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Performance Warranty Guidelines for Wind Turbines in Icing Climates

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Technical Report

Performance Warranty Guidelines for Wind Turbines in Icing Climates

Prepared for the
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List of definitions

CC	Cold Climate
$E_{A,\ IPS}$	Actual Energy production with an IPS
$E_{A,\ No\ IPS}$	Actual Energy production without an IPS
$E_{P,\ IPS}$	Potential Energy production with an IPS
$E_{P,\ No\ IPS}$	Potential Energy production without an IPS
IC	Icing Climate
IEA	International Energy Agency
IPS	Ice Protection System
IPT	Ice Protection Technology
LTC	Low Temperature Climate
OE	Operational Envelope
OEM	Original Equipment Manufacturer

Executive Summary

IEA Wind Task 19 considers wind turbine performance testing in icing climates as a key element to mitigate risks when developing wind farms in cold climates and for accelerating wind turbine technology improvements in cold climate conditions. The first edition of the Performance Warranty guidelines for wind turbines in icing climates was published in May 2018. The aim of this second edition is to present and further detail the most promising available options on how wind turbines with icing climate adaptations can be warranted and tested with affordable and reasonably accurate test methods.

It is recommended that an ice protection system (“IPS”) should be considered as part of the procurement process within the turbine contract and to include a turbine performance warranty for icing climates. The IPS should be viewed as an integral sub-system of the turbine, subject to similar level of expectations and service as for any other sub-system in the wind turbine and as such should carry the same warranty protection as the turbine (*e.g.*, related to product performance and availability).

A turbine performance warranty for a wind turbine in icing climate should define a test method designed for measuring a clearly defined performance criteria within the IPS’s operational envelope at reasonable cost, accuracy and test duration. The performance criteria may differ depending on the chosen test method. Consequences for failed tests should be aimed firstly at rectifying and improving turbine performance and secondly at providing liability coverage.

Three different turbine-level IPS performance test methods have been identified as the most promising and commonly used in the industry. The three turbine performance warranty tests are:

- **The turbine self-comparison test –** self-comparison of a test turbines performance during icing events and outside of icing events .
- **The side-by-side comparison test** – comparison of two or more turbines positioned in similar locations, with similar wind and icing climate, where one wind turbine is run with an active IPS and the other with a deactivated IPS.
- **The power performance test** – similar to IEC 61400-12, based on the standard power curve testing standard.

1. Introduction

1.1. Background

Wind farm development in cold climates is becoming more common. One contributing factor to this is that methods used in the project development phase to quantify icing risks and icing losses have become more reliable, therefore reducing the uncertainties in energy production estimates. Another contributing factor is that there is more mature IPS technology available than before.

In the latest IEA Wind Task 19 Recommended Practices report (IEA Wind Task 19, 2017), the IEA Wind Task 19 published a guide for developing wind farms in cold climates by providing more information on the complexity of the icing phenomenon. The first edition of the "Performance warranty guidelines for wind turbines in icing" was published in May 2018 to provide a first guide to include the Ice Protection System ("IPS") in a turbine procurement contract (IEA Wind Task 19, 2018). Although a considerable amount of experience and knowledge already exists about the operation of wind turbines in cold climates, many uncertainties still remain. More work is needed to better understand challenges associated with operating wind turbines in cold climates to further reduce uncertainties in energy production estimates.

One of the largest uncertainties while developing wind farms in cold climate is to quantify impacts of ice build-up on the turbine (see Figure 1). Ice build-up on the blades can lead to aerodynamic performance degradation, or even bring a turbine to a complete stop, which leads to icing losses. It can also increase loads which in turn can lead to premature failure of components. Ice build-up on blades, hub and the tower can also increase health and safety risks. Turbine components, ancillary electrical components, such as pad mount transformers, can be damaged by ice fall or ice throw. Required maintenance can be delayed because of safety risks due to ice falls.

A number of wind turbine Original Equipment Manufacturers ("OEMs") and IPS manufacturers now offer solutions to reduce the icing losses by mitigating ice build-up on the blades and/or reducing losses via an operational strategy during icing. Eliminating the icing losses completely may be out of reach, however, with time, it is expected that wind turbines developed for icing conditions will become increasingly efficient.

An icing climate turbine adaptation warranty can benefit the industry in several ways including making operation of wind farms in icing climates more predictable and setting up a means to compare the expected efficiency of technologies. First, a contractual warranty increases stakeholders' confidence that the IPS will keep the turbine running at an agreed level during and after icing events. Moreover, sharing the risk with the IPS manufacturer increases security to the owners and investors during the development, pre- and postconstruction phases. In addition, a warranty will also increase the incentive to optimise wind turbines operations in icing climate, as it may become a competitive advantage. This may open new markets and increase the share of wind power in icing climates.

To construct a warranty, a good understanding of the functionality of the IPS is needed, from ice detection to the physics behind the ice removal, all the way to the turbine operational strategy and expected performance of the turbine operating under various weather conditions. Indeed, different cold climate conditions, which could even vary within a single wind farm, may require different operational settings, which can be reflected in different warranted performance levels. In addition, it is important to understand the limitations of the system to enable realistic, pre-development calculations of potential icing losses, allowing for proper quantification of the risks.

To summarise, the main reasons why it is important to ensure that the performance of a wind turbine in icing climates is warranted are:

- To decrease uncertainties in energy production estimates due to icing conditions;
- To enable increased understanding of expected turbine performance in various icing conditions, including limitations of the IPS;
- To incentivise the OEMs to optimise the IPS settings and overall turbine operations.

Figure 1. Icing on wind turbine blades in different parts of the world (source: Task 19).

1.2. Scope

This document defines general level performance warranty guidelines for wind farm developers and OEMs operating in cold climate areas where there is a risk of icing. The goal of this document is to present and describe the most promising options available to contractually warrant and test the efficiency of icing climate adaptations. There are a number of different technologies available on the market for mitigating icing effects on power performance on wind turbines. This document should be seen as a guide since different warranty methods could be applicable to different technologies.

These guidelines can also form the basis for warrantying retrofitted IPSes. However, these guidelines focus on the turbine energy production in icing climates, which can be affected by the turbine operational strategy during the same period. Since the operational strategy is the responsibility of the OEM and cannot be controlled by the IPS retrofit provider, these guidelines may not be directly applicable to warrant retrofitted IPS performance.

The main objective for an icing climate turbine adaptation warranty is to include a contractual coverage to compensate potential performance shortfall of the IPS to mitigate the negative impacts on production and revenue. A warranty is important to establish a mutual contractual understanding of the expected turbine behaviour and performance in icing conditions. A warranty also states how the performance of the turbine adaptation will be monitored after its commissioning.

It is assumed that a detailed site assessment of climatic conditions has been carried out to ensure that the operational envelope of the IPS is suitable for the site. The site assessment best practices are not addressed in this document. For guidelines related to site assessment in icing climate, refer to IEA Wind Task 19 Recommended Practices (IEA Wind Task 19, 2017).

These guidelines focus on the operational performance of turbines in icing climates and do not address ice throw risk. For more information on ice throw please refer to IEA Wind Task 19 Recommended Practices (IEA Wind Task 19, 2017) and Recommendations for Ice Fall and Ice Throw Risk Assessment (IEA Wind Task 19, 2018).

2. Definitions

2.1. Cold Climate

The general cold climate definitions described below are extracts from the IEA Wind Task 19 Recommended Practices report (IEA Wind 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, 2019)

A cold climate area can be either a **low temperature climate (“LTC”)** and/or an **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.

Within IC areas, the following icing definitions apply (see Figure 2):

- **Meteorological icing**: a period during which the meteorological conditions (temperature, wind speed, liquid water content, droplet distribution) allow ice accretion.
- **Instrumental icing**: Period during which ice is present/visible on a structure and/or a meteorological instrument.
- **Rotor icing:** Period during which ice is present at the rotor blade of a wind turbine. Due to differences in dimension, shape, flow velocity and vibrations, rotor icing is typically not equivalent to instrumental icing. In many cases, incubation and ablation time for rotor icing are shorter than for instrumental icing.

