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VTT TECHNOLOGY 341

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ISBN 978-951-38-8673-8 (URL: http://www.vttresearch.com/impact/publications)

VTT Technology 341

ISSN-L 2242-1211
ISSN 2242-122X (Online)
http://urn.fi/URN:ISBN:978-951-38-8673-8

JULKAISIJA – UTGIVARE – PUBLISHER

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Cover image: Mikko Tiihonen (VTT), 2012

Preface

The goal of this project was to anonymously benchmark state-of-the-art wind turbines equipped with Ice Protection Systems (IPS, active blade heating using anti- or de-icing strategy) used to mitigate production losses due to icing in icing climates. The performance and maturity of wind turbines in various icing climates was analysed using historical SCADA data. In addition, weather observations and modelling data was used to assess site-specific icing conditions for IPS gain evaluation.

This report was funded by Blaiken Vind Ab, Vattenfall AB, Taaleri Energia Oy and VTT.

Contents

1. Introduction

Cold climate wind power markets are one of the largest “special” climate markets in wind energy today and growing +12GW/a between 2016-2020 [1]. Areas with cold climate conditions are becoming more and more attractive for investors and project developers because of high wind speeds, increased air density due to low temperatures and low population density enabling to develop large, cost-efficient wind farms.

The main challenge for wind turbines in cold climate sites with icing conditions, is the ice build-up on blades, see Figure 1. Ice accretion on blades causes production losses, potential additional wear and tear on components, increased noise emissions and increased safety hazards from ice throw.

Figure 1. Challenge of ice accretion on wind turbine blades in different countries without blade heating ice protection systems

Most of the largest wind turbine manufacturers in the world (Enercon, Vestas, Nordex Group and Dongfang) are offering today blade Ice Protections Systems (de- and anti-icing) to mitigate ice accretion challenges on wind turbine blades. The commercially available, state-of-the-art Ice Protection System (IPS) solutions today include active blade heating solutions in the form of blade hot air or electro-thermal heating elements integrated in turbine blades to mitigate ice induced production losses. These Ice Protection Systems (IPS) sum up to 4.8 GW of cumulative installed capacity by end of 2015 [2].

Since WinterWind 2015 conference, owners and operators of IPS equipped turbines have publicly requested performance guarantees form OEM’s. In addition to performance guarantees, public information about IPS performance and maturity is typically not available, making the selection of the appropriate technology for site-specific conditions very challenging. To date, only Enercon hot air system has been publically assessed by independent 3rd parties regarding the performance of the hot air IPS [3] [4] [5] [6] [7] [8].

This report has 9 chapters including this introduction. In chapter 2 the goals of this study are explained. Chapter 3 describes the wind farm cases used in the report and chapter 4 describes the analysis methods used. Chapter 5 shows the core results for the chosen one-year benchmark time period. Chapter 6 reviews the limitations and uncertainties of the methods and data sets used. Chapter 7 presents the analysis and discussion of the results followed by chapter 8 with summary and conclusions. Future work and references are presented in chapter 9.

2. Goals

The goals of the project are:

- To shift from current status quo on very limited or case-by-case IPS performance and system maturity analyses to a public, comprehensive IPS benchmark analysis
- Analyse anonymously Enercon, Vestas, Nordex Group and Dongfang wind turbines equipped with IPS using historical SCADA data
- Develop a consistent and comparable benchmark analysis method for comparing all wind turbines with IPS for
  - Evaluating the icing losses based on actual production data and model references
  - Evaluating the gain of production for IPS compared to non-IPS turbines and
  - Evaluate IPS maturity from O&M perspective

After the project, the owner/operators of wind farms globally will have a better view about performance and maturity of state-of-the-art IPS out in the market allowing for better decisions on future IPS investments. For wind turbine manufacturers, the results will boost healthy competition for development of more efficient and more mature IPS. For financiers, the results will shed light to what is the current level of IPS performance and maturity for more enhanced benefit and risk evaluation for wind farm finances. For the research community, the results will reveal potential areas of improvement for IPS and generate a starting point for innovations for next generation IPS development. The novelty content of this project is high, due to the extensive scope of the analysis. The results of the project will benefit both industry and research community worldwide.

3. Description of wind farm cases

The scope of work includes a detailed historical SCADA (Supervisory Control and Data Acquisition) data analysis using 10-minute averages from four different wind turbine models and analysis of icing conditions on all sites (site summary in Table 1). The turbine Original Equipment Manufacturers (OEMs) used in the analysis are (in alphabetical order) Dongfang, Enercon, Nordex Group and Vestas. The OEMs have been assigned a random identifier, which will be used for the rest of the document see Table 1.

The benchmark period was from May 1st 2017 to end of April 30th 2018 as this is the period with concurrent data from all sites. In total, the benchmark period from 4 sites contains 116 turbines. All OEMs and results in this report are anonymous. All turbine models are +2MW +80m in rotor diameter representing the state-of-the-art, modern wind turbines all equipped with Ice Protection Systems (IPS) operated either via anti- or de-icing strategy to mitigate ice accretion on the turbine blades. All IPS technologies use either hot-air circulation inside the blades or electro-thermal heating elements on the blades. For more information on general definitions for IPS technology and anti- de-icing control strategy see here [9] and more OEM specific IPS technology information here [2]. All wind farms have been operational for some years.

Table 1. Summary of sites

Turbine OEM	Region
A	Nordics
B	Nordics
C	Central EU
D	Nordics

4. Analysis method

The analysis method consisted of three main phases: 1) calculation of icing loss and IPS maturity indicators from SCADA data, 2) evaluation of site-specific icing conditions from WIceAtlas and WRF model and 3) IPS maturity and gain evaluation. As this report focuses on anonymised benchmarking of OEMs to each other, special care was taken in order to have an analysis approach that generates inter-comparable results without revealing the site locations or turbine OEMs.

4.1 SCADA analysis of icing losses and IPS maturity indicators

The T19IceLossMethod was used for icing loss and maturity analysis from SCADA data. The T19IceLossMethod is an open source Python code that is publically available via Task19 website [10]. The T19IceLossMethod method has been developed using existing standards and industry best practises.

The T19IceLossMethod does not require icing measurements as input. The T19IceLossMethod is a robust, easily adaptable method that estimates the icing losses directly from the production data of the wind turbines using the turbine itself as an ice detector. The required SCADA signals are listed in Table 2.

Table 2. List of required SCADA data signals for T19IceLossMethod

Signal	Description	Unit
Ws	Heated anemometer nacelle wind speed	m/s
Temp	Ambient temperature from nacelle	°C
Pwr	Turbine output power	kW
Nacdir	Nacelle yaw angle	deg
mode	Turbine operational mode	-

Prior to the calculation of the power curve, data is cleaned as well as possible. The filtering process uses turbine status and fault information whenever possible to filter out unwanted periods from the data e.g. curtailment or other suboptimal turbine operation. The method also produces an estimate for the turbine availability

Ice build-up on turbine blades gradually deteriorates the power output (or results to apparent overproduction due to iced anemometer) so, to increase accuracy, the method uses three consecutive 10-minute data points for defining start-stop timestamps for icing events. Iced turbine power losses are defined by comparing the measured performance to the expected power curve. The expected power curve is calculated from the production data during the analysis.

