Icing losses - what can we learn from production and meteorological data?

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Abstract

In cold climates the performance of wind turbines may be significantly reduced by ice accretion on the blades. The magnitude of production loss has been seen to exceed 50% during winter months, and surpass 10% over the course of a year. These losses have been observed at wind farms that typically remain operational during icing conditions; higher losses would be expected should the turbines be shut down as soon as ice is detected.

DNV GL has assessed data from over 20 operational wind farms and more than 70 masts located in Scandinavia.

A strong polynomial relationship between hub height altitude and icing loss was found for all Swedish wind farms included in the study. The relationship between altitude and icing was observed to be different for the coastal Norwegian sites and those in Finland, suggesting the icing climate seems to increase in severity eastwardly. From this relationship, an icing map of Sweden has been developed which applies this function to the topography of the country.

For sites outside the map, the estimate of ice loss can rely on the correlation between icing in mast data and production losses.

Results also show high inter-annual variability in such losses (up to 65% for a site with 5% annual mean loss). Inter-annual variability in anemometer icing was found to mirror this result. A method to put icing losses into a long-term context which is based on temperature and relative humidity data from long-term meteorological station has been developed.

Keywords

Icing losses; Icing map; production data; meteorological data; altitude; Inter-annual variability; control strategy; long-term context of icing losses

1. Introduction

In cold climates the performance of wind turbines may be significantly reduced by ice accretion on the turbine blades. The magnitude of production loss can reach over 50 % during winter months, and exceed 10% on an annual basis. The impact of icing on turbine performance is therefore a challenge for developing and operating wind farms in cold climates.

The ability to correctly estimate future icing losses is of critical importance. This is an area that has seen substantial R&D effort in the past few years from the industry as a whole, and a number of sophisticated models (atmospheric and others) have been developed by the wind industry. Uncertainty remains regarding the accuracy of these models as validation is still limited and, at the moment, there is no industry wide agreed approach to estimate these losses.

In addition, icing levels are highly variable between years, leading to high uncertainty in predictions of icing from short datasets. Understanding the variability and related uncertainty in icing is therefore important in project development.

To overcome these challenges a validated method is needed to quantify the impact of icing on the performance of wind farms in the Nordic region, and to understand the variability and inherent uncertainty in these predictions. At the 2014 Winterwind conference, DNV GL presented the findings of a study of actual icing losses based on operational SCADA data collected at 10 operating wind farms located throughout Sweden [1]. This paper presents updated results considering two additional years of data from some of these wind farms, an additional 10 wind farms, along with the analysis of over 70 meteorological masts.

2. Methodology

2.1. Analysis of the production data

Data from 20 operational wind farms have been available for this research. The length of the datasets range between 1.5 years and 6.6 years and consists of turbine data recorded by the SCADA system and meteorological mast data recorded by the SCADA system. For each of the wind farms, the following analyses have been undertaken.

2.1.1. Identification of ice-induced downtime

In order to identify records where the turbines have been shut down due to icing conditions, the following analysis has been conducted:

- The 10-minute SCADA data of each turbine has been analysed to identify records where the turbines have been out of operation, e.g. ‘un-available’. This assessment has been based on a detailed review of the 10-minute nacelle anemometer wind speed, power, blade pitch angle, generator rotational speed, ambient temperature and availability counters.
- The SCADA alarm and fault data were analysed to identify periods of time where the turbines were shut down due to icing events.
- The results from Step 1 and 2 above were merged into a single dataset of icing shut-down periods.

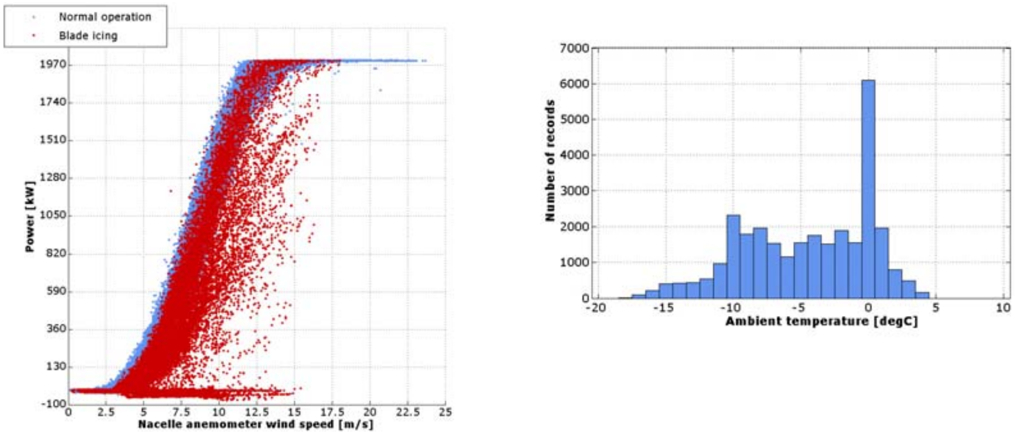
Based on the above analysis, each 10-minute record in the SCADA database was ‘flagged’ as being associated with either ‘available to operate’, ‘un-available due to icing’ or ‘un-available due to non-icing’.