For an area to be defined as an **icing climate**, **instrumental icing** is present more than 1% of the year and/or **meteorological icing** is present more than 0.5% of the year.

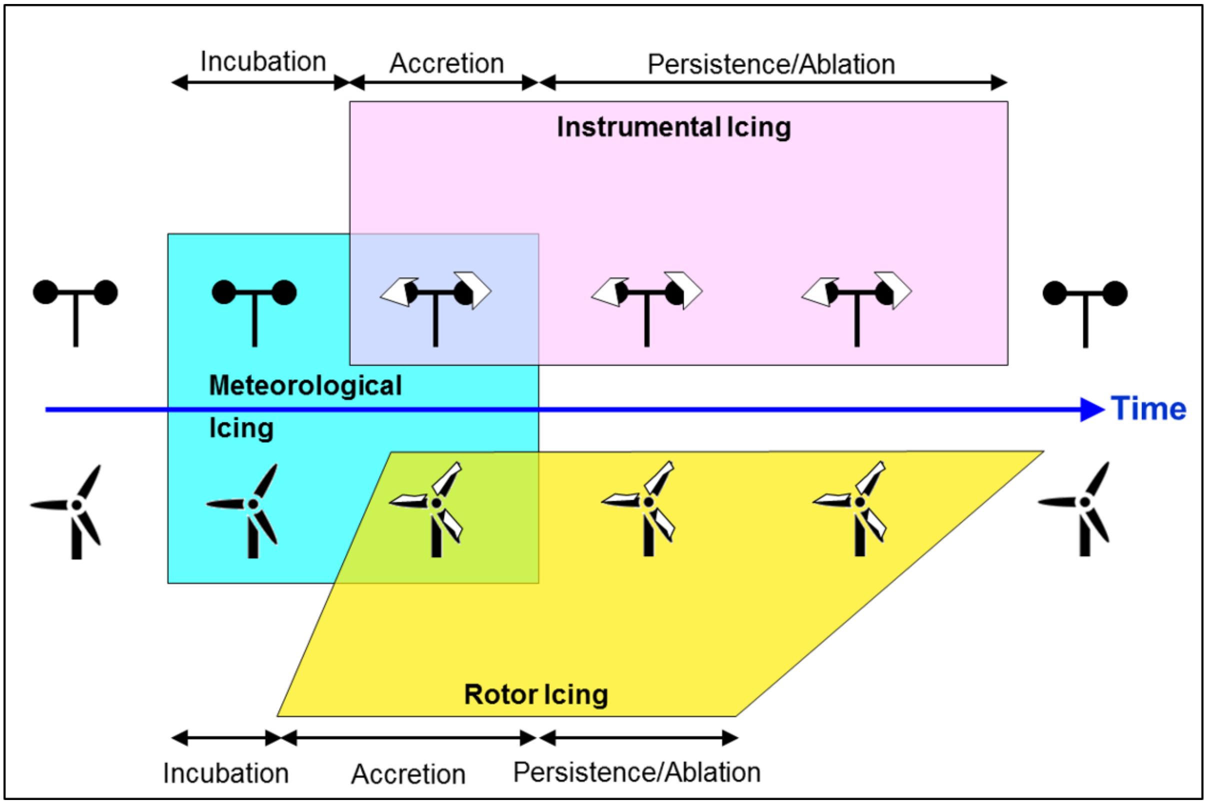

Figure 2. Differences between meteorological, instrumental and rotor icing. (IEA Wind Task 19, 2017).

Within **low temperature climate**, the following definitions apply:

- If minimum temperatures below -20°C have been observed during long-term measurements (preferably 10 years or more) on an average of more than nine days a year, the site is defined as an LTC site. The nine-day criterion is fulfilled if the temperature at the site remains below -20°C for one hour or more on the respective days or;
- The long-term average annual air temperature of the site is below 0°C.

Figure 3 illustrates the definitions of cold climate, low temperature climate and icing climate (IEA Wind Task 19, 2018).

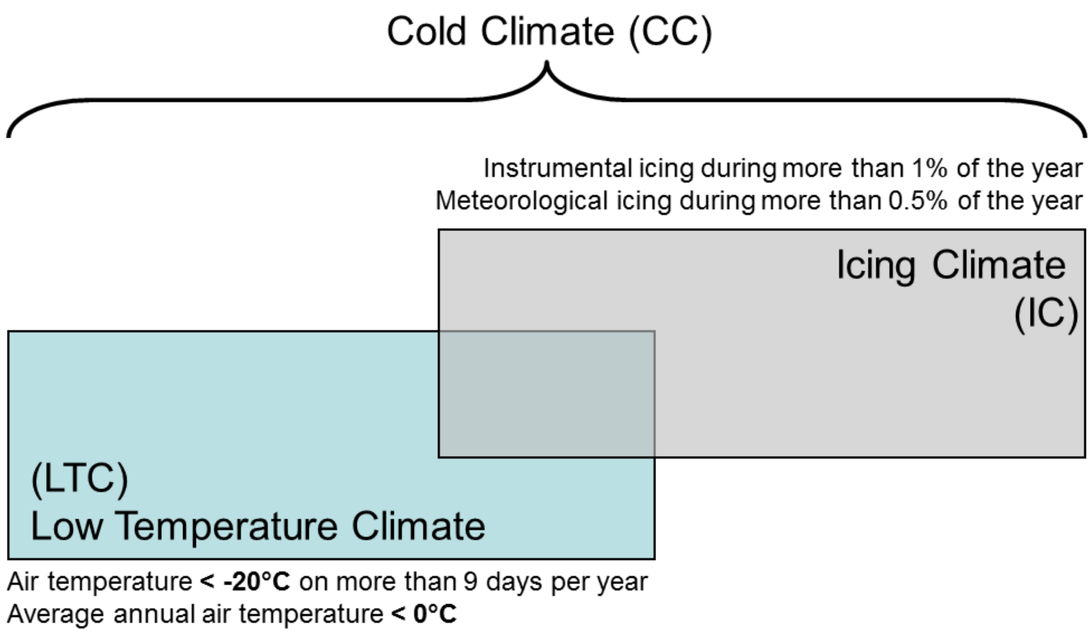

Figure 3. Definition of Cold Climate, Low Temperature Climate and Icing Climate (IEA Wind Task 19, 2018).

Icing climate conditions are not only prevalent in cold climate sites with low temperatures, but can also be found in sites where the temperature is around 0°C during the winter. The amount of icing experienced by the wind farm may also depend on the terrain (*e.g.*, exposed hilltops may experience more icing than surrounding terrain at blade tip height).

2.2. Cold Climate wind turbine

A cold climate wind turbine has design adaptations to withstand LTC and IC. The combined cold climate solution ultimately dictates the performance of the turbine in CC conditions.

An example of **LTC turbine adaptions** are special lubricants (grease and oils) and hydraulic fluids suitable for low temperatures. Another example are heaters for components (*e.g.*, for a generator, gearbox, yaw and pitch systems, control boxes, converters and transformers).

IC turbine adaptations are needed to mitigate production losses and ice throw. Examples of IC turbine adaptations to mitigate ice throw are ice detection methods triggering turbine standstill. For more information on ice throw, please consult the Task 19 "International Recommendations for Ice Fall and Ice Throw Risk Assessments" report (IEA Wind Task 19, 2018).

IC turbine adaptations to mitigate production losses due to icing are composed of the IPS, (described with sub-systems in section 2.3) and the turbine operational strategy (described in section 2.4). These adaptations affect the production and behaviour of the wind turbine during icing conditions.