In this case, with IPS turbines, there are additional categories for losses in the results. Blade heating is considered to be a separate operational mode for the turbine. Production losses during blade heating are calculated separately. IPS status is obtained from turbine SCADA data. Finally, an estimate for IPS self consumption (the energy required for heating) is calculated and added to the icing losses.

On a generic level, the method involves the following steps:

- **Data filtering and clean up:** faults and other known stops are removed from the data. Curtailments and other suboptimal operational modes are filtered out of the data mostly based on error codes. Data is then corrected for air density variation.
- **Calculating the expected, reference power curve:** based on the data where turbine is operating normally in non-icing conditions (temperatures above +3°C, one wind sector 0-360°)
- **Count the production losses versus the reference power curve:** the icing losses consist of 3 components for temperatures below +1°C
  - **Losses due to reduced power curve:** reduction in output power during operation when blade heating was not activated
  - **Losses during blade heating:** total difference between the reference power curve and measured output during periods when blade heating is active
  - **Blade heating system self-consumption:** total power used for blade heating on turbine level

All totals are reported as % of the total power produced during the analysis period.

Another main part of the analyses in this report focuses on the maturity indicators for the entire wind turbine and IPS as sub-component. The idea is to analyse technical reliability of the wind turbine and IPS during wintertime. The developed maturity indicators are:

- **Wind turbine time and energy based availability [%]**: wind turbine level time based availability (TBA) is calculated from SCADA data "Availability" signal defined by turbine owner/operator and wind turbine level energy based availability (EBA) is calculated as the ratio between the production measured during a given period and the production expected for the same period. The expected production is calculated based on the nacelle anemometer measurements and the reference power curve.
- **IPS heating duration [hours]**: comparing turbine level IPS heating durations inside a wind farm to each other and identifying malfunctional IPS behaviour

Figure 2 shows an example 48 hour time series plot from one turbine in site A during normal power production in November 2017. Top plot shows how the T19IceLossMethod calculated expected, reference (dark orange line) wind bin average power compares to the measured output turbine power (blue). The calculated, reference power has also the wind bin specific scatter available as the bin wise standard deviation of output power (light orange area around the average orange line). The uncertainty of reference power curve for this turbine in site A is 11.4 % for benchmark period May 2017 to April 2018. Uncertainty is defined here as standard deviation of power divided by wind bin average power. Turbine level uncertainty is calculated as the average of all wind specific bins for wind speeds between 5 m/s to rated power.

The EBA for this example 48 hour period was 107 % (expected production was 53.7 MWh while measured production was 57.3 MWh) being in the range of the 11.4 % reference power curve uncertainty. The EBA value of 107 % is also visible from the top plot that the blue line is following the orange line at slightly higher values.

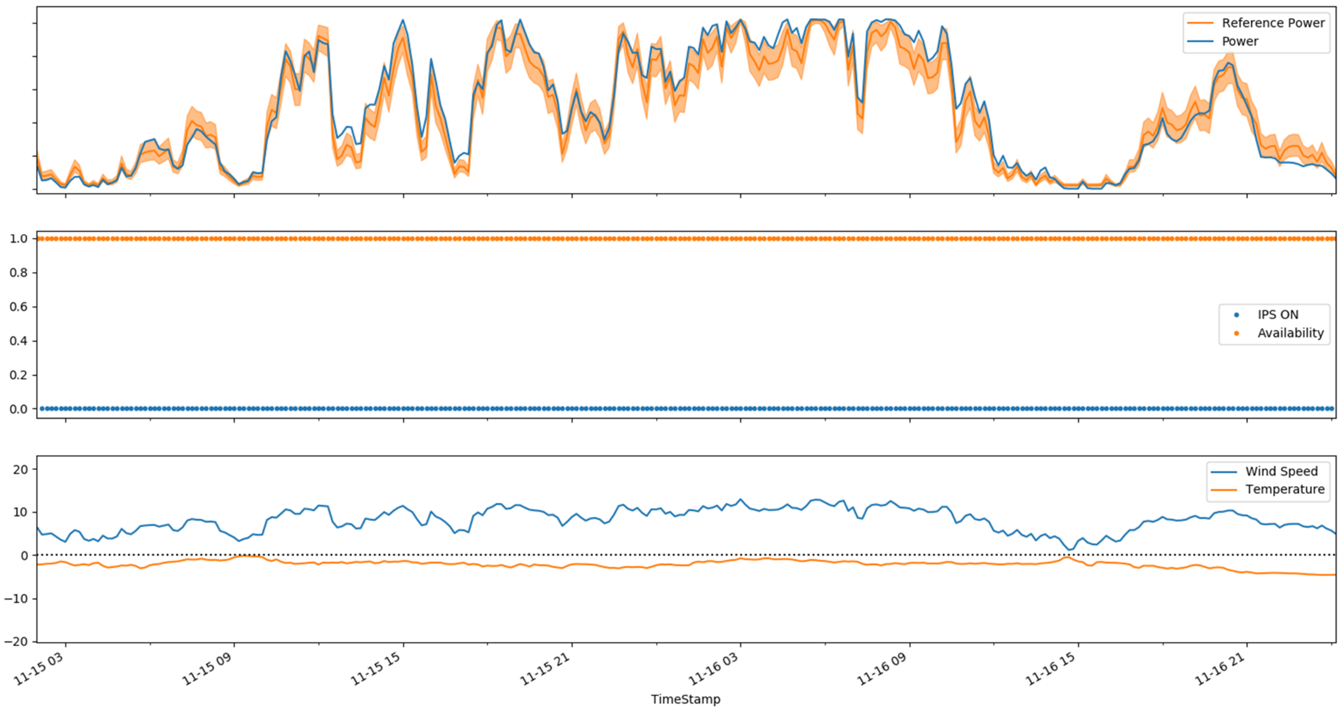

Figure 2. Example 48 hour time series from one turbine in site A with no icing, top: average reference power and wind bin wise standard deviation (orange) and measured power (blue), middle: turbine availability (orange dots) and IPS activation (blue dots), bottom: measured ambient wind speed (blue) and temperature (orange)

The middle plot shows that the turbine was available all this time so the turbine level TBA was 100 % for this 48 h time period. The middle plot shows the IPS is deactivated during this period (value of zero). The T19IceLossMethod did not detect any icing events during these 48 hours. The bottom plot shows the ambient wind speed and temperature measured from top of the turbine nacelle.

In addition to IPS performance and maturity, rotor icing durations were extracted from T19IceLossMethod (data points detected below P10 threshold as reduced power curve due to icing and during active IPS operation) in order to get indicative and supportive information for evaluation of site-specific icing conditions.

4.2 Evaluation of site specific icing conditions

One of the main goals of the report is to evaluate the potential energy gain (the amount of production recovered by the IPS ability to mitigate ice on blades) of different IPS compared to turbines without IPS. This potential production gain is typically one of the main business drivers for wind farm owners and investors to invest in IPS. As no comparable icing measurements or reference non-IPS turbines were available from all sites, the potential IPS gain evaluation had to be performed based on the meteorological icing conditions. Three sites had icing measurements of some sort available but these were all different to each other thus not usable for IPS benchmarking purposes.

