impact resulting in injury outside this distance is considerably lower than other injury risks in society. Although this report does not act as an official regulation, it is used as a guideline by wind project developers and permitting authorities in Sweden.

Another piece of regulation that influences the use of wind turbines in icing climates is the European Union Machinery Directive (2006/42/EC) which aims to ensure a common safety level in any machinery put on the market or put in service in all member states. The process of conformity assessment to EU directives requires the manufacturer to conduct a risk analysis and assessment for its product and the intended use thereof, and covers the design, manufacture and operation of the product.

In several jurisdictions, regulatory bodies require manufacturers and operators to take specific measures to mitigate the risk of harm or injury to people, property and the environment. Special CC recommendations for manufacturers consist of an assortment of features, including heating systems, as well as special materials and lubricants for low temperature. Operators should plan for several risk mitigation strategies. These include control options such as power optimization, preventive stops, load reduction, ice protection systems and reduction of ice throw risk (IEA Wind TCP Task 19, 2018a) .

In that context, in some jurisdictions (e.g. Austria, Germany), the permitting authorities for wind farms require wind turbines to be systematically stopped during icing to reduce risk in the vicinity of the plant. This has led to the development of several ice detection methods that are able to stop the turbine automatically and, in some cases, restart it after the icing event has ended. While managing safety has been a major driver for ice detection technology development, there are several other applications for ice detection on wind turbines, as discussed in Section 5.

4 Available Technologies

Task 19 has already published an extensive description of ice detection technologies on wind turbines in Chapter 6 of its Available Technologies for Wind Energy in Cold Climates report (IEA Wind TCP Task 19, 2018a). For further details on the various technologies, please refer to this extensive review. Meteotest has also published a report describing in detail the different measuring principles of commercially available ice detection systems (Cattin et al., 2016).

In this document, no commercially available ice detection system is discussed in particular. Instead, the systems are classified based on their underlying characteristics, such as location and measuring principle. Hereafter, the ice detection methods are discussed based on this classification.

The first classification criterion is the location of the ice detection, distinguishing between nacelle/met mast and rotor. The second criterion is the type of icing that can be detected (meteorological, instrumental or rotor).

Then, depending on the measuring principle, the ice detection signal can be discrete or continuous. Discrete signals (true/false or categories) can only identify periods where a given icing load (type, severity) is present while continuous measurements are required to obtain specific metrics such as ice accretion rate (in mm/h, kg/h or kg/m·h) and severity (in mm, kg or kg/m).

Table 1 summarizes the classification of the available technologies used in the remainder of this document.

Table 1: Classification of commercially available ice detection methods

Location	Icing type	Icing detection signal	Measuring principle
Wind turbine nacelle or met mast	Meteorological icing	Discrete (True or false)	• Infrared reflection + heating • Atmospheric conditions (T, RH, visibility, etc.) • Vibrating wire or probe + heating
		Continuous intensity (in mm/h, kg/h or kg/m·h)	• Load cell attached to a rotating cylinder • IP cameras coupled with image analysis • Heat transfer rate on a probe • Change of impedance + heating
	Instrumental icing	Discrete (True or false)	• Double anemometry • Infrared reflection
		Continuous severity (in mm, kg or kg/m)	• Load cell attached to a rotating cylinder • IP cameras coupled with image analysis • Heat transfer rate on a probe • Change of impedance
Wind turbine rotor	Meteorological icing	Discrete (True/false or categories)	• IP cameras coupled with image analysis • Change of impedance
		Continuous intensity (in mm/h, kg/h or kg/m·h)	▯ Change in blade eigenfrequencies
	Rotor icing	Discrete (True/false or categories)	• Power curve + Pitch curve • IP cameras coupled with image analysis • Change of impedance
		Continuous severity (in kg or kg/m)	▯ Change in blade eigenfrequencies

5 Ice Detection Applications

The main objective of this document is to guide the wind energy industry towards the selection of the most suitable ice detection method for given wind industry applications. Based on an industry survey conducted in 2019, the following ice detection applications were listed (in order of importance):

- Control of ice protection systems
- Evaluation of performance losses associated with icing
- Ice fall and ice throw risks mitigation
- Wind turbine control in icing and prevention of structural damage
- Research and validation (forecast input data)
- Resource assessment (planning phase)