Together, the IC and LTC turbine adaptations form a combined cold climate wind turbine solution provided by the OEMs. The focus of this report will be on the turbine adaptations for IC to mitigate production losses due to icing.

Figure 4 shows an overview of the cold climate wind turbine adaptations defined in sections 2.2 to 2.4.

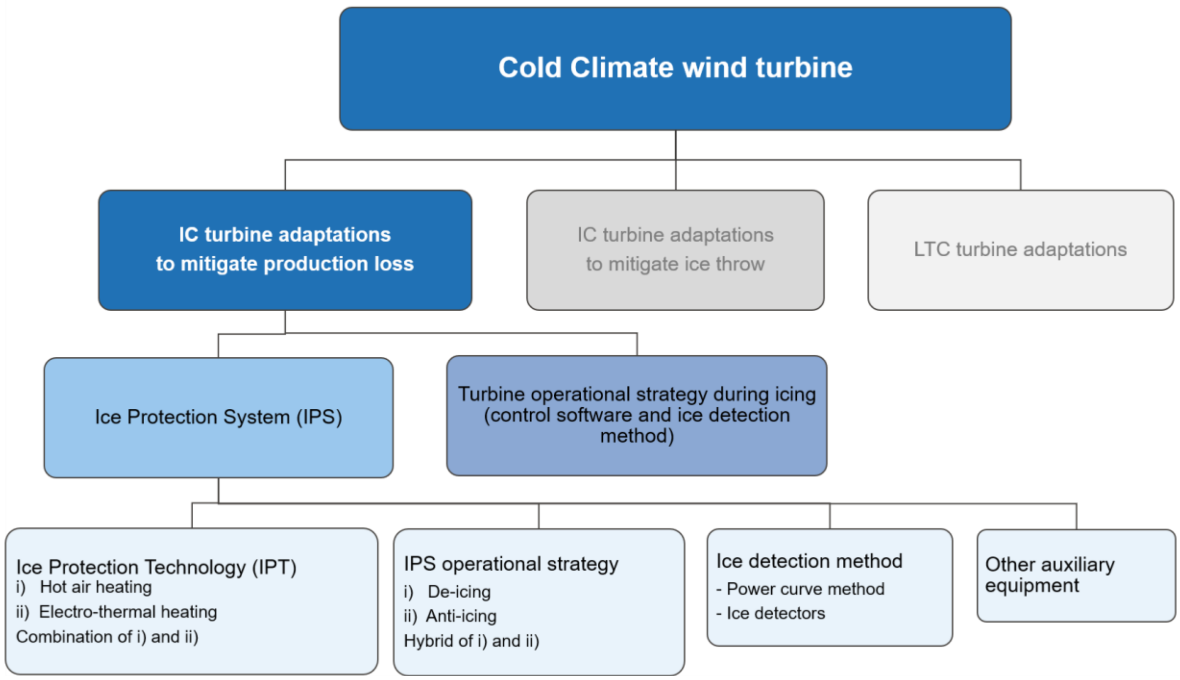

Figure 4. Cold Climate wind turbine overview.

2.3. Ice Protection System

A wind turbine IPS is defined as a combination of many sub-systems and encompasses the following:

- The core Ice Protection Technology (IPT) used to prevent or mitigate ice build-up on a wind turbine rotor;
- An ice detection system used for IPS control;
- The operational strategy of the IPS (anti-, de-icing or hybrid);
- All other electro-mechanical equipment and auxiliary systems.

2.3.1. Ice Protection Technology

There are two main categories of active Ice Protection Technologies ("IPT") that are currently commercially available for wind turbine blades:

- hot air heating and
- electro-thermal heating.

IPTs combining both hot air and electro-thermal heating also exist.

There are other active IPTs currently being explored in R&D projects such as, microwave technologies and other mechanical removal methods. There is also research into passive technologies for example icephobic coatings (IEA Wind Task 19, 2018).

These guidelines will focus on the commercially available active technologies of hot air and electro-thermal heating. IPTs that are not commercially available from the majority of IPS manufacturers are excluded from these guidelines. However, more technologies may become commercially available in the future and it is recommended that these guidelines be updated accordingly.

2.3.1.1. Hot air heating

The hot air heating technology consists of a heater through which air is forced by a fan inside the blade. The heater-fan units are usually located in the blade root. Hot air is forced into the blade towards the leading edge to heat the outer blade surface by conduction through the blade material. Depending on the blade structure, the air may be forced through ducts or allowed to circulate freely towards the blade tip. The colder return air is then recirculated through the heater-fan unit. Generally, the heater-fan units are powered by cables and connectors coming from the nacelle and through the hub. For shorter blades (<45 meters), only one heater-fan unit in the hub may be sufficient, if sized accordingly.

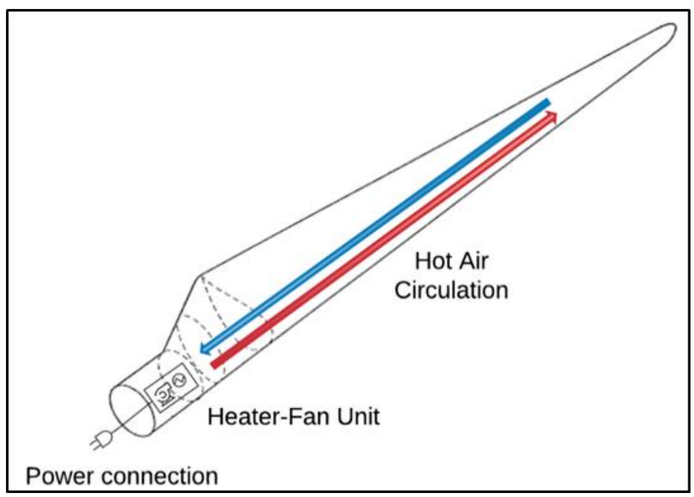

Figure 5. Conceptual view of the hot air heating technology in a wind turbine blade.

2.3.1.2. Electro-thermal heating

The electro-thermal heating technology consists of electro-thermal elements placed primarily on the leading edge of the blade. The electrical current passing through the resistive elements generates heat, which is transported to the blade's outer surface by conduction. The elements can be embedded under the resin/gel layer of the blade, or be added on the outer blade surface using adhesives. In all cases, the elements are powered by cables and connectors coming from the nacelle and through the hub.

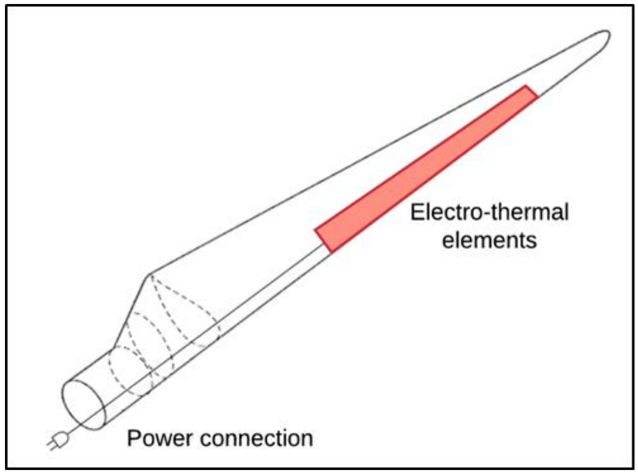

Figure 6. Conceptual view of the electro-thermal heating technology in a wind turbine blade.

2.3.2. Ice detection method

The ice detection method is an integral part of the IPS. It allows the turbine to detect ice and indicates when the IPS shall activate. Ice detection methods used in commercially available IPS either rely on turbine performance degradation (the power curve method) or on dedicated sensors (ice detectors) or a combination of the two methods. One or more ice detection methods can be directly integrated in the turbine SCADA by the OEM and be available as a status of the wind turbine.