In order to evaluate the site specific icing conditions, two main approaches were selected:

1. Wind Power Icing Atlas (WIceAtlas) developed by VTT that uses measurements of cloud base height from nearby weather stations combined with reanalysis MERRA-2 temperature for evaluating icing conditions at wind farm sites and

2. Weather Research and Forecasting (WRF) model utilized by Kjeller Vindteknikk for numerical mesoscale modelling the meteorological icing conditions based on ISO 12494 theory and Kjeller in-house IceLoss tool for predicting the icing losses.

4.2.1 WIceAtlas

The Wind Power Icing Atlas (WIceAtlas) was developed by VTT with the goal to provide information on in-cloud icing severities worldwide [11] [12] [13] [14]. WIceAtlas consists of over 4000 meteorological stations globally with +20 years of measurement and observation data from time period 1979-2015. In WIceAtlas, icing severity is defined as icing frequency (% of time) resulting from in-cloud icing.

The public WIceAtlas map uses cloud base height and temperature < 0°C as a proxy for in-cloud icing conditions from the >4000 meteorological stations and interpolates between stations icing conditions to 150 m above ground level to create icing frequencies for large geographical areas. To achieve a more accurate temperature at 150 m, vertically interpolated MERRA-2 reanalysis data was used for temperature.

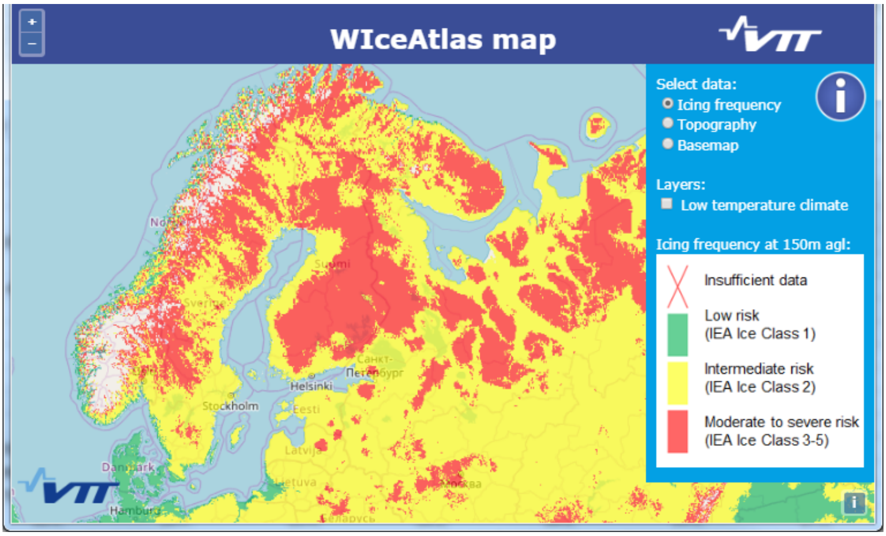

Figure 3. Example of publically available WIceAtlas icing map tool interface via web browser [14]

For this report, the public WIceAtlas map (Figure 3) was only used to describe the historical long-term average icing conditions for years 1979-2015. For the benchmark period from May 2017 to end of April 2018, cloud base height measurements from nearby meteorological stations were selected for more detailed analysis. Some weather stations had missing data during 5/2017-4/2018 thus gap filling from other nearby airports was needed to achieve > 95 % met station data availability.

Table 3 summarizes the distance from nearest met station to each site used to evaluate the site icing conditions for the benchmark time period. Average horizontal distance for all four sites is 40 km and elevation different from met station to rotor icing height is 560 m. In general, the uncertainty of the WIceAtlas method increases with distance and elevation difference.

Table 3. Nearest WIceAtlas met station distance to sites

Site	Horizontal distance to nearest WIceAtlas met station	Elevation difference to nearest WIceatlas met station
A	40 km	550 m
B	30 km	490 m
C	60 km	660 m
D	40 km	520 m

4.2.2 WRF model

Kjeller Vindteknikk AS provided for this work some Weather Research and Forecasting (WRF) model (version 3.2.1) simulations run both with a hindcast setup, with input data from Final Global Data Assimilation System (FNL) [15]. The area covered by a 4 km x 4 km resolution grid is given as the inner domain. The simulations are setup with 32 layers in the vertical with 4 layers in the lower 200 m. The Simulations used the Thompson microphysics scheme [16] and the Yonsei University Scheme [17] for boundary layer mixing.

The icing rate on a standard cylindrical icing collector was calculated according to ISO 12494 [18]. The modelled ice load at a given time t, is defined as a function of the icing rate, melting rate and sublimation rate. A detailed description of the terms for the melting rate is given in [19]. Sublimation has been included in the icing calculations. During the process of sublimation it has been observed that the accreted ice becomes brittle and that small ice-pieces are continuously shed from the cylinder. The shedding is included by multiplying the sublimation rate with a factor of 2.5. [15]

To estimate the production loss it has been assumed that energy production will continue with ice on the rotor blades, and that there is a direct relation between the ice load on the standard ISO cylinder and the production loss experienced by the turbines. Ice on the blades will disrupt the aerodynamic structure of the blades, which leads to a lower energy yield at any wind speed. The energy production follows the principle of a three-dimensional power curve. [15]

4.2.3 Final site icing analysis

In total four different values for icing losses were available for benchmark period 5/2017-4/2018 and two different values for long-term icing losses, see Table 4.

Table 4. List of different methods for evaluating the site specific icing conditions for different time periods

Timeperiod	Method
5/2017-4/2018	**WRF met icing [% of time]:** the duration of meteorological icing for icing intensities above 10 g/m/h at 150 m.a.g.l.
5/2017-4/2018	**WRF Pice loss [% of production]:** icing losses on a reference wind turbine using the Kjeller in-house IceLoss tool.
5/2017-4/2018	**WRF stop loss [% of production]:** icing losses on a reference turbine using the Kjeller in-house IceLoss tool and assuming the turbine stops very frequently due to icing.
5/2017-4/2018	**WIceAtlas met icing [% of time]:** nearby, closest meteorological station measurements of cloud-base height combined with MERRA-2 reanalysis temperature at rotor icing height (hub height + 2/3 rotor radius) for evaluation of meteorological icing duration.
2007-2015	**WRF met icing map 2007-2015 [% of time]:** mapping the long-term average duration of meteorological icing at 100-120 m.a.g.l. generated by Kjeller for Norway, Sweden or Finland
1979-2015	**WIceAtlas met icing map 1979-2015 [% of time]:** mapping the long-term average duration of meteorological icing at 150 m agl generated by VTT

Table 4 meteorological icing and icing losses were finally connected to the IEA Ice Classification (see Table 5) in order to ensure site anonymities and intercomparability of the results. The average IEA Ice Class from first 4 indicators during 5/2017-4/2018 from Table 4 was calculated as the final Ice Class for non-IPS turbines to be used for production gain evaluations.