2.1.2. Identification of ice-induced power curve degradation

In order to study the operating power performance of each turbine in detail, power curves have been derived from the 10-minute average turbine power and nacelle anemometer wind speed measurements recorded by the SCADA system. This assessment was conducted for all records identified as representing periods where the turbines were ‘available to operate’. The general method employed in the power curve analysis is described below:

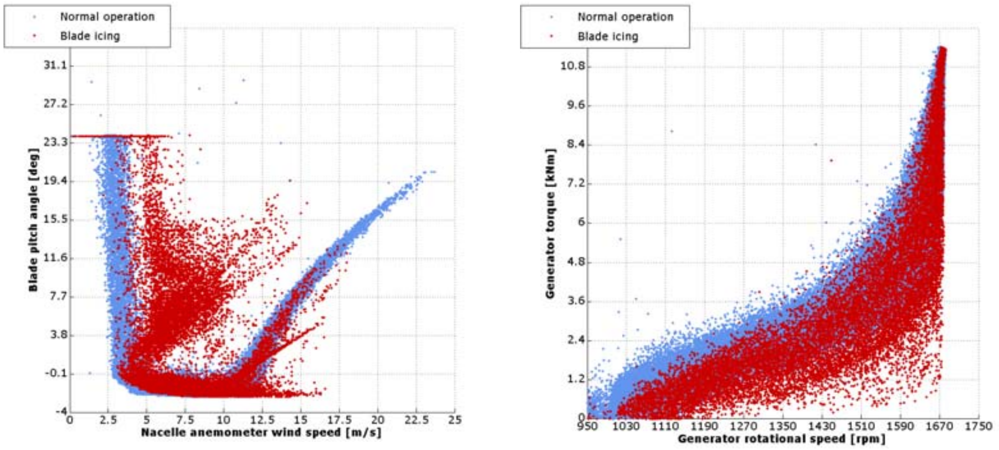
1. The consistency of the power curves measured by the SCADA system was assessed in order to identify any trends in performance between turbines and over time;
2. Any outlying turbines or periods identified in Step 1 were investigated further in order to identify:
    a. any measurement inconsistencies in the data;
    b. any systematic variations in the operation of the turbines; and
    c. any intermittent variations in turbine performance. The intermittent variations in performance included, among other issues, ice-induced power curve degradation.

Based on the above analysis, each record in the SCADA database was flagged as being associated with a specific measurement consistency period, systematic performance variation period or a specific intermittent performance issue, or not being affected by any performance issue (i.e. ‘normal performance’). Figure 2.1Figure 2 presents typical operational characteristics during blade icing events.



(a) Nacelle anemometer power curve

(b) Frequency distribution of icing temperature range



(c) Pitch control during blade icing events

(d) Speed / torque control during blade icing events

Figure 2.1 Operational characteristics during blade icing events

2.1.3. Quantification of ice-induced energy loss

In order to quantify the energy loss incurred due to icing induced un-availability and power curve degradation, the following method has been applied:

1. A series of reference power curves were derived on a per-turbine, per measurement consistency period and per calendar month basis, in order to determine a baseline level of performance that represents the normal operation of the turbines. These curves are based on the data identified as representing ‘normal performance’;
2. The energy loss incurred due to ice-induced un-availability and power curve degradation was calculated by comparing the actual power of the turbine to that expected given the applicable reference power curve and the actual observed wind speed for each 10-minute record.

2.2. Production data ice induced energy loss investigations

Following the quantification of icing losses described above, the following investigations have been undertaken.