The power curve method requires access to standard measurement from a wind turbine (*e.g.*, wind speed, rotational speed, power output, blade angle, etc.). This rotor-based approach detects icing through the reduction of the expected turbine power output. Therefore, the turbine must be in operation to detect ice with this method. There are several variations of this method depending on the IPS provider.

Several dedicated ice detectors are commercially available. These are typically located on the nacelle roof or mounted directly on or in the blade. Depending on the operating principle and location, the ice detector will either detect meteorological icing, instrumental icing or rotor icing (see Figure 2). Turbine operation is not required for ice detection with a dedicated sensor although some rotor-based sensors require a minimal wind speed to be able to detect icing. Refer to the IEA Wind Task 19 Available Technologies report (IEA Wind Task 19, 2018) for an exhaustive list of available ice detectors on the market.

2.3.3. IPS operational strategy

There are two main IPS operational strategies that can be used: **anti-icing operation** or **de-icing operation**. Some hybrid control strategies are also being used, for example, in cases of intense ice-build up where the anti-icing operation will change to a de-icing operation to remove the ice with the rotor stopped or idling. The IPS operational strategy should always be considered in combination with the turbine operational strategy, which is described in section 2.4.

2.3.3.1. Anti-icing

The anti-icing operation is a strategy with the objective of limiting the ice build-up on the blades while the turbine is in operation and actively producing energy. The anti-icing operation is triggered by the ice detection method when icing is assumed to accrete on the blades or when icing conditions are present. The system will remain active as long as the conditions are in line with the pre-set ice detection criteria. Anti-icing designs can also be used with a de-icing operational strategy if conditions are out of the anti-icing operational envelope (see section 4.1) or if ice build-up has formed during turbine standstill.

2.3.3.2. De-icing

The de-icing operation is a strategy that stops or idles the turbine rotor before initiating ice removal. The de-icing cycle is triggered by the ice detection method when the likelihood of ice build-up is confirmed or after the turbine has shut down due to icing conditions (*e.g.,* when vibrations caused by ice accretion reach levels that can be dangerous for the integrity of the turbines). The turbine will then be in standstill or idling mode during the ice removal cycle. The ice removal time and performance will depend on the IPT, ice build-up, ambient conditions, operational setup and ice removal strategy (one or three blades at the same time). The de-icing cycle time can range from under an hour to several hours. Once a de-icing cycle has been completed, the turbine will then attempt to restart. If the ice detection method identifies that ice has not been sufficiently removed, the system will start another de-icing cycle. This process will be repeated until the ice has been removed and the turbine can be restarted within acceptable operational parameters. After a de-icing cycle has been completed, some ice may remain on the blade, thus preventing a return to full production. In some other cases, if the ice has not been removed after a given number of cycles, or if new ice has been accreted on the blades within the removal cycle or quickly after its restart, the de-icing may stop for a predefined period of time before a new de-icing attempt is made or until the conditions reach a specific point within the IPS operational envelope.

2.3.4. Other auxiliary equipment

Other auxiliary equipment encompasses all sub-systems required to operate the IPS which are not covered in the previous sections. These sub-systems are required to provide electrical power to the IPS (*e.g.,* electrical cabinets, slip rings or some other power transmission system), ensure equipment safety (*e.g.,* circuit breaker, surge protection, over temperature relays, etc.) and collect and exchange data with the turbine controller to operate the IPS (*e.g.,* sensors, data acquisition hardware, etc.). The auxiliary equipment mandatory for the IPS operation and its safety shall be considered an integral part of the IPS and should be considered to be under the warranty of the IPS with which it is utilised.

2.4. Turbine operational strategy during icing

The turbine operational strategy during icing refers to a specific control algorithm used during icing conditions. This specific control can be a dedicated software or simply a specific set of operational parameters that are modified in the turbine controller during icing periods. It does not require an accompanying IPT installed to function properly. However, if an IPT is installed, it should be considered in close combination with the IPS operational strategy during a wind turbine performance warranty evaluation. When warrantying a retrofit IPS, the impacts of the turbine operational strategy during icing on the wind turbine's performance, implemented by the turbine OEM, must be considered if the IPS manufacturer has no control over the operational strategy.

There are several turbine operational strategies that can be used to improve turbine performance during icing. An example of a turbine operational strategy is to keep the turbine in operation during icing but to reduce rotational speed or adjust the blade pitch angle to limit the impact of icing on the overall aerodynamic performance of the rotor. Another example is advanced load control software for optimising the balance between ice induced turbine loads and power production. These operational strategies during icing are generally defined in the control software documentation provided by the OEM and will depend on the ice detection method integrated in the turbine SCADA.

3. Warranty options

It is recommended to consider an IPS option when developing a wind project in icing climates. The IPS should be part of the turbine procurement process and include a turbine performance warranty for icing climates[*]

The IPS should be viewed as an integral sub-system of the turbine, subject to similar level of expectations and service as for any other sub-system of the wind turbine. As such, it should carry the same warranty protection as the turbine (*e.g.*, related to product performance and availability).

It is strongly recommended that an IPS warranty should be covered as part of a turbine availability warranty (described in 3.1) and have a separate performance warranty (described in 3.2). The focus of these guidelines is on the turbine performance warranty (described in

[*] A **warranty** is not explicitly defined in this document as it has different legal interpretations depending on country and wind farm case nor is there a widely accepted definition available within the wind industry. However, in the context of this guideline, a warranty in the case of wind turbines in icing climates could be roughly described as a legally binding assurance, promise or guarantee that a wind turbine fulfils predefined specifications, functionalities or performance.

3.2.1); however, this does not exclude the possibility of warranting the turbine for a CC site in other ways.

It is recommended that all warranties in the Turbine Supply Agreement are seen in conjunction and that down-time of the turbine caused by any maintenance or malfunction of the IPS is covered by the warranties, either the performance warranty, the availability warranty, or the turbine contract itself.

3.1. Availability warranty

This type of warranty is a commercial standard and typically warrants that the IPS will be technically available to be turned on, should an icing event be detected by the wind turbine. The warranty can be solely linked to IPS components or included in the more general availability warranty of the entire turbine. Such a warranty does not address the risk due to poorly performing systems that many investors are looking for, but only that the system is ready to work when expected. The terms of such warranty are typically the same as the ones in the Service Management Agreement, or longer and generally in line with the availability criteria defined in an accompanying Full Services Agreement.

3.2. Performance warranty

Within the envelope of a performance warranty, there are two main directions that have been identified. The first is the **Turbine Performance Warranty in Icing Climates,** which takes into account the performance of the complete turbine during and after icing events. The second is the **Ice Protection Technology Performance Warranty,** which focuses purely on the function of the IPT.

3.2.1. Turbine performance warranty in Icing Climates

A turbine performance warranty in Icing Climates, which is the main focus of these guidelines, takes into account the energy production of the complete wind turbine, including the IPS (IPT, ice detection method and IPS operational strategy), during icing events. Examples of factors that affect the turbine performance in icing climate could be the capability of the IPS to get the turbine back into operation and its ability to keep the turbine operating above a defined performance threshold.

The advantage of such a warranty is that it considers the overall wind turbine performance and not only the IPS or IPT. It increases the potential for optimisation based on site conditions and turbine operation. The disadvantages are that there are more factors to consider when developing the test method. If an IPS is purchased separately from the turbine as a retrofit, this type of warranty would require the OEM and IPS manufacturers to collaborate, since the turbine performance is outside the IPS manufacturer’s control.

3.2.2. Ice Protection Technology performance warranty

An IPT performance warranty is solely focused on the performance of the IPT itself and not the IPS and turbine as a whole. It only looks at the capacity of the IPT to remove ice from the blade, but doesn't assess the capability of the turbine to resume or increase power output. It is considered simpler than the Turbine Performance Warranty in Icing Climates.