Table 5. Modified IEA Ice Classification [20] with icing losses presented as ice class mean with associated icing loss range

IEA Ice Class	**Meteorological icing**	**Instrumental icing**	**Icing loss**
	% of year	% of year	% of gross annual production
5	> 10	> 20	> 20
4	5-10	10-30	17.5 ± 7.5
3	3-5	6-15	7.5 ± 4.5
2	0.5-3	1-9	2.8 ± 2.2
1	0-0.5	<1.5	0.25 ± 0.25

4.3 Analysis of IPS maturity and gain of production

The final benchmark period is chosen to be from May 2017 to end of April 2018 as this is the period with concurrent data from all sites. For the performance analysis, wind farm specific icing losses are compared to expected non-IPS average IEA Ice Class icing loss (e.g. average icing loss for Ice Class 3 is 7.5%) with Ice Classes chosen based on WRF and WIceAtlas analysis. The full turbine maturity is analysed from turbine level winter time based availability (TBA) and the IPS maturity from availability and deviation analyses of IPS blade heating durations.

5. Results for one year benchmark time period

All results presented in this chapter are calculated from selected benchmark year from beginning of May 2017 to end of April 2018.

5.1 Site temperature conditions

Table 6 presents comparison of modelled hourly MERRA2 and WRF temperature offsets to measured SCADA temperature. A negative bias means that modelled temperatures are colder than measured SCADA temperatures. Site B and D have the biggest cold temperature bias in both MERRA2 and WRF. Davis [21] reported a WRF simulated cold bias of 2.5°C versus turbine nacelle based ambient temperature measurements but that nacelle temperature biases can also be very turbine model dependant [22]. The temperature biases are in 3 sites out of 4 quite large at 2°C or more. The cause of this bias is unknown (potentially from excess nacelle heat). Taking this temperature bias and potential uncertainty in SCADA temperature measurements for future analysis with T19IceLossMethod, a +3°C threshold for reference power curve calculations is assumed.

Table 6 presents average MERRA2 site winter temperature between 1st of December 2017 and end of March 2018. Site A and D have the coldest temperatures, site C was the warmest.

Table 6. MERRA2 and WRF temperature bias to SCADA data and Site average winter temperatures

Site	MERRA2 vs SCADA Temp. offset	WRF vs SCADA Temp offset	MERRA2 Mean Winter Temperature Dec-Mar
A	-2.2°C	-1.9°C	-10.7°C
B	-5.1°C	-4.4°C	-7.6°C
C	2.4°C	-	+1.5°C
D	-3.6°C	-3.5°C	-10.5°C

5.2 Icing losses and IPS behaviour from SCADA data

Figure 4 shows the time and energy based availability calculated as wind farm average for full year from May 2017 to end of April 2018 and winter time from 1st of December 2017 to end of March 2018. In all cases except site C, the time based availability (TBA) reduces in winter time compared to full year TBA. Winter TBA ranges are from 96 % to 100 % with 4 site average being 97 %. A bigger reduction is seen in energy based availability in all cases except site C. Winter EBA ranges are from 73 % to 93 % with 4 site average being 82 %.

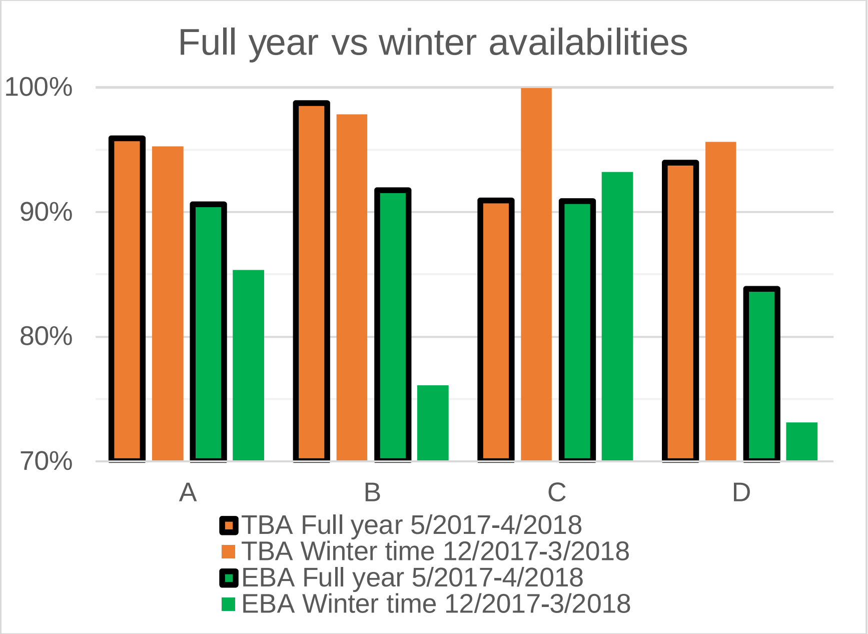

Figure 4. Time and energy based availability summaries from all wind farm cases

Figure 5 shows the icing losses for all sites separated into different categories. The magnitude of icing losses per category varies significantly between different sites.

For site A, total icing losses are slightly over 8 % with majority of icing losses are seen during active IPS operation with smaller icing losses during normal production and standstill icing losses. Almost 1.5 % of the year's production is used for IPS self-consumption.

For site B, icing losses are slightly over 6 %. The IPS was activated only for some minutes during entire year thus most of the losses are due to reduced power performance during normal operation.

For site C, icing losses are at 3 % and all icing losses are distributed almost evenly among all categories. Site C has the lowest total icing loss of all sites.

Site D has the majority of icing losses during active IPS operation. It also has the largest self-consumption power usage of about 2 % and has the largest total icing loss of 10 %.

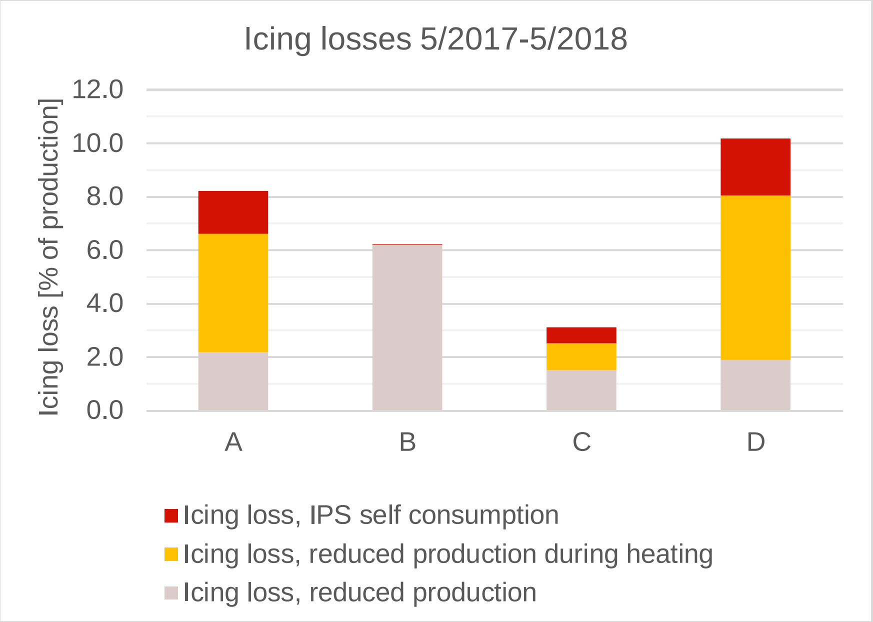

Figure 5. IPS icing loss categorization with reduced power curve implying an ice detection or IPS control delay (grey), reduced power curve during active IPS (orange) and IPS self-consumption (red)

5.3 Validation of site specific icing conditions

Figure 6 presents the validation analyses for site icing conditions for all sites evaluated from WIceAtlas, WRF and icing induced production losses computed from SCADA data. The dotted column outlines indicate the long-term expected IEA Ice Class values, which were used for preliminary site ice assessment and do not influence the icing analyses here. The average of the 4 columns with black outlines defines the final IEA Ice Class for time period 5/2017-4/2018 and final classes are presented in the blue spheres per site. In green is the ice class based on observed total icing losses from SCADA data for benchmark period 5/2017-4/2018.