5.1 Control of Ice Protection Systems

As described in the Performance Warranty Guidelines for Wind Turbines in Icing Climates (IEA Wind TCP Task 19, 2020), the ice detection method is an integral part of an Ice Protection System (IPS), which also consists of the Ice Protection Technology and several other subsystems such as temperature sensors, surge protection devices, controller, etc. In this specific application, the objective is to detect the presence of icing so that the IPS can remove the accumulated ice on the blades in the case of a de-icing system or prevent the accumulation of ice on the blades if it is an anti-icing system. As the two approaches differ, so do the requirements of the selected ice detection method.

5.2 Ice Detection Methods for a De-icing IPS

The de-icing strategy requires the wind turbine to stop or idle to activate the heating elements. Because it requires the turbine to stop, de-icing is typically activated only after that a given level of rotor icing (typically of medium severity) is detected. Both discrete and continuous rotor icing detection methods are well suited for the activation of a de-icing IPS, as long as they offer good accuracy at medium icing severity. The power curve method, which consists of measuring a degradation in the expected power production, does not require any additional sensor and is widely adopted by wind turbine OEMs.

For this application an ice detection method must:

- Identify periods of rotor icing
- Differentiate between levels of severity of rotor icing (low sensitivity) to identify when the de-icing IPS must be activated
- Be easily integrated in the turbine control
- Be equipped with self-monitoring capability

Discrete rotor icing detection methods, e.g. the power curve, are recommended for this application. Continuous rotor icing detection methods are also suitable.

5.3 Ice Detection Methods for an Anti-icing IPS

The anti-icing strategy entails starting the IPS as soon as or even before ice begins to accumulate on the wind turbine blades. It is therefore important to detect the early stage of rotor or meteorological icing. Highly sensitive methods should be given precedence.

Additionally, anti-icing IPS typically act as de-icing if a given icing severity is exceeded despite the anti-icing being activated. Therefore, ice detectors for anti-icing IPS's should reliably detect both:

- Icing of low severity for the activation of anti-icing actions; and
- Icing of medium severity for the activation of de-icing actions.

While the power curve method is often used for controlling anti-icing IPS, this method might not be the best suited, as its sensitivity is limited by the natural scatter of the power curve. Power curve scatter can be due to vertical wind shear or turbulence.

A highly sensitive rotor icing detector or a meteorological icing detector augmented with a discrete or continuous rotor icing detection method should be given precedence. These two functions can be integrated in the same system and two separate sensors are not necessarily required. The selected method must also integrate into the turbine control for the automatic activation of the IPS.

For this application an ice detection method for anti-icing IPS must:

- Have high sensitivity, i.e. high accuracy at low icing severity, for the activation of antiicing actions;
- Have high accuracy at medium icing severity for the activation of de-icing actions;
   Be easily integrated in the turbine control; and Be equipped with self-monitoring capability.

<u>A highly sensitive rotor icing detector or a meteorological icing detector augmented with a discrete or continuous rotor icing detection method are recommended for this application.</u>

5.4 Evaluation of Production Losses Associated with Icing

In this application, the objective is to categorize a performance loss observed on one or several wind turbines as an icing loss (i.e. a production loss due to icing). For clarity, this refers only to operating wind farms. Evaluating losses in the pre-construction phase is discussed in Section 5.8 (resource assessment).

During periods of icing, ice accumulates on the blades, which leads to a reduction in the rotor's aerodynamic performance and therefore to reduced production. This production loss can lead to significant financial losses if the icing has not been properly evaluated during the project development phase. Evaluating icing losses helps validate the business model of a CC wind farm in the first years of operation.

Since icing can vary across a given facility, it is ideal to rely on a method that is applicable to all turbines with limited hardware and installation costs. Double anemometry (SwytinkBinnema et al., 2019) and the power curve are common methods used in the wind industry. Task19 has released an open source software to calculate icing losses through the power curve method using standard SCADA data (IEA Wind TCP Task 19, n.d.).

For this application, an ice detection method must:

 Identify periods of instrumental or rotor icing; Be applicable to all wind turbines of a CC site; and Have limited cost.