The criteria set out in this type of warranty only relates to the physical performance of the IPT to mitigate or remove ice. For example, the test method could focus on the time it takes the IPT to remove ice from the heated parts of the blade or the time it takes for the blade surface to reach a defined temperature setpoint dependent on the environmental conditions. Examples of sensors needed for the test are temperature sensors on the blade, infrared cameras or ice detection systems.

The main advantage of this type of warranty is its simplicity, as it takes fewer factors into consideration. The main disadvantage is that it only considers the performance of the IPT and not the whole IPS impact on wind turbine performance. For example, an IPT that only mitigates icing effects on a small portion of the blade may provide no or limited energy gain, although the system would be triggered automatically and function according to the design envelope.

This guideline does not recommend IPT performance warranties for OEM-provided IPSes since they exclude many factors and do not provide insight into the turbine behaviour and performance in IC. It is however recommended that these types of tests should be conducted by the OEMs and IPS manufacturers themselves, or by a third party, as a validation of the IPT design envelope and specifications. This information can then be provided as a supporting document to a project developer or owner.

4. Performance warranty guidelines

In principle, a basic warranty document should include the following:

- Clearly defined Operational Envelope ("OE") for which the warranty is valid;
- Clearly defined data selection and filtering;
- Methodology for measuring the Performance Criteria within the Operational Envelope;
- Clearly defined and warranted performance criteria;
- Consequences based on the results of the test.

4.1. Operational envelope

The performance of a wind turbine in IC shall be warranted within a clearly specified OE. The OE will determine when it is suitable to conduct the performance test and how to filter the data based on several factors such as: availability of the wind turbine, operational state, weather conditions, turbine maintenance, availability of the IPS, IPS design envelope, etc.

When defining the OE, the design envelope of the IPS needs to be considered. Preferably, the IPS manufacturer should provide the design envelope of the IPS. The design envelope defines the ambient conditions for which the IPS is expected to remove the ice from the blades. For example, it can be represented on a 2D graph with wind speed and ambient temperature (see Figure 7), although some recent research suggests that the Liquid Water Content (LWC) plays an important role in the operational envelope coverage (Roberge, et al., 2019). If sufficient knowledge is available, several design envelopes can be provided to cover distinct operating conditions as well as different icing severities. It is recommended to investigate to what extent the local site conditions are covered by both the design envelope of the IPS and the OE of the warranty test.

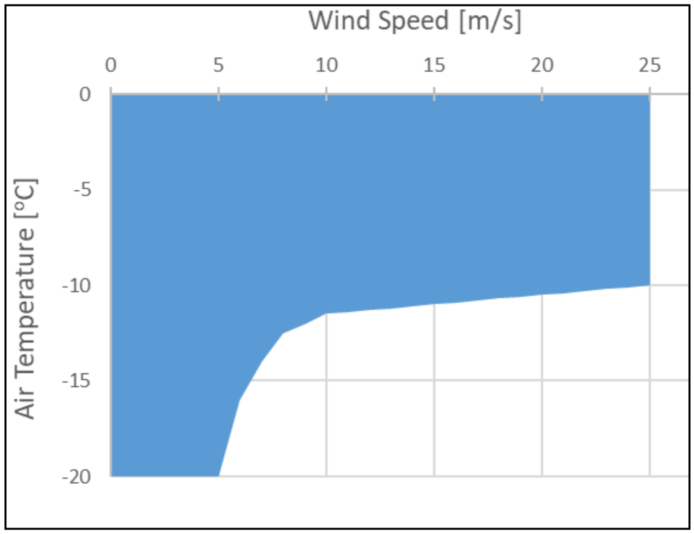

Figure 7. Illustrative graph of a OE.

4.2. Data selection and filtering

Prior to the test, there needs to be an agreement on data selection and filtering in order to ensure that the test results are reliable.

There needs to be a clear definition of the following:

- Duration of test
- Required data coverage of the test
- Exclusions
- Icing event definition
- For the self-comparison and side-by-side tests, how to split the available data into reference and test datasets.

Before the performance metrics can be calculated, the data should be filtered. Filtering requirements need to be specified in the warranty document and all filtering needs to be reported. The warranty should specifically list how to identify the relevant test dataset and all the events to exclude. For example, all non-icing-related faults, maintenance periods, data outside of the OE of the IPS and other factors affecting turbine performance (*e.g.*, curtailment, wake, different operating states, etc.) should be explicitly stated. Required corrections (*e.g.*, due to changes in air density) needs to be done for the entire dataset.

Test duration can be defined as a time period (one winter or a number of months) or as a number of icing events or total amount of icing hours. Because large variance in icing conditions between winters on any site is quite common, defining the required test coverage as number of icing hours or as a number of icing events under specified icing conditions can ensure that tests done during different years are more comparable to each other and ensure sufficient test coverage. If there are too few icing events during a winter to properly evaluate the performance of an IPS, the test should continue until a required number of icing events or a required amount of icing hours have been recorded.

The conditions during the test period may lead to gaps in test coverage, where some conditions remain untested. It should be clearly defined what the minimum required data collection is in order for it to be deemed conclusive. If this minimum data threshold is not obtained, either the test is considered inconclusive, the test period needs to be extended, or another solution for dealing with gaps in the test coverage is needed.

Test methods described in sections 4.3.14.3.1 and 4.3.2 below, require a reference power curve to detect and calculate icing losses and the potential production during the icing loss periods. This can be calculated with the T19IceLossMethod tool (IEA Wind Task 19, 2019). When binning the data for reference power curve calculation, the data should be split into bins at least according to wind speed and optionally wind direction. Whether directional binning is required depends on the local geography, the wind farm layout and the amount of available data. The binning must be the same in the reference power curve dataset as it is in the test dataset. There also needs to be requirements for data availability of the reference data, usually defined as minimum number of samples in a bin. One solution is defined in the IEC power performance standard: IEC 61400-12-2 defines the minimum requirements for data coverage as 30 minutes per bin and recommends that a single incomplete bin can be estimated by linear interpolation from the two adjacent complete bins. (IEC, 2013)

Before the start of the test campaign, there also needs to be an agreement on how to define the performance criteria for the test and when the performance of the turbine is evaluated. If the performance of the turbine is only evaluated during icing events, there needs to be a clear definition of an icing event.

Icing events can be defined based on an external measurement (i.e., an icing detector) or based on turbine behaviour (i.e., power curve, for example T19IceLossMethod, etc.). The ice detection can be a feature of the turbine SCADA or a component of the IPS or an external source. It is important that the same icing event definition is used throughout the test and that this definition is documented in the warranty documents. It should be noted that the definition of an icing event can be connected to the ice detection method and/or instrument.

It is also important to consider the OE of the IPS when defining both the exclusions from the data set and the subset of the data where the performance criteria is evaluated. Icing events that occur outside of the OE of the IPS can be excluded from the performance evaluation or treated as a special case.

Only after the data has been filtered according to the defined criteria and the required pre-processing has been done, the performance criteria can be calculated for the test dataset.

4.3. Test methods

A warranty that only sets out performance criteria without a clear test method is incomplete and inadequate. The test method needs to be:

- Practicable for the turbine, IPS and site in question
- Cost-effective
- Based on criteria and parameters that are measurable and unambiguous, and with clear data sources
- Representative of the site conditions
- Carried out according to a well-defined performance criterion, including the pass/fail threshold
- Sufficiently comprehensive to ensure statistical relevance

The warranty agreement must define a minimal number of turbines to be tested. The most important factors to consider, to cover the variability of the IC within the site, are the size and layout of the site and complexity of the terrain. For a small site in simple terrain, one turbine might be enough to represent the wind farm, while for a large site in complex terrain several turbines might be needed to cover the IC variations within the site. The prevailing wind direction during icing season can also affect turbine selection. For example, a side-by-side test setup should minimize the probability of one turbine being in the wake of another during the test period.

There are currently a number of different possible test options identified for testing the IPS system as part of the turbine performance. Three approaches, the “side-by-side”, “turbine self-comparison” and “power performance” test methods are presented below.