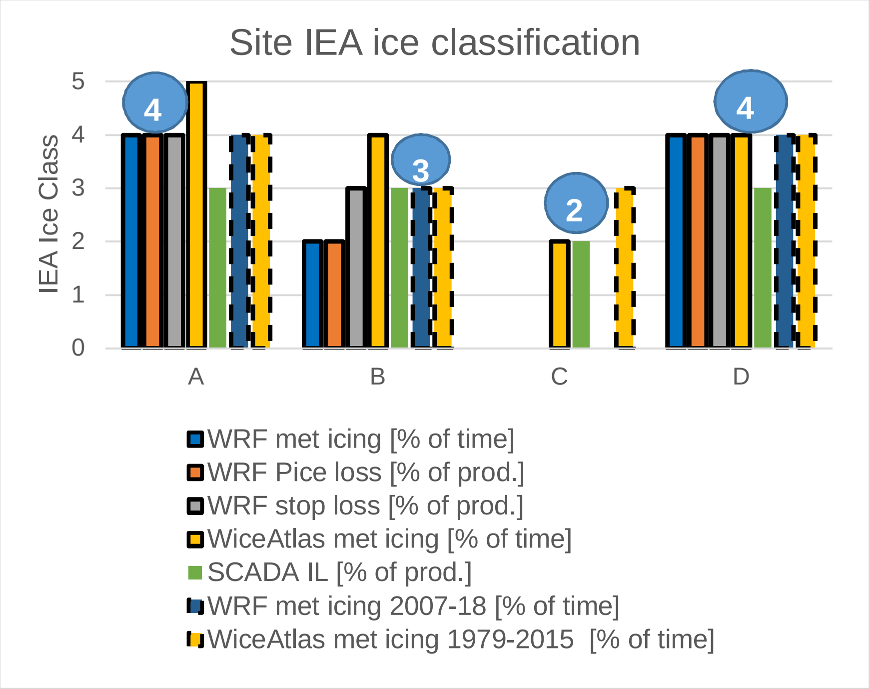

Figure 6. Site IEA Ice Classification validation

For site A, the selected IEA Ice Class is 4. All 3 WRF icing indicators show IEA Ice Class 4 and WIceAtlas just reaching to Ice Class 5 (10.4% of time) for the benchmark year. Expected long-term Ice Class is 4 from WIceAtlas and WRF. The calculated icing losses from SCADA are in Ice Class 3. Average rotor icing duration indicator was 31 % (not shown in Figure 6) indicating Ice Class 5 icing conditions (assuming rotor icing is equal or shorter in duration than instrumental icing).

Site B is IEA Ice Class 3. Site B has the most scatter in terms of icing indicators with WiceAtlas showing Ice Class 4 and WRF Ice Class 2 and 3. An average Ice Class of 3 is obtained from the 4 indicators. The calculated icing losses from SCADA are in Ice Class 3. As the IPS activation duration was almost zero, the SCADA icing losses can be considered as non-IPS icing losses at Ice Class 3. Average rotor icing duration indicator was 10 % (not shown in Figure 6) indicating

Ice Class 3-4 icing conditions (assuming rotor icing is equal or shorter in duration than instrumental icing).

For site C, the selected IEA Ice Class is 2. WRF analyses were not available thus only WiceAtlas is used for icing condition evaluation ending up to Ice Class 2 for benchmark period and Ice Class 3 for expected long-term icing conditions. The calculated SCADA icing losses are Ice Class 2. Average rotor icing duration indicator was 4 % (not shown in Figure 6) indicating Ice Class 2-3 icing conditions for benchmark year (assuming rotor icing is equal or shorter in duration than instrumental icing).

For site D, the selected IEA Ice Class is 4. All 4 icing indicators show IEA Ice Class 4 for benchmark year and expected long-term. The calculated icing losses from SCADA are in Ice Class 3. Meteorological icing was measured at the site with dedicated ice detectors showing an average meteorological icing duration of 7.9 % (not shown in Figure 6) indicating Ice Class 4 icing conditions. Average rotor icing duration indicator was 17 % (not shown in Figure 6) indicating Ice Class 4 icing conditions (assuming rotor icing equal or shorter in duration than instrumental icing).

IPS maturity and gain of production

Figure 7 shows example power curve plots as output from T19IceLossMethod for one example turbine per wind farm cases A,B,C,D. IEA Ice Classes (IC) and winter average temperatures are also visible per site.

In site A, the expected icing conditions are harsh at Ice Class 4 (average expected icing loss at 17.5 %) with very low winter average temperature of almost -11°C. The icing losses during normal production (red dots) had some very low values at high winds. Standstill losses (black dots) were limited and some over production (green dots) values are seen. The power performance during active IPS is mostly with normal power curve range and most of the underperformance is visible at higher wind speeds. The active IPS hours are the largest compared to sites B, C and D. The site average reference power curve uncertainty is 14 % ranging from 10 % to 28 % per turbine.

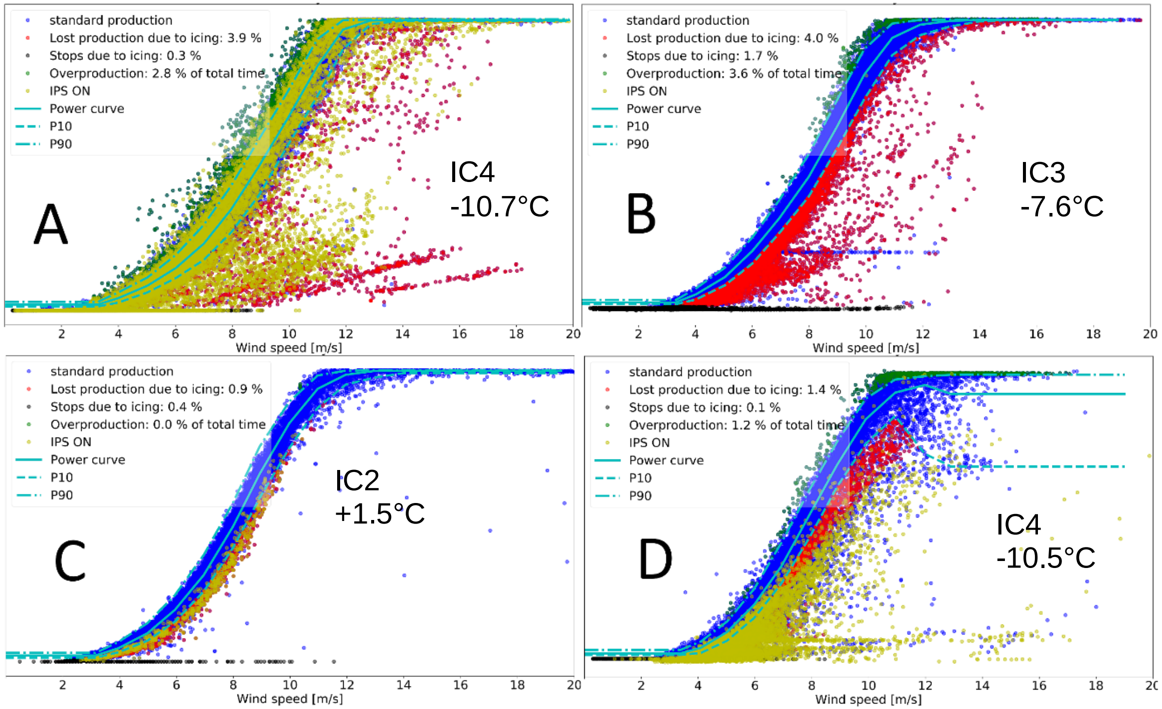

Figure 7: Example power curves from every site with different event classes coloured. (Standard production (blue), icing during production (red), stops due to icing (black), overproduction (green), IPS operational (yellow)). IEA Ice Class (IC) and winter average temperature shown per site.