<u>Discrete instrumental and rotor icing detection methods such as double anemometry or power curve are recommended for this application.</u>

5.5 Ice Fall and Ice Throw Risks Mitigation for Safety Considerations

Because of the hazards, risks and regulations related to ice fall and ice throw listed in Sections 3.4 to 3.6, some jurisdictions require that these risks be actively mitigated while operating wind turbines under icing conditions. A thorough risk analysis during the project development phase (IEA Wind TCP Task 19, 2018b) and consultation with the permitting authorities determine the most suitable operation strategy under icing conditions and the ice risk mitigation measures that should be undertaken. Given the actual regulations across the globe, the following cases apply:

1. In areas where ice throw risks are low (IEA Ice Class 1 or remote areas) the turbine may continue to operate in icing conditions.
2. In areas of moderate to high ice throw risk (e.g. close to public roads or infrastructure), the turbine may be required to shut down in icing conditions.[1] Different operational strategies can apply:
   a. The turbine is shut down and not restarted below a given temperature (e.g. +3°C) (very conservative approach).
   b. The turbine is shut down with a discrete nacelle or rotor-based ice detection method and restarted by visual inspection in person or by video (conservative approach, requires certification of the ice detection method).
   c. The turbine is shut down with a rotor icing detector when the ice severity surpasses a threshold indicating the presence of ice throw risk. When the ice detector signal goes below the ice throw risk threshold, the turbine is restarted (less conservative approach, requires certification of the ice detection method).
   d. The power output of the wind turbine is curtailed (reduced rotational speed) to reduce the area under ice throw risk. Curtailment can be activated by a meteorological, instrumental or rotor icing ice detection method (less conservative approach only partly reducing the ice throw risk).
   e. The turbine continues to operate at rated power, but warning signs are installed around the site to inform passers-by of the presence of ice fall and ice throw risks. These warning signs can be activated by a meteorological, instrumental or rotor icing ice detection method (least conservative approach).

In cases where icing detection is mandatory:

- **Shutdowns based on ambient temperature should be limited to sites with very scarce icing events and milder temperature** (annual average temperature well above the shutdown threshold), as otherwise it will lead to prolonged downtime on a typical CC site.
- **For active warning signs around a wind farm**, the ice detection method must identify periods of meteorological, instrumental or rotor icing.
- **For shutdowns based on a discrete nacelle or rotor-based ice detection method and restarts by visual inspection,** the ice detection method must:
  - Be certified (see Section 7);
  - Identify periods of meteorological, instrumental or rotor icing;
  - Have high sensitivity;
  - Be easily integrated in the turbine control;

[1] See Section 5.1.1 (De-icing) and 5.4 (Prevention of structural damages) for other cases of turbine shutdown icing conditions which are not related to ice throw risk mitigation

- Be equipped with self-monitoring capability; and
- Limit itself to shutting down the turbine, a visual inspection being required to restart the turbine.

- **For automated shutdowns and restarts**, the ice detection method must: ▪ Be certified (see Section 7);
  - Identify periods of rotor icing (presence of icing on the blades);
  - Have medium sensitivity;
  - Be easily integrated in the turbine control;
  - Be equipped with self-monitoring capability;
  - Ensure that there is no risk of ice fall or ice throw:
    - Concretely for eigenfrequency-based systems: the turbine should be stopped as soon as the icing index exceeds the signal corresponding to 1.5-2 cm of glaze ice along the leading edge.
    - Concretely for an impedance-based system: the turbine should be stopped as soon as one sensor measures more than 1 cm of ice or twothirds of all tip sensors measure more than 1 mm of ice.

5.6 Wind Turbine Control in Icing and Prevention of Structural Damage

In this application, the objective is to apply a specific set of operational parameters such as an adjusted rotational speed, pitch angle or forced stop during periods of icing. The motivation is to limit the risk of aerodynamic stall and extreme loads on the wind turbine, thus preventing structural damage. In this regard, the selected ice detection method must accurately detect severe instrumental or rotor icing. It has been demonstrated that the power curve method can overestimate the icing categorization, with wind turbines showing no production in non-severe icing conditions (Muukkonen, 2019) (Froidevaux et al., 2019). It has also been demonstrated that the severity of icing on the nacelle and rotor correlates (Jolin et al., 2019). An instrumental or rotor icing detector able to detect severe icing conditions should therefore be preferred to prevent lost production due to false alarms. The rotor icing detectors relying on a change in blade eigenfrequencies are an example of an applicable method for the prevention of structural damage.