- The ice induced energy losses for each turbine were analysed with respect to geographic location and hub height altitude in order to understand the factors determining the icing at projects. Correlations of annual icing loss as a function of hub height altitude have been derived for each individual turbine, and the same has been done for latitude and longitude.
- The benefit, in terms of avoided energy loss, of allowing turbines to remain operational during icing events has been estimated from the SCADA data analysis. This evaluation was performed by assessing the magnitude of the energy loss which would have been incurred if turbines had been shut down during periods when they were actually operational but affected by ice-induced

performance degradation. This assessment was based only on projects where the turbines remain operational during the vast majority of icing events.

- Inter-annual variability (IAV) of icing losses, as defined by the standard deviation of annual icing losses divided by the mean icing loss, has been calculated for each project with 3 or more years of data. These have then been correlated with the mean annual icing loss seen at each project.
- Using the relationship between the average annual losses observed in the operation data and altitude, an icing map has been developed for the majority of Sweden using topographical data for the country and an assumed hub height of 100m.

2.3. Analysis of pre-construction meteorological data

More than 70 meteorological masts throughout the Nordic region have been available for this research. These masts have all been historically analysed by DNV GL as part of commercial energy production assessments over the past 7 years. In the dataset over 500 individual sensors have been analysed including several cup anemometer and wind vane models, various heating arrangements and a number of ultra-sonic sensors. The datasets available were between 1 and 6 years long.

The data from the masts included in this study have each been manually inspected on a 10-minute basis to identify periods of suspected icing or partial icing. In this review icing periods are identified by comparing the wind speeds and directions between different sensors at different levels, parallel sensors at the same level, sensors with different heating arrangements and corresponding temperature and relative humidity values where available. The time spent iced at each sensor is then summed by month and the monthly averages combined into an annually representative mean.

Following the review of ice effected periods described above, the following investigations have been undertaken.

- The amount of icing observed at sensors installed in parallel or within 10 meters in height has been compared. Comparisons include anemometers, wind vanes and sonic anemometers; heated, partially heated and unheated sensors.
- Using the reviewed data from primary unheated cup-anemometers, the influence of latitude, longitude and altitude has been investigated by comparing the annually representative icing value observed for masts as functions of their location.
- The inter-annual variability (IAV) has been calculated for each mast with greater than 2 full years of measurements, and compared with the mean days of icing at the masts.

2.4. Development of a methodology for predicting long-term energy losses due to icing from pre-construction data

Following the analysis of the icing observed in pre-construction data and the energy loss due to icing in operational turbines, a methodology using anemometer icing in pre-construction data to predict icing losses during wind farm operation is presented. The annual icing loss predicted using this method is validated against the production data.

Correlations have been undertaken at a number of masts between the percentage of time iced and the average temperature and relative humidity. Thereafter, a matrix approach has been developed to consider both relative humidity and temperature and to depict the likelihood of icing under combinations of these conditions. From these matrices and reference station temperature and relative humidity datasets, a methodology to extrapolate historical icing events and inform a long-term adjustment is presented.

3. Results

3.1. Analysis of icing in operational data

3.1.1. Icing loss variation with topography

Figure 3.1 shows the correlation between hub height elevation and the annual icing loss for all wind turbines analysed in the dataset.

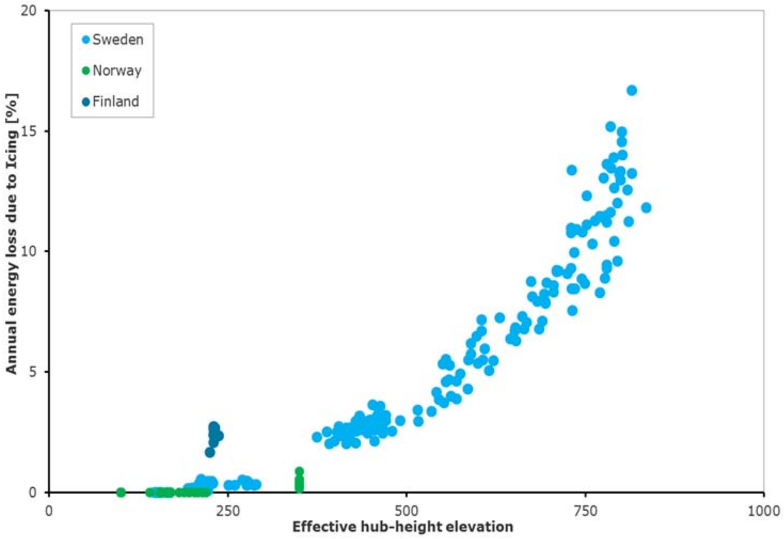


Figure 3.1 Annual production icing loss Vs hub height altitude for each of the wind farms analysed

There is a strong and non-linear correlation between icing energy loss and altitude. A similar but less strong correlation with latitude was observed, however this is due to a secondary correlation between altitude and latitude (the more northerly sites are located in the upland areas bordering Norway, and therefore also have higher altitudes).