Ideally, the aim should be to choose the most cost-effective test method, which provides the lowest uncertainty regarding the final performance test result. However, cost effective does not always go hand in hand with lowest uncertainty, so there must always be a cost-benefit analysis to find the right balance between the two. In all tests, the factors affecting the uncertainty of the test method needs to be assessed prior to starting the tests in order to understand the reliability of the test results.

4.3.1. Turbine self-comparison test

This methodology is based on the comparison of the performance of the selected test turbines during icing events and outside of icing events. The test method aims to assess the turbine performance differences based on individual turbine SCADA data alone.

The turbine self-comparison test requires a large set of data to be collected from the turbine that is to be tested. The dataset should be large enough to ensure good coverage of different wind and icing conditions. A baseline could be a full year, depending on icing conditions.

The full dataset needs to be split into two parts: the reference dataset and the test dataset. The reference dataset needs to be selected so that there are no icing events in the data. The test dataset can be split from the data using a number of different criteria: temperature, ice detector, power curve deviation, or a combination thereof. It is important that there is no overlap between the two datasets. The performance criterion is then only evaluated in the test dataset.

After the data is split, a reference power curve is calculated from the reference dataset. The reference power curve is used, in combination with wind speeds from the test dataset, to produce an potential energy production ($E_{P,IPS}$) estimate for the test data.

The ratio of actual energy production to the potential energy production, is then used to calculate the maintained energy as the performance criterion for the test, shown in Equation 1 (section 4.4). In Equation 1, $E_{A,IPS}$ is the actual energy production in the test data set, which is then compared to the potential energy production, $E_{P,IPS}$, calculated from the reference power curve using wind speeds form the test data. Figure 8 shows a flowchart overview of the self-comparison test process.

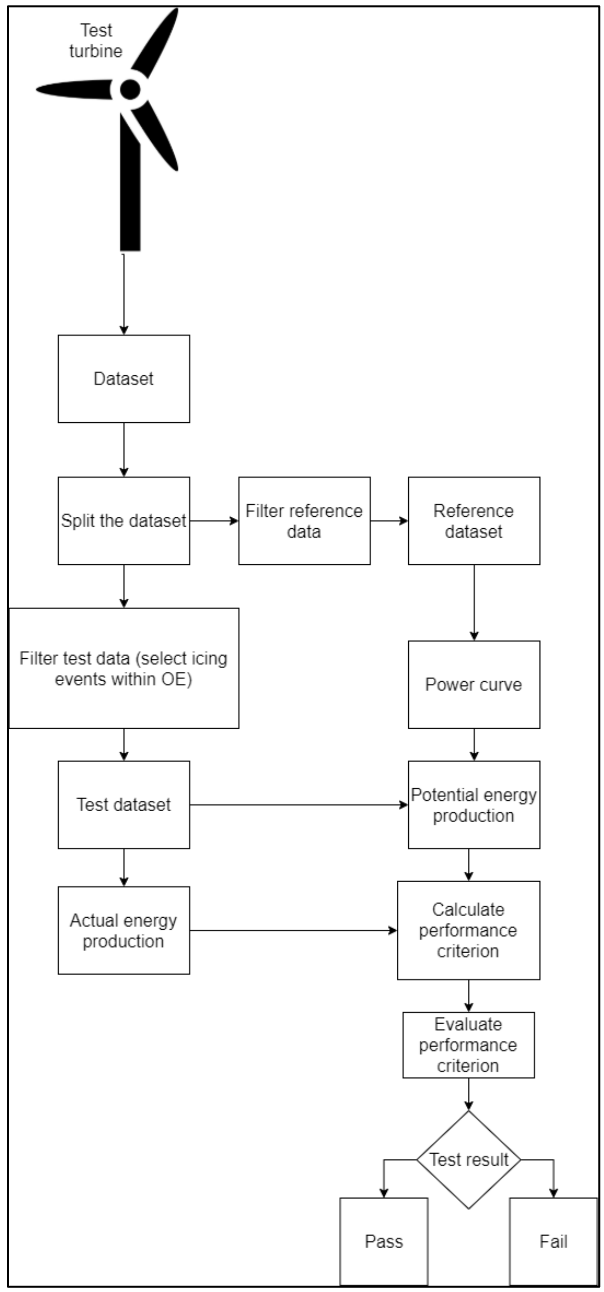

Figure 8. Process flowchart for self-comparison test.

The advantages of the self-comparison test are that it does not require any external reference data, allowing all turbines to operate normally with the IPS on during wintertime. It is also possible to test all the turbines within a site at the same time, making turbine selection less of an issue and increasing statistical relevance of the final performance result.

The disadvantage is that seasonal variations, especially concerning wind direction and roughness, may affect the performance in the test year. For sites with large seasonal differences in wind conditions, the self-comparison test can suffer from data availability issues. Another disadvantage of this warranty is that it doesn't take into account how a turbine without IPS would have performed. Hence it is not clear how much the IPS will increase the performance of the site. The reference being an estimate instead of a direct measurement can introduce additional uncertainty into the performance metric.

4.3.2. Side-by-side comparison test

This methodology is based on the comparison of two or more turbines positioned in similar locations, with similar wind and IC as well as similar operational mode, where the test wind turbines operate with an active IPS and the reference turbines have a deactivated IPS system or simply no IPS at all. This methodology does not imply that two neighbouring turbines are a good pairing. The selection of appropriate turbines has a direct impact on the quality of the results and this step must be completed carefully. Several test and reference turbines can be selected and their performance can be averaged to constitute an average test turbine performance and an average reference turbine performance.

Once the turbines are selected, the process is similar to the self-comparison test. Two periods are defined (test and reference) and the data is filtered according to the guidelines presented in section 4.2. The energy recovery of the test and reference turbines are compared to constitute the performance criteria shown in Equation 2 (section 4.4). Per the required values to calculate that performance metric, the relative icing loss of each turbine can be calculated in a similar way as for the self-comparison test. The side-by-side comparison test can therefore provide both performance criteria presented in section 4.4. Figure 9 shows a flowchart overview of the side-by-side comparison test process.