For this application an ice detection method must:

- Identify periods of severe instrumental or rotor icing;
- Differentiate between high levels of icing severity of rotor icing to identify when the severity of icing can lead to structural damage (high accuracy at high icing severity); Be easily integrated in the turbine control; and Be equipped with self-monitoring capability.

Continuous instrumental or rotor icing detectors able to identify severe icing periods are recommended for this application.

5.7 Research

Atmospheric icing is a phenomenon involving a number of atmospheric parameters and complex interactions of meteorological processes at the mesoscale and microscale levels. Key drivers of the icing process are temperature, wind speed, liquid water content and median volume diameter of water droplets. Cloud coverage, solar radiation and temperature play a key role in ice removal (Makkonen, 2000)(Bégin-Drolet et al., 2013). In order to provide detailed site observation data, some icing detectors provide additional information for research purposes such as the validation of meteorological or CFD ice accretion models and the development of new IPS technologies or control strategies in icing conditions.

For this application an ice detection method must:

- Provide continuous data to represent the ice accretion rate (mm/h, kg/h or kg/m·h) and severity (mm, kg or kg/m); and
- Have high accuracy across a wide range of icing intensities.

<u>Continuous meteorological, instrumental or rotor icing detection methods are particularly interesting since they can be used to quantify icing severity. Depending on the research project budget and scope, all methods can potentially be interesting.</u>

5.8 Resource Assessment

During the development phase of a wind project in CC, the impact of icing on the energy yield estimate must be taken into account. Icing can interfere with wind speed measurements from unheated anemometers and may impact the wind resource assessment. Moreover, additional uncertainties due to CC conditions need to be incorporated in Annual Energy Production (AEP) calculations (IEA Wind TCP Task 19, 2017).

It is recommended that a time series of wind, icing periods and temperature be produced for the resource assessment. While wind data must be obtained from measurements, icing and temperature data can be obtained from mesoscale data or icing maps when available (IEA Wind TCP Task 19, 2018a). The use of a dedicated ice detection method during the measuring campaign as well as the systematic identification of icing events are highly recommended at CC sites for two reasons:

- For assessing the impact of icing on production; and
- For correcting, or at least cleaning, the measured wind speed time series.

If chosen for this application an ice detection method must:

- Identify periods of meteorological and/or instrumental icing.

For energy yield impact purposes, it is also desirable to:

- Be easily scalable at several measurement locations for large wind farms.

<u>Discrete meteorological or instrumental icing detection methods are recommended for this application. Double anemometry is frequently used for this purpose, as heated anemometers are often required in any case for a proper assessment of the wind resource at CC sites.</u>

<u>In the event that an icing model is used for resource assessment purposes, the recommendation for forecast validation data (see Section 5.9) shall apply.</u>

5.9 Forecast or Long-term Icing Model Validation Data

Numerical Weather Prediction (NWP) models simulate the evolution of atmospheric conditions based upon a full set of fluid dynamic equations and parametrizations. NWP models can be divided into two broad categories: global models and regional models. Global models only have boundary inputs from the model surface, while regional models rely upon output from the global models for horizontal boundary conditions. In addition to boundary conditions, NWP models require input conditions to initialize the state of the numerical atmosphere (IEA Wind TCP Task 19, 2018a). These models can also be used to estimate the long-term icing climate at a wind site during the resource assessment phase.

Some icing detection methods can be used as validation data for NWP models to increase the forecast or long-term model accuracy. Since icing is a complex phenomenon, more detailed observations are ideal for this purpose.

For this application an ice detection method must:

 Provide continuous data to represent the ice accretion rate (mm/h, kg/h or kg/m·h) and severity (mm, kg or kg/m); and Have high sensitivity.

Continuous meteorological, instrumental or rotor icing detection is recommended for this application.