The magnitude of the losses can be seen to vary greatly; from less than 0.5% to greater than 16% at the sites with the highest altitude. The outliers in the trend are turbines located in either Finland or Norway. From this, although the dataset in each case is small, it is suggested that a different slope of correlation may exist in these countries. Although the cause of this difference is not the focus of this paper, the influence of the Atlantic Ocean in coastal Norway and the continental location of Finland may play major roles in this difference.

3.1.2. Influence of operational strategy in the icing losses

In the majority of wind farms analysed, very few episodes of shutdown due to icing were observed, suggesting that in Scandinavia, operators prefer to keep turbines running during icing events. The observed icing losses have been compared to an estimate of the losses which would have been incurred had the turbines been shut down during icing, thus producing no power. Figure 3.2 demonstrates the correlation of energy losses between the two possible strategies. The error bars presented in the figure represent the uncertainty in the applied assumptions relating to the sensitivity of the control algorithm for ice detection and the subsequent point that shutdown occurs.

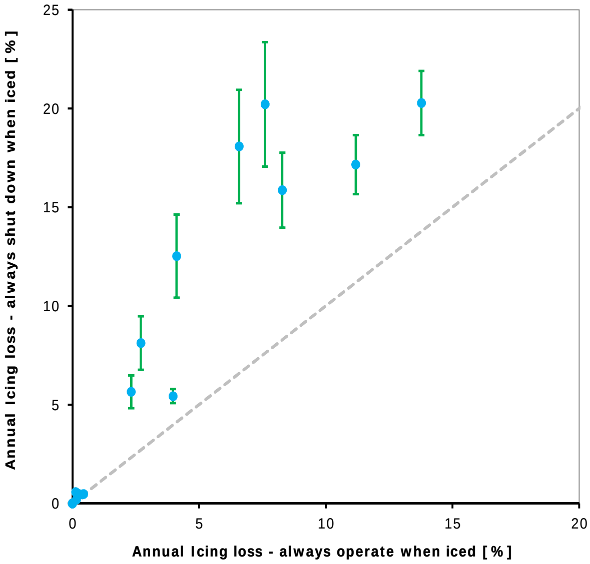


Figure 3.2 Observed annual icing loss Vs estimated annual icing loss

The results show that, as expected, energy losses when turbines remain operational during icing events are lower than for shutdown strategies. For projects in milder climates, the losses can be reduced by around 50% by allowing the turbines to remain operational during icing events. As icing losses increase, the relative benefit declines, however the absolute avoided loss is still large. This diminishing relative benefit is expected as, in harsher climates, the icing events are expected to be more severe, resulting in greater power curve performance degradation during icing events.

3.1.3. Inter-annual variability of ice loss in operational wind farms

Figure 3.4 below shows the IAV of icing losses as a function of the mean ice loss. The graph suggests that at sites with only a small energy loss due to icing, the variability in energy loss between years can be very high, at approximately 80% of the average value. By contrast, at sites with severe energy loss, the variability between years is lower, at below 40%.

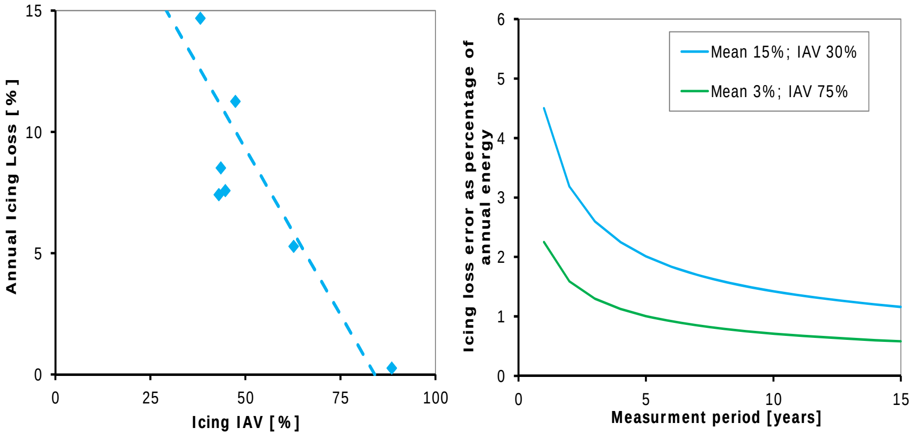


Figure 3.4 Inter-annual variability of production loss as a function of mean annual loss and the resulting expected error in icing loss predictions based on short measurement periods

Analysis of the IAV highlights the need for long datasets when predicting future ice induced energy losses. The graph to the right highlights that, at sites with for example 3% mean annual loss, the potential error can be over 1% of annual energy production for datasets less than 5 years in length; even after 15 years, the certainty in the prediction will only be ±0.5% of annual energy production.