In site B, the expected icing conditions are at Ice Class 3 (average expected icing loss at 7.5 %) with cold winter average temperatures around -8°C. As can be seen from site B power curve plot, the IPS was not activated at all so all icing losses are during normal production or icing related standstill. The site average reference power curve uncertainty is 13 % ranging from 12% to 15 % per turbine.

In site C, the expected icing conditions are mildest at Ice Class 2 level with warmest winter average temperature of almost +2°C. Icing losses during operation and icing related standstills are small. The power performance during active IPS is similar to icing losses without IPS. No overproduction is seen. Site C had night time noise curtailment which was filtered from the results. The site average reference power curve uncertainty is small at 10 % ranging from 9 % to 10 % per turbine.

In site D, the expected icing conditions are harsh at Ice Class 4 with very low winter average temperature of almost -11°C. The site power performance during active IPS is heavily masking other results for wind speeds below 8 m/s. Limited icing losses during normal operation and standstill due to icing are seen. Most of the underperformance is seen during active IPS. The P10 threshold value for high winds is very low due to larger scatter of power at high winds. The site average reference power curve uncertainty is largest at 16 % ranging from 12 % to 18 % per turbine.

6. Limitations and uncertainties

The main uncertainties affecting the results presented in this report can be categorized in to two main parts:

- Quantifiable uncertainties for the expected (using IEA Ice Class) and measured (T19IceLossMethod nacelle anemometry-power curve) icing losses and
- Other uncertainties from evaluation of icing conditions and SCADA data analysis

6.1 Quantifiable uncertainties

The first, and most likely largest source of uncertainty on expected icing losses, comes from the IEA Ice Class production loss uncertainty ranges. Using the IEA Ice Class average icing losses as the reference, expected non-IPS turbine introduces the uncertainty from the Ice Class loss ranges. For example, the IEA Ice Class 2 average icing loss is 2.8 % ranging from 0.5 % to 5 %. This means that an expected 2.8 % icing loss for the reference, non-IPS turbine has a ± 2.2 % uncertainty around the mean value. This is a feature of the chosen method and no uncertainty mitigation actions are performed.

The second quantifiable uncertainty source is from the T19IceLossMethod. The T19IceLossMethod uses nacelle anemometry for calculating the power curve, which introduces uncertainty to the expected, reference and measured power curves. The T19IceLossMethod itself is a sources of uncertainty regarding the results presented in this report. This is mostly due to the nacelle wind measurements being highly affected by the upstream rotating rotor resulting to high scatter levels seen in the turbine power curves.

Power curve uncertainties in the wind farms were between 10…16 % for a one-year data period. This average power curve uncertainty is larger in reality as here only the method uncertainty is calculated but not e.g. wind anemometer or nacelle transfer function uncertainty, as the parameters were not known.

The two quantifiable uncertainties can be combined using square-root summing assuming that both uncertainties are independent from each other [23]. Table 7 presents the icing loss uncertainties for the expected icing losses (derived from IEA Ice Class) and power curve uncertainty (derived from P10-P90 threshold power curve differences to the mean wind bin average power curve. Finally it is possible to calculate the gain and resulting uncertainty by square-root summing the relative icing loss uncertainty and icing loss uncertainty. As an example for site A, the gain is 1 – 8.2/17.5 = 53 %. For site A, the relative expected icing loss is 7.5/17.5 = 43 % and measured relative icing 1.3/8.2 = 16 % resulting to sqrt((43 %)^2 + (16 %)^2)) = 23 % combined uncertainty for the gain. Site B gain is 0 % because the IPS remained deactivated almost all year. Site D gain is calculated to be -11 % but is marked as 0 % in all results for clarity having an upside 9 % combined gain uncertainty. The combined uncertainty in Table 7 should be considered as a minimum uncertainty as some uncertainty sources are unknown or difficult to quantify.

Table 7. Expected icing loss observed icing loss, and gain including combined uncertainties

Site	Expected Icing Loss	Icing loss	Gain
A	17.5 ±7.5 %	8.2 ±1.3 %	53 ± 23 %
B	7.5 ± 4.5 %	6.2 ± 0.9 %	0 ± 0 %
C	2.8 ± 2.2 %	3.1± 0.5 %	0 + 9 %
D	17.5 ± 7.5 %	10.2 ± 1.8 %	42 ± 19 %

Figure 8 summarizes the performance including uncertainty and maturity of all cases analyzed as calculated in Table 7. The performance gain is the ratio of icing losses compared to site average IEA Ice Class icing losses.The full turbine winter time based availability (TBA) was chosen as the main maturity indicator. The IPS heating duration was also analysed and used as the IPS maturity indicator but these results are not shown in Figure 6.

Site A has the second highest gain of 53 ± 23 % with the winter TBA of 95 %. Other uncertainties are evaluated to have a minor impact to the calculated gain uncertainty. One turbine had a deactivated IPS indicating a small maturity challenge (not shown in Figure 6).

Site B did not have any gain as the IPS system remained deactivated almost all year (also the IPS heating duration remained zero) but the winter TBA remained high at 98 %. The uncertainty for the gain is evaluated to be 0 % as the IPS remained deactivated almost all time.

Site C average gain was also 0 % for active IPS mainly due to benchmark year having light icing conditions according to WIceAtlas. The winter TBA is the highest at 100 %. The uncertainty of the gain is 9 %. No challenges or deviations are seen on the IPS heating duration hours indicating no big reliability issues.

Site D average gain was 42 ± 19 % with the winter TBA of 96 %. Other uncertainties are evaluated to have a minor impact to the calculated gain uncertainty. No challenges or deviations are seen on the IPS heating duration hours indicating no big reliability issues.