5.10 Ice Detection Method Selection Based on Wind Energy Applications

Table 2 presents a summary of the recommended ice detection method based on the desired application in the CC wind energy context.

Table 2: Summary table for ice detection method selection based on wind energy applications

Application	Important metric	Required sensitivity	Additional considerations	Recommended ice detection method
Activation of a de-icing system	Presence of a given level of rotor icing	Low	Easy to integrate in turbine control Equipped with selfmonitoring capability	Discrete or continuous rotor icing (power curve)
Activation of an anti-icing system	Early stage of rotor or meteorological icing for activation of antiicing Presence of a given level of rotor icing for activation of de-icing	High accuracy at low and medium icing intensity	Easy to integrate in turbine control Equipped with selfmonitoring capability	Highly sensitive rotor icing or Meteorological icing + discrete rotor icing
Application	Important metric	Required sensitivity	Additional considerations	Recommended ice detection method

Postconstruction evaluation of production losses associated with icing	Instrumental or rotor icing periods	Low	Cover all wind turbines of a given site Limited costs	Discrete instrumental or rotor icing (power curve)
Ice fall and ice throw mitigation – Temperaturebased	Temperature below a given threshold	High	N/A	Thermometer. Application recommended only for sites with scarce icing events and milder temperatures
Ice fall and ice throw mitigation – Active warning signs	Presence of icing risks on site	Medium	Communication link to active warning signs on site Equipped with selfmonitoring capability	Meteorological, instrumental or rotor ice detection method
Ice fall and ice throw mitigation – Icing detection + visual inspection	For shutdown: meteorological, instrumental or rotor icing periods For restart: visual inspection in person or by video	High	Certification required Easy to integrate in turbine control Equipped with selfmonitoring capability	Meteorological, instrumental or rotor ice detection method AND Visual inspection
Ice fall and ice throw mitigation – Automated	For shutdown: rotor icing periods For restart: demonstration that there is no more risk of ice fall or ice throw	Medium	Certification required Easy to integrate in turbine control Equipped with selfmonitoring capability	Impedance- or eigenfrequency-based rotor icing detection
Wind turbine control in icing and prevention of structural damage	Severe instrumental or rotor icing periods	Medium	Easy to integrate in turbine control Equipped with selfmonitoring capability	Continuous instrumental or rotor icing
Research	Ice accretion rate and icing severity	High		Continuous meteorological, instrumental or rotor icing
Resource assessment	Meteorological or instrumental icing periods; Instrumental icing severity	Low	Variation of icing across large wind farms and terrain elevation	Discrete meteorological or instrumental icing on a met mast
Forecast or long-term icing model validation data	Ice accretion rate and icing severity	High		Continuous meteorological, instrumental or rotor icing

6 Performance Evaluation

Based on an industry survey conducted by Task 19 in 2019, 46% of the cold climate wind community wishes to have more information when purchasing icing detectors. The vast majority of the industry would welcome performance validation done by field tests (96%), while 41% would want the performance to be validated in a lab environment.

Like other sensors widely used in the wind industry (e.g. anemometers), icing detection methods should be tested with quantitative and objective metrics that allow the characteristics of the systems to be compared against one another and that ensure reliability for critical applications. In the future, these metrics could be provided as standard information on an ice detector datasheet. The datasheet should at least describe the type of icing that is detected (meteorological, instrumental or rotor) and the range of icing severity for which the system has good accuracy.

There are already several icing wind tunnels across the globe with the capacity to measure such metrics in a controlled environment. There is also a large number of wind farms in cold climates and a few dedicated test sites that can be used to conduct field tests. This section presents metrics to evaluate the performance of ice detection methods as well as specific requirements and differences related to lab and field testing. It should be noted that lab testing and field testing are two complementary test methods and it is highly recommended to perform both since they can be used to measure different KPIs.

6.1 Lab Testing

Lab testing such as in Icing Wind Tunnels (IWT) is essential for research, development and early validation of ice detection technologies. Lab testing should offer a means of establishing standards and benchmarks prior to the commercial release of ice detection systems in order to provide standardized information to the end user (Jokela et al., 2017).