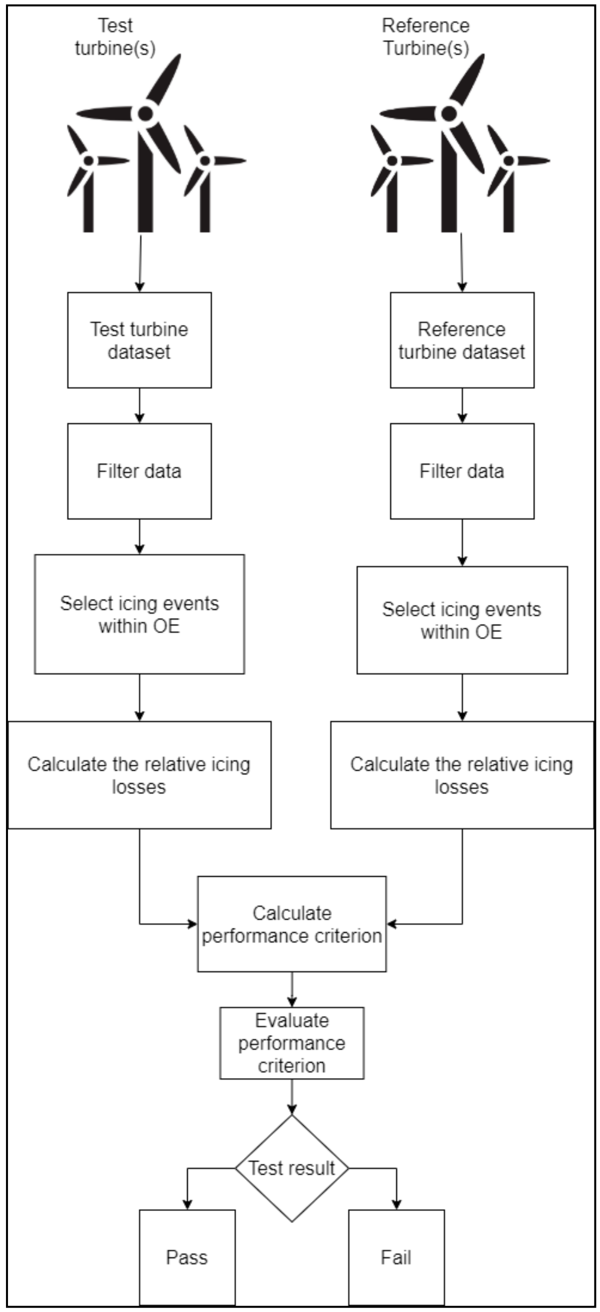

Figure 9. Process flowchart for side-by-side comparision test

The main advantage of such a test is to provide a clear insight on the performance gain of the IPS in terms of energy production during icing compared to a turbine without IPS. It provides a simple estimate of the IPS performance given that most of the factors could be considered equal for both turbines. Knowing how much more energy is recovered by the IPS turbine can help evaluate the return on investment of the selected IPS option.

Compared to a turbine self-comparison test (Section 4.3.1), the disadvantages of this method are that it is not scalable to all the turbines of a site and that it adds bias and uncertainty from comparing two neighbouring turbines. On a complex site, it may be difficult to find two suitable wind turbines for a side-by-side comparison and careful attention shall be applied to selecting turbines operating in similar conditions. For new sites where all turbines are equipped with an IPS, another key disadvantage is the reduced production from the wind turbine with the deactivated IPS throughout the duration of the test.

4.3.3. Power performance test

This methodology is based on the comparison of the performance of selected wind turbine(s) with an IPS against a reference performance based on the warranted power curve and wind data collected from one or more met masts at the site. This method can therefore to some extent be based on the IEC 61400-12-1 methodology as used in power performance testing. There are however some important deviations.

The most important deviation is the filtering of the test data. Time periods where the turbine experiences icing are, instead of being excluded, defined as part of the test data set. To minimise data loss in the test dataset during icing periods from the anemometers in the met mast, ultrasonic or heated cup anemometers should be used.

The ratio of the actual energy production to the potential energy production, can be used as the performance criterion for the test, shown in Equation 1(section 4.4). In Equation 1, $E_{A,IPS}$ is the actual energy production during the test period, which is then compared to the potential energy production, $E_{P,IPS}$, calculated from the warranted power curve and the met mast wind speed.

Another way to use Equation 1is to define $E_{A,IPS}$ as the actual energy production, calculated based on a wind distribution and the power curve measured with the met mast under icing conditions. The potential energy production, $E_{P,IPS}$, is then calculated based on the warranted power curve and a wind distribution. Since icing conditions might not be present at all wind speeds, it is recommended to have an agreement on when enough bins in the measured power curve are filled. To make sure enough data is collected, filtering criteria on turbulence intensity and wind shear exponent might need to be set broader in comparison to a normal power curve test. Figure 10 shows a flowchart overview of the power performance test process.

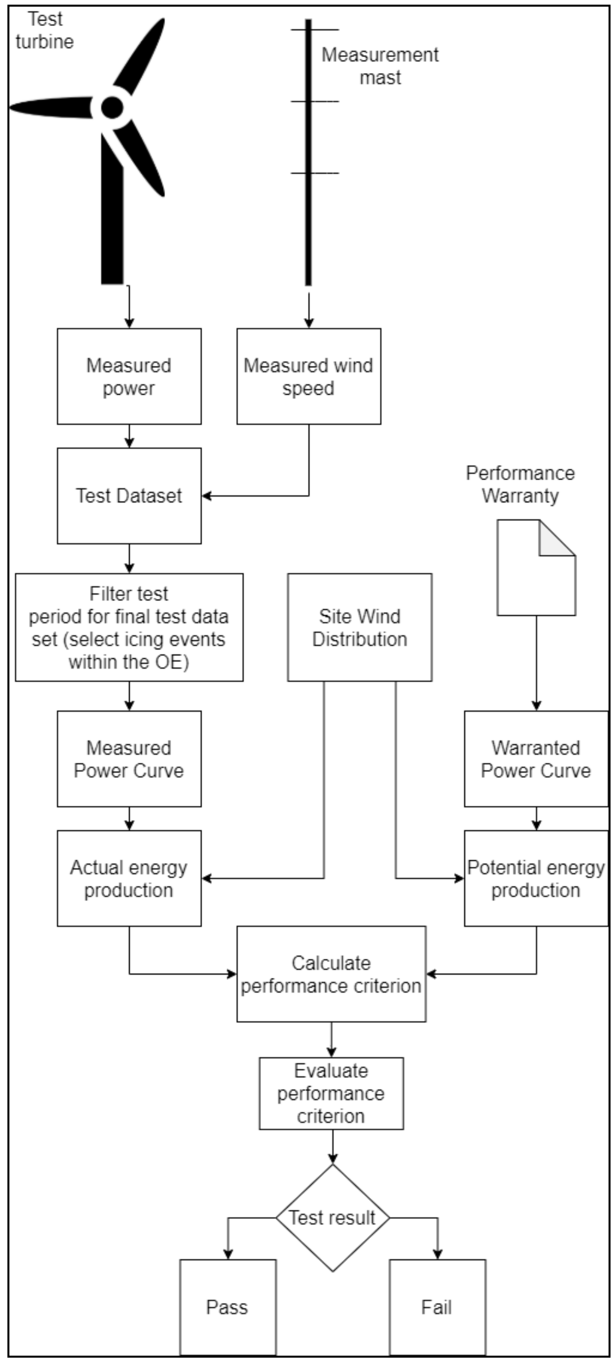

Figure 10. Process flowchart for power performance test

The main advantage of this methodology is that it is an established method for power performance testing in the wind industry. This facilitates the setup of the test and the calculation of uncertainties. For projects where a standard power curve test is already planned to be performed with a met mast, the performance test in winter would just be an addition to the existing campaign.

The disadvantages are that, unless a met mast is already available on site, it is costly, and, should a site calibration be required, it takes additional time and should be planned well in advance. Similarly to the side-by-side test, it is expensive to test several turbines and careful attention needs to be applied to selecting representative turbines. Another disadvantage of this test method is that it doesn't take into account how a turbine without IPS would have performed. Hence it is not clear how much the IPS increases the performance of the site.

In accordance with the IEC 61400-12-1, this test could potentially also be carried out using remote sensing technology, which utilises a mix of masts and remote sensing devices (e.g. ground-based LiDAR) to measure the wind speed.

4.4. Performance criteria

In a turbine performance warranty in IC, the performance criteria should be defined from quantities that:

- Have clear connections to the turbine performance during icing;
- Can be measured using simple and affordable sensors that provide a reasonable level of accuracy.

The choice of a performance criteria and of a measuring method are therefore closely connected. The performance criteria generally consist of two components. The first component is the measured performance during and after icing events. The second component is the reference performance that serves as the baseline for the comparison.

There are many ways to define a performance criterion that can be calculated from the data collected in the test methods described in section 4.3. Two common criteria are presented below.

A performance criterion that calculates the maintained energy in a turbine self-test and power performance test:
This performance criterion estimates the level of energy production a turbine is able to maintain during and after icing conditions. For a defined test dataset, after all filtering is completed, the measured performance during icing is the actual energy production [MWh] during the filtered test period. The reference performance is defined as the estimated potential energy available to be harvested [MWh] assuming no ice had been present during the filtered test period. The warranted value is the ratio of the actual energy production compared to the potential energy production during the filtered test period expressed as a percentage.