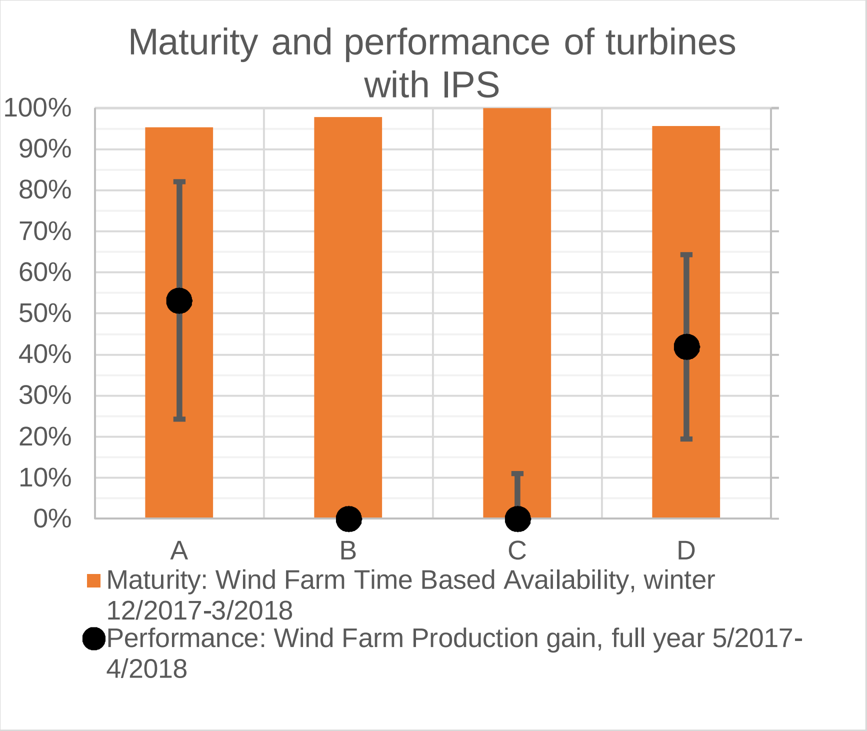

Figure 8. Summary of performance (black dots) including uncertainties and turbine maturity (orange bars)

6.2 Other uncertainties

Other uncertainties presented here are seen important to acknowledge but these uncertainties are not used in the uncertainty quantification.

First, the method chosen for evaluation of site specific icing conditions had some limitations as very limited icing measurements were available from all sites increasing the uncertainty of IPS production gain evaluation. In order the mitigate the uncertainty for evaluating the site icing conditions, both WIceAtlas and WRF were used as data sources as well as turbine SCADA data for supportive information. The WIceAtlas has shown good accuracy in predicting a site specific IEA Ice Class [24] and WRF [25] has shown good accuracy in evaluation the icing losses for pre-construction energy yield assessment in Nordics.

Second, as the other main source of the results came from wind turbine SCADA data, the analysis method encountered several challenges. Even when SCADA documentation was available, the interpretation of SCADA alarms and fault codes always includes some level of subjectivity and uncertainty. In all cases, the wind turbine operator know-how and guidance was mandatory for the analysis to proceed and to mitigate the errors from misinterpretation of SCADA data. In order to ensure comparable and benchmarkable results, all SCADA results were analysed using identical T19IceLossMethod software version with no turbine specific modifications.

Some limitations in the report are due to the data anonymization. The anonymization of wind farms prevents disclosing information that may reveal the site location. This also limits the presentation of results.

Table 8 presents the relative uncertainty quantification per site together with detailed explanations for the two main uncertainty sources:

1. Evaluation of site specific icing conditions used for calculating the IPS production gain and
2. Calculation in IPS icing losses from SCADA data

Table 8 summarizes the main other uncertainties important to acknowledge but these do not influence the final gain evaluation as these uncertainties cannot be directly quantified.

Table 8. Summary other uncertainties potentially effecting the expected IPS gain in production, reducing uncertainty marked as plus and increasing uncertainty marked as minus

Site	Icing conditions	SCADA
A	+ IC4 icing condition selection supported by all WRF showing IC4, WIceAtlas just crossing to IC5 and rotor icing duration indication of IC5 + SCADA icing losses IC3 seem logical to IC4 icing condition selection - No ice detection available	+ High winter TBA of 95 % - Large reference power curve uncertainties: site average 14 % and scatter from 10 % to 28 % in per turbine - Large scatter in intrafarm icing losses from 2 % to 14 % per turbine - IPS consumption not measured directly, mean IPS power assumed
B	+ IC3 icing condition selection supported by SCADA icing losses IC3 support as IPS not activated at all and rotor icing duration indication of IC3-4 - Large scatter between WRF and WIceAtlas from IC2-4 - No ice detection	+ Very high winter TBA of 98 % + Low average reference power curve uncertainty of 13 % - Large cold temperature bias from models vs measured - IPS activated only for some minutes
C	+ “Easy winter” IC2 icing condition selection seem logical compared to SCADA icing loss IC2, power curve plot and average rotor icing duration IC2-3 - No WRF, only WIceAtlas IC2 - No ice detection	+ Low reference site average power curve uncertainty of 10 % + Very high TBA of 100 % - No nacelle temperature, nearby met station used - Night time data filtered due to noise curtailment reducing analysed dataset by 40 % - IPS consumption not measured directly, mean IPS power assumed
D	+ All WRF and WIceAtlas show IC4 supported by available average ice detection measurements IC4 and rotor icing duration indication of IC4 + SCADA icing losses IC3 seem logical to IC4 icing conditions selection	+ High winter TBA of 96 % - Large reference site average power curve uncertainty of 16 %, challenges with mean and P10 power curve at high winds - Scatter in intrafarm icing losses from 6 % to 12 % - Issues with some temperature measurements

7. Analysis and discussion

In the best and most desirable case regarding the full turbine time based availability (TBA) seen in Figure 4 results, TBA should be higher at wintertime than for the one year average. Typical turbine maintenance is scheduled for summertime (lowering the full year TBA) and typically no maintenance is scheduled at winter time (increasing winter TBA) thus turbines should be kept at 100 % TBA during wintertime when production is highest due to high seasonal winter winds, high air densities and high electricity market prices. However, this TBA trend is clearly seen only in site C and moderately for site D. A similar trend is desirable for EBA but only site C shows this.

The site A 53 ± 23 % gain result is the highest of all cases. The high 8 % icing losses for site A seem logical as there the icing conditions are very harsh (IEA Ice Class 4) combined with the lowest winter mean temperature (almost -11°C) putting the IPS heating performance requirements to a high level. Site A has also high 1.5 % IPS self-consumption results most likely due to the severe winter conditions combined with sensitive ice detection criteria. For site A, the power performance with activated IPS in the power curves reaches the reference power curve quite often but still the icing losses during activated IPS sum up to 4 % of production. A high 95 % winter time based turbine availability (TBA) indicates a relatively high turbine maturity for severe winter conditions but some challenges are seen as one turbine in the wind farm showed an abnormal IPS heating duration (deactivated IPS for one year). The uncertainty for the gain remains the highest at ± 23 %, which mainly can be explained by the large IEA ice class 4 expected icing loss range from 10 to 25 %. Other uncertainties are expected to be low due to uniform WIceAtlas and WRF non-IPS icing loss assessment and long-term icing conditions, with most indicators showing Ice Class 4. As conclusion, site A seems like a technically reliable system but there is room for improvement in ice detection and heating control in order to boost the gain from the 8 % icing losses seen.