Figure 4: Testing of an icing detector in an icing wind tunnel, courtesy Sommer GmbH

Figure 5: Lab validation of icing severity detection (Moser, 2017)

IWTs allow testing under environmental conditions that can be precisely set, modulated and monitored. In addition to wind speed, temperature, liquid water content (LWC) and water droplet size can be controlled. However, the common limitations of IWTs are the difficulty of replicating the larger droplet size of freezing rain and freezing drizzle. Due to operational costs and physical constraints, the test duration in an icing wind tunnel remains limited (hours) when compared to field testing (months).

Continuous rotor icing detectors based on changes in eigenfrequencies cannot be easily tested in an IWT since they require a full turbine blade to measure the full set of KPIs listed in Table 3. Alternative lab testing methods such as using standardized mass could be used. With the large turbine fleet already in operation in cold climates, these are better suited for field testing.

The IEA Wind TCP Task 19 Available Technologies report (IEA Wind TCP Task 19, 2018a) provides a list of Icing Wind Tunnels across the globe with references in Section 12.1.

6.2 Field Testing

Field testing is paramount for the industry. In a survey conducted by the IEA Task 19 in 2019, 96% of respondents expressed interest in field testing of ice detection systems. Validating behaviour and performance over long periods is impractical in a lab setting. It is also difficult in a lab to completely replicate the complex environment on site that an ice detector ultimately needs to be able to handle. Field testing allows for observation of instrument behaviour under different types of icing events and environmental conditions and remains the best setting to assess time accuracy, reliability and durability of the ice detection methods. The maximum severity of ice is also significantly greater in the field than in a lab due to the duration of some meteorological icing events (Cattin et al., 2016) (IEA Wind TCP Task 19, 2018a) (Wickman, 2013). Due to added background noise and the increased risk of failure in the field, it is important to document the set-up and how to mitigate disturbances and avoid failure due to erroneous installations.

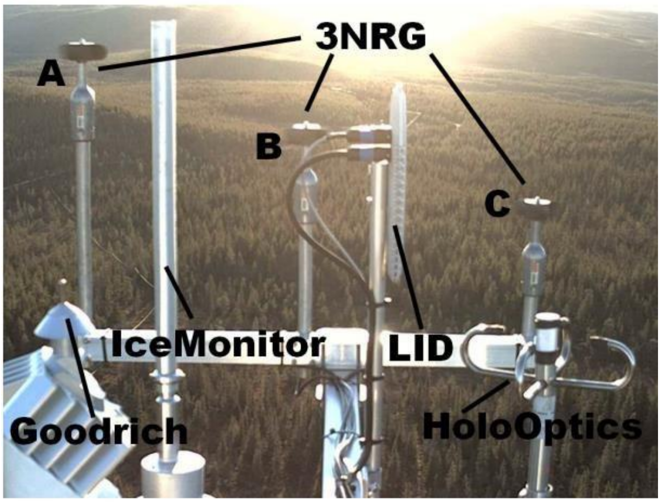

Figure 6: Field test of different ice measurement methods for wind power on a met mast in Sweden (Wickman, 2013)

Figure 7: Validation of rotor icing detectors using images, by Meteotest in Sweden (left) and Nergica in Canada (right) (Froidevaux & Cattin, 2021) (Godreau, 2019)

Contrary to lab testing, field testing cannot precisely set and control the icing conditions that the ice detector aims to measure. To validate observations in field testing, a reliable reference is the only means of comparison and evaluation. In field testing, visual inspection of icing remains the most used reference (Froidevaux & Cattin, 2021)(Godreau, 2019), though it is tedious, time consuming and has limitations, e.g. measuring icing on blades in low visibility conditions. Power curve data can be used for the validation of ice detection on rotor blades, but not necessarily for the nacelle and mast, though some correlation is to be expected (Jolin et al., 2019). However, it has been demonstrated that the power curve method has important limitations that strongly limit its legitimacy as a reference. Currently, the most meaningful field validations of ice detection systems might come from direct intercomparisons of the systems, e.g. those performed by Nergica (Godreau, 2019) and Meteotest (Froidevaux & Cattin, 2021). In general, the wind industry would stand to benefit from developing an icing detector of excellent quality, precision and reliability that could become an adopted standard for field testing.