Equation 1 – Performance criterion that calculates the maintained energy

$$\frac{E_{A,IPS}}{E_{P,IPS}} \geq Warranted\ percentage$$

Where

$E_{A,IPS}$	measured Actual Energy production during the filtered test period, and.
$E_{P,IPS}$	is the calculated Potential Energy production during the filtered test period.

To see a simplified example of how Equation 1 can be used, refer to Appendix A.

A performance criterion that calculates the recovered energy in a side-by-side test:
This performance criterion estimates how much of the losses can be recovered by installing an IPS in comparison to a turbine not having an IPS in similar icing conditions. For a defined filtered test period (section 4.2), the measured performance during icing is the estimated relative icing loss [%] with an IPS. The reference performance is here defined to be the estimated relative icing loss [%] without an IPS. The warranted value is the expected recovery from a reference value expressed as a percentage. This performance criterion requires that there

is a reference turbine without any ice adaptation activated at the same time as the turbine that measures the performance with ice adaptions (see section 4.3.2 Side-by-side comparison test).

Equation 2 - Performance criterion that calculates the recovered energy.

$$\frac{\left(\frac{E_{A,IPS}}{E_{P,IPS}} - \frac{E_{A,No\ IPS}}{E_{P,No\ IPS}}\right)}{\left(1 - \frac{E_{A,No\ IPS}}{E_{P,No\ IPS}}\right)} \geq Warranted\ percentage$$

Where

$E_{A,IPS}$	is the measured Actual Energy production during the filtered test period for the turbine with an IPS;
$E_{P,IPS}$	is the calculated Potential Energy production during the filtered test period for the turbine with an IPS;
$E_{A,No\ IPS}$	is the measured Actual Energy production during the filtered test period for the turbine without an IPS, and
$E_{P,No\ IPS}$	is the calculated Potential Energy production during the filtered test period for the turbine with an IPS.

To see a simplified example of how Equation 2 can be used, refer to Appendix A.

The Warranted percentage in both equations above usually includes or considers the measurement uncertainty. A test method that leads to a high level of measurement uncertainty (for example inter annual variability) will likely get less coverage by the warranty than a method that has a low level of measurement uncertainty.

It is important to note that the Warranted levels in Equation 1 and Equation 2 cannot be compared since they are based on different quantities. The simplified example in Appendix A shows how the results varies dependent on the IPS efficiency and equation used. If we assume the potential energy production is the same for all test turbines, Equation 1 will always give a higher value than Equation 2. The level that is possible to warrant in the two equations also depends on the site conditions and turbine type and operational strategy. For example, the performance criterion that calculates the recovered energy, would yield lower values for wind turbines from OEMs that deal better with icing conditions (without an IPS) than wind turbines from OEMs that have an operational strategy that performs worse during icing (without an IPS).

4.5. Consequences

The consequences of a failed test result should be clearly outlined and solidified in the warranty. When outlining the consequences, it is important to keep in mind that the goal of a performance warranty is to get the wind turbines operating to the expected level so that the wind project meets technical and financial objectives.

If the first test fails, there should be an opportunity for corrective action, with the aim of improving turbine performance, followed by a re-test. When corrective actions and re-testing have failed, monetary compensation, usually in the form of Liquidated Damages (LDs), shall come into play.

If the test surpasses the expected performance target, there can also be a bonus for the IPS manufacturer.

4.6. Risks

In general, it is important to consider the risks when developing a wind project in CC. The developer has the responsibility to get good quality, representative pre-construction measurements or modelling. It should therefore be responsible for the “weather risk” and the site’s baseline icing data. Once these are set and agreed, the developer should seek to cooperate with the OEMs to ensure that the most suitable turbine, including its IPS, is chosen for the site. Thus, the IPS manufacturer should be responsible for the technology solution and carry the 'technology risk’. The risk is therefore justly shared between parties, and the warranty should distribute the commercial risk in a just and fair way between OEM, IPS, the manufacturer, the developer and the investors.

With regard to track record, there are a number of OEMs and IPS manufacturers with IC adaptations in the market that have a few years of track record and, depending on the sites this could be a consideration to minimise risk. A good warranty should also weigh heavily in any decision.

Cold climate sites are a challenge for all parties involved, from the development process through the operating life of the wind farms. With the uncertainties and risks related to these sites, there is a considerable advantage for the industry in working together to increase knowledge, reduce risk and establish standard frameworks enabling the improvement of CC technologies.

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Appendix A - Performance Criteria Calculation Example

This example assumes three wind turbines (WT) standing in similar wind and icing climate. One of the turbines has an IPS and the other turbines do not have an IPS.

Table 1. Performance criteria calculation examples with high icing losses.

		WT 1 No IPS	WT 2 IPS	WT 3 IPS
Yearly gross energy production	MWh	12000	12000	12000
Yearly icing loss %	%	12%	6%	2%
Yearly icing loss	MWh	1440	720	240
Test period (T)	month	6	6	6
Actual Energy production during T (E_A)	MWh	4560	5280	5760
Potential Energy production during T (E_P)*	MWh	6000	6000	6000
Performance Criterion Eq. 1		76%	88%	96%
Performance Criterion Eq. 2		-	50%	83%

*Assuming all energy production loss due to ice occurs during test period

Table 1 shows how the performance criterion from Equation 1 and 2 varies in result, depending on the IPS efficiency for turbines 2 and 3.

Calculate performance for turbine self-test or power performance test
For the performance criterion that calculates the maintained energy during the test period for turbine 1 with an IPS, we can calculate turbine-specific icing losses according to Equation 1:

$$\frac{E_{A,IPS}}{E_{P,IPS}} = \frac{5760}{6000} = 0.96$$

For turbine 3 without an IPS, we get:

$$\frac{E_{A,NoIPS}}{E_{P,No\ IPS}} = \frac{4560}{6000} = 0.76$$

This means that the IPS turbine 3 is able to maintain 96% of the potential energy production during the selected icing periods and that it loses 4% due to icing, while turbine 1 without an IPS maintains 76% of the potential energy production during the same period (and loses 24% due to icing).

Calculate IPS performance for a side-by-side test
For the performance criterion that calculates the recovered energy during the test period for turbine 3 with an IPS in comparison to turbine 1 one without, we get the following, according to Equation 2:

$$\frac{\left(\frac{E_{A,IPS}}{E_{P,IPS}} - \frac{E_{A,No\ IPS}}{E_{P,No\ IPS}}\right)}{\left(1 - \frac{E_{A,No\ IPS}}{E_{P,No\ IPS}}\right)} = \frac{(0.96 - 0.76)}{(1 - 0.76)} = 0.83$$

In other words, this means that turbine 3 with an IPS recovers 83% of the relative ice loss of the turbine without an IPS. In this example, the IPS turbine loses 4% to icing, where the turbine without an IPS loses 24%. An ideal IPS would reach an energy recovery of 100%, meaning the IPS turbine would suffer no production loss due to icing. The 83% recovery can also be expressed by:

$$\frac{0.24 - 0.04}{0.24} = 0.83$$

If turbine 1 without an IPS would experience a lower icing loss, Table 2 shows how the performance criterion from Equation 1 and 2 are affected if the icing losses on turbines 2 and 3 are assumed to be the same as in Table 1.

Table 2. Performance criteria calculation examples with lower icing losses.

		WT 1 **No IPS**	**WT 2** **IPS**	**WT 3** **IPS**
Yearly gross energy production	MWh	12000	12000	12000
Yearly icing loss %	%	8%	6%	2%
Yearly icing loss	MWh	960	720	240
Test period (T)	month	6	6	6
Actual Energy production during T (E_A)	MWh	5040	5280	5760
Potential Energy production during T (E_P)*	MWh	6000	6000	6000
Performance Criterion Eq. 1		84%	88%	96%
Performance Criterion Eq. 2		-	25%	75%

Table 2 shows that it is more difficult to achieve a high value with performance criterion 2 if the icing losses are low on the turbine without an IPS.