For site B, the gain is at 0 % as the IPS was not activated. The IPS was not activated at all with only a few exceptions summing up to an icing loss of 6 % consisting mainly of reduced production also seen in the power curves. The cause for the deactivated IPS is unknown but could be related to an ice detection issue as the SCADA ice detection signal remained zero for the benchmarking year of 2017-2018. The gain is thus at 0 % as the IPS was not activated. The TBA remains very high at 98 % for winter time but obviously the IPS has maturity challenges as it was not activated at all and this is not captured by the TBA. The energy based availability (EBA) is low at 76 % during winter time mostly due to icing losses without IPS activated (reduced power curve). The uncertainty of the results is only related to the SCADA analysis as the IPS remained deactivated most of the time. The SCADA uncertainty is increased slightly mainly due to the large nacelle cold temperature bias of -5°C and SCADA uncertainty is reduced by the smooth, site average reference power curve uncertainty of 13 % with a limited range from 12 % to 15 %. As conclusion, site B had major maturity issues.

For site C, IPS icing losses of 3 % and expected non-IPS icing losses of 2.8 % result into a 0 % gain. No substantial IPS benefit is seen in the power curve plot nor are there any substantial underperformances in the power curve indicating a mild winter in terms of icing conditions. The lack in gain may indicate that the IPS heating power or IPS control is insufficient to remove or prevent ice build-up during operation even though the site has the warmest average winter temperature at +1.5°C. In the absence of modelled WRF data and measured nacelle temperature, some additional uncertainty, regarding the production gain, is present. The system maturity is high (TBA 100 % and no IPS heating duration anomalies) indicating a high turbine level maturity and reliability for winter conditions. Some uncertainty in the SCADA analysis remains as nacelle temperature measurements are missing and substantially curtailment periods summing up to 40% are filtered out of the analysis.

For site D, icing losses of 10 % are in line with the harsh Ice Class 4 icing conditions and low winter mean temperatures resulting to a production gain of 42 ± 19 %. Even though the winter TBA is high at 96 % and no IPS heating duration anomalies are detected indicating a high turbine and IPS level maturity, winter EBA is the lowest at 73 % compared to all other sites (indicating performance challenges). The main reason for low winter EBA is that the power performance during activated IPS is still below the expected values (seen also in the power curve plot). During activated IPS, the IPS is often insufficient to recover the power performance close to expected power performance. A low IPS heating power or IPS control may be the reason for the underperformance. The gain uncertainty is reduced by the uniform WiceAtlas and WRF non-IPS icing loss assessment and long-term icing conditions. As conclusions, the system winter maturity seem high, but icing losses seem to be high for a heated turbine at 10 %. There should be room for improvement in the system performance.

In general, the icing losses and gains seen in this report are in line with publically available results from turbine OEMs and consultants for different IPS icing losses being 1 to 8 % [26], [27], [24] with production gains around 60 to 80 % [28], [29], [30], [27] compared to reference turbines without IPS.

8. Summary and conclusions

The goal of this report was to anonymously benchmark state-of-the-art wind turbines equipped with Ice Protection Systems (IPS, active blade heating using anti- or de-icing strategy) used to mitigate production losses due to icing in icing climates. The performance and maturity of Enercon, Vestas, Nordex Group and DongFang +2MW wind turbines in various icing climates was analysed using historical SCADA data. The results are presented for the benchmark period from May 2017 to April 2018.

All SCADA data was analysed using a modified T19IceLossMethod Python code and the expected, reference power curves and icing losses were extracted in addition to IPS blade heating durations, rotor icing durations, time and energy based availabilities.

In absence on fully comparable site ice measurements, weather observations (WIceAtlas) and – modelling (WRF) data was used to assess site specific icing conditions for identifying the non-IPS reference icing losses based from IEA Ice Classification. Additional, supportive information from SCADA icing losses and rotor icing durations were used to gain confidence in the site icing conditions for the benchmark period.

The IPS gain is calculated by comparing the IPS icing losses to expected, average IEA Ice Class icing losses for turbines without IPS. The full turbine maturity is analysed from turbine level winter time based availability and the IPS maturity from availability and deviation analyses of IPS blade heating durations.

An uncertainty analysis was performed regarding the gain evaluation indicating that there is some uncertainty for the calculated gains. Other, unquantifiable and potential sources of uncertainty were also documented.

As a summary, 2 sites out of 4 showed gain of production compared to reference, non-IPS icing losses. For the 2 sites that showed production gain, the average gain and uncertainty was 48 ± 21 % being comparable in lowering the IEA Ice Class icing losses by 1 class. 2 sites out of 4 did not show gain in production. The analyzed gains in this report are mostly in line with other public results for IPS production gain. For turbine and IPS level maturity, only site B showed major challenges with IPS maturity.

The different turbines equipped with IPS in various icing climates are showing promising results in the ability to mitigate icing losses. However, there are needs and opportunities to improve the efficiency and reliability of the turbine and IPS in various winter conditions by IPS optimization and increased system maturity.

9. Future work

As a next step, it is highly recommended to perform a similar analysis as described here and include more than one full year in the benchmarking period. Additionally introducing 1-2 new sites would increase the confidence in the results.

Icing conditions can have a large year-over-year variance. In light of this, looking at production of turbines with an IPS over longer time period would very interesting. Because of the large differences between icing conditions between different years, a longer term study is needed to properly capture the variance in production gain via IPS.

The relationship between gain and site is also an interesting question. From the results of this study it is hard to tell how one type of IPS would perform on different type of site. Repeating a similar study with identical turbines on two or more sites with different icing conditions would be useful to shed the light on this relationship.

On important factor to consider as well is the accuracy of pre-construction production estimates. When developing a site in icing conditions an estimate for icing losses needs to be made, the accuracy of these estimates should be evaluated against actual production.

Reducing the uncertainty of the production gain evaluation is seen as one of the most important things to consider. For example, assuming a certain turbine behaviour control strategy during icing (e.g. run with iced blades as long as possible), it is possible to substantially reduce the uncertainty of the reference, non-IPS icing loss evaluation using the IEA Ice Class. Following the IEC 61400-12 standard for power performance wind speed measurements is advised e.g. co-located met mast or remote sensing LIDAR or SODAR as the alternative source of wind measurements to increase the confidence in the measured wind speed. Alternatively knowing the nacelle transfer function (NTF) wind speed measurement uncertainty would be helpful in order to quantify the power curve uncertainty more accurately. In addition to better and more reliable wind measurements, having one deactivated IPS turbine could be realistic to reduce the reference, non-IPS icing loss uncertainties.

Acknowledgements

This report was done together in collaboration with the project steering group and with the help of an external collaboration group. The authors greatly benefitted from the active involvement of the steering group and external collaboration group regarding access to data as well as support in data analyses.

In Espoo, 12.10.2018

Ville Lehtomäki, Timo Karlsson, Simo Rissanen

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Series title and number

VTT Technology 341

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Author(s)	Ville Lehtomäki, Timo Karlsson & Simo Rissanen
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ISBN, ISSN, URN	ISBN 978-951-38-8673-8 (URL: http://www.vttresearch.com/impact/publications) ISSN-L 2242-1211 ISSN 2242-122X (Online) http://urn.fi/URN:ISBN:978-951-38-8673-8
Date	October 2018
Language	English
Pages	38 p.
Name of the project	
Commissioned by	
Keywords	Wind Power, cold climate, icing, blade heating, ice prevention
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111

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ISBN 978-951-38-8673-8 (URL: http://www.vttresearch.com/impact/publications)
ISSN-L 2242-1211
ISSN 2242-122X (Online)
http://urn.fi/URN:ISBN:978-951-38-8673-8