6.3 Performance Metrics

To assess the performance of icing detection methods under varying icing conditions (temperature, ice type, icing severity, etc.), key performance indicators (KPI) previously used in this context are presented. Table 3 presents suggestions for KPIs for lab and field testing. Due to the differences between these two types of testing (see previous sections), not all KPIs can be measured with both test methods. It shall also be noted that, even though some KPIs will be able to be measured with both test methods, differences in test conditions, test set-up and choice of reference can all impact KPI values. For example, in field testing, background noise and the need to rely on another ice detector as a reference can affect KPI values compared to a lab test, where background noise can be kept to a minimum and the icing conditions are closely monitored and controlled. In field tests, results are dependent on a correct installation, and variations in installations can lead to different levels of sensitivity and resolution, for example.

Table 3: Key performance indicators for lab testing

KPI Name	Description	Units	Test method	
			Lab	Field
Response time	Time from start of icing conditions to positive detection (for a given set of controlled icing conditions or reference)	Duration (s)	X	X
Sensitivity	Minimum icing level that can be detected reliably considering background noise	mm/h, kg/h, kg/m·h (Met. icing) mm, kg, kg/m (Inst. or Rot. icing)	X	X
Resolution	For continuous methods, the amount of icing required to observe a change in the	mm/h, kg/h, kg/m·h (Met. icing) mm, kg, kg/m (Inst. or Rot. icing)	X	X

KPI Name	Description	Units	Test method	
			Lab	Field
	signal that is significantly higher than the background noise			
Icing measurement range	For continuous methods, the total range of available icing measurement, from min. to max.	mm/h, kg/h, kg/m·h (Met. icing) mm, kg, kg/m (Inst. or Rot. icing)	X	X
Availability	Percentage of data recovered over the test	%	X	X
Signal-tonoise ratio	Ratio of the desired signal to the level of the background noise	dB	X	
Repeatability	Mean absolute deviation of other metrics listed above when tested under the same conditions		X	
Mean time between failures	Average time between system breakdown, as a measure of reliability	Duration (h)	X	X
Icing time	Hours of measured icing type over two winters* compared to a reference	Total duration (h)		X
Icing severity	Hours of measured ice thickness over two winters compared to a reference classification	Total duration (h)		X
Time accuracy (skill scores)	Comparison of ice detection signal against a reference with the means of skill scores such as percentage correct, hit rate, false alarm rate, KSS, etc.	None		X
Durability	Percentage of the ice detection method affected by wear after the test	%		X

* As recommended by DNV-GL Recommended Practice DNVG-GL-RP-0175; see below.

It is to be expected that some ice detection methods will perform better than others for detecting different types of ice cover (rime, glaze, wet snow, hoar frost) or under varying icing severity depending on whether they are designed for met masts, nacelles or rotor blades (IEA Wind TCP Task 19, 2018a). The test performed shall be explicit on the type of icing observed, the type of ice cover and the quantity of ice. The test set-up shall be thoroughly detailed since it, especially for the field test, can have a significant effect on the results.

The recommended duration of two winters is taken from DNV-GL's Recommended Practice DNVG-GL-RP-0175: Icing of wind turbines (DNV-GL, 2017), Section 5.2 ("Ice detection"):

> "For all ice detection systems, the functionality and performance should be shown in field tests or by lab tests. The duration of in field tests should be at least two winter seasons showing significant icing conditions and durations and the boundary conditions may for future use not exceed the conditions tested or seen in field."

6.4 Performance Evaluation Outcomes

When an approved performance evaluation campaign is completed, the metrics calculated should be made available to the industry, either in independent reports or directly included in ice detector data sheets. As a minimum, the test method, icing types tested and KPIs measured should be explicitly stated. In the future, standardized tests methods should be developed for critical applications and used in the certification process of ice detection methods.

6.5 Warranty and Operational Envelope

Conducting robust testing will also reduce risks for technology developers and users since the operational limits, sensitivity and measurement range of the ice detection method will be clearly defined. This would help technology developers to define warranties for their ice detection technology as well as the operational range of environmental and icing conditions for which this warranty would be valid. Such information would also help end users of the technology as well as regulators determine their expectations.

7 Certification

In some jurisdictions and for some applications, the ice detection methods must be certified. A typical application often requiring certification is the mitigation of the ice throw hazard (see Section 5.5).

During the elaboration of this report, all commercial ice detection methods available on the market were certified by DNV-GL, now know as DNV. In 2017, DNV-GL issued the Recommended Practice RP-0175 "Icing of wind turbines" (DNV-GL, 2017), which states that:

> "For all ice detection systems, the maximum dead time between icing situation and ice alarm should be taken into account.
>
> For all ice detection systems, the functionality and performance should be shown in field tests or by laboratory tests. The duration of in field tests should be at least two winter seasons showing significant icing conditions and

durations and the boundary conditions may for future use not exceed the conditions tested or seen in field.

Ice sensors should be equipped with self-monitoring capability. They should give at least a signal for ice/no-ice and a signal for operative/testing/faulty to the control system.

…

If ice throw is not tolerated the ice sensor system should be able to detect whether ice on the blades and other components of the turbine is present or not, to enable an automatic restart of the wind turbine. For the restart measurement points are located on the blade leading edge, trailing edge, pressure side, suction side and if necessary on hub, nacelle and tower (need to be evaluated in a risk assessment)."

The certification process ensures that the ice detection meets the defined safety requirements and that it can be integrated into the turbine control in a reliable manner.

Table 4 presents the list of certified ice detection methods by DNV (DNV, n.d.).

Table 4: Ice detection methods certified by DNV

CERTIFICATION SCHEME	CERTIFICATION SCHEME, LONG	CUSTOMER/ APPLICANT	CERTIFICATE/ STATEMENT	IDENTIFICATION OF OBJECT/ PROJECT	DATE ISSUED	VALID UNTIL
CC GL2010	Component Certification	eologix sensor technology GmbH	CC-GL-IV-100526-4	Ice sensor system	2018-04-04	2023-02-18
CC GL2010	Component Certification	Labkotec Oy	CC-GL-IV-103644-1	LID-3300IP Ice Detector Systems LID-3300IP Control Unit (Type 1) with LID/ISD Ice Sensor (Type 1) and LID-3300IP Control Unit Type 2 with LID/ISD Ice Sensor Type 2	2018-11-26	2023-09-20
CC GL2010	Component Certification	PHOENIX CONTACT Electronics GmbH	CC-GL-IV-104168-0-EN	Phoenix Contact ID-S ice detection system	2018-09-12	2023-09-11
CMS	Certification of Condition Monitoring Systems	fos4X GmbH, now owned by Polytech A/S	TC-DNVGL-SE-0439-04235-0	Rotor blade ice detection system	2018-09-21	2020-09-20
CMS	Certification of Condition Monitoring Systems	Weidmüller Monitoring Systems GmbH	TC-DNVGL-SE-0439-04314-0	Ice detection system BLADEcontrol ICE Detector (BID)	2018-10-18	2020-10-17
CMS	Certification of Condition Monitoring Systems	Wölfel Wind Systems GmbH	TC-DNVGL-SE-0439-03577-1	Ice detection system	2019-06-12	2021-06-11

8 Risks

While state-of-the-art ice detection and certification is available for the integration of ice detection in wind energy applications, some risks remain and should be thoroughly assessed when choosing a specific ice detection method.

- Commercial risk: What is the impact of a faulty or unavailable ice detection method on revenue (e.g. energy production) and compliance?
- Redundancy: Is there an alternative ice detection method if the preferred one becomes unavailable?
- Communication protocol: Is the ice detection signal compatible with the wind turbine controller? Since there is no standard for integrating third-party component signals to wind turbines, the controller may not be able to read the ice detection signal.
- Performance of the ice detection method: Is sufficient information available to understand in which conditions the ice detection method will provide an ice detection signal?
- Safety: None of the commercial ice detection systems is approved under the scope of the European Union Machinery Directive as a system with performance level D (Probability of Dangerous Failure per Hour between 10^{-7} and 10^{-6})

When integrating an icing detection method for a wind energy application, it is suggested that these risks be discussed with ice detection manufacturers, wind turbine OEMs and relevant permitting agencies to ensure safe and reliable integration.

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