These findings highlight two main conclusions: Firstly, there is a significant decrease in uncertainty if short measurements periods (1-2 years) are extended to approximately 5 years. Secondly, even if the long-term average loss is known, future energy losses may vary significantly from this, even when averaged over 20 year periods such as the typical lifetime of a wind farm.

3.2. Analysis of icing in pre-construction wind data

3.2.1. Sensor types

Analysis of the cup anemometry data has revealed the following:

- Partially heated anemometers, where only the shaft bearings are heated and not the cups, are affected by ice as frequently as non-heated anemometers. This is due to ice accretion on the anemometer cups causing even when the shaft remains ice free due to the heating.
- Data loss in fully heated anemometers can be reduced by as much as 80% relative to unheated anemometers. However, the benefit of fully heated anemometers is inconsistent, due to either power supply issues or the different effectiveness of heating per climate.

In addition, a number of observations were made in relation to wind vanes.

- Wind vanes suffer less from icing than anemometers. During light icing events the wind vane will still be able to indicate the wind direction even if affected by ice. Also, ice accretion rates on vanes may be lower due to their smaller frontal area and reduced rotation.

The small total number of ultra-sonic anemometers available makes the analysis of these difficult and inconclusive. Nevertheless, initial findings suggest that fully heated ultrasonic instruments can be more resistant than fully heated cup anemometers.

3.2.2. Variation with geography and height

Figure 3.5 shows the correlation between sensor altitude and number of days of icing. The graph shows a linear increase with altitude. The slope of this correlation will increase as we move eastwardly.

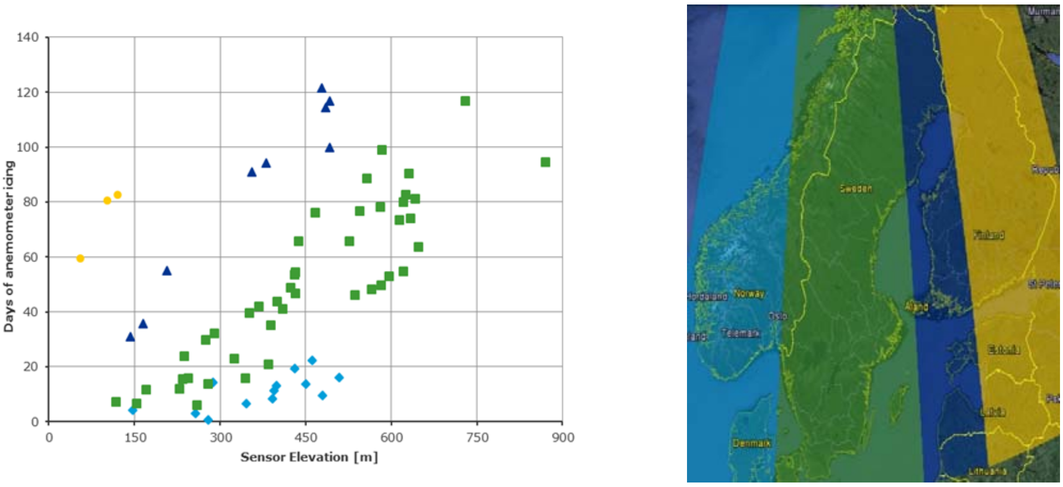


Figure 3.5 Sensor icing as a function of altitude and longitude

In-cloud icing is understood to be the main cause of icing in the Nordic region, factors such as cloud base height and fog are important and may be driving the higher level of icing in Finland and the most northerly parts of Sweden, [2][3].

The lower amount of icing seen in the coast of Norway is explained by the moderating effect of the Atlantic Ocean and the golf stream. The Gulf of Bothnia on the other hand frequently partially freezes over during winter for latitudes above approximately 63˚. Here, proximity to the sea appears to have little influence on sensor icing, particularly above a certain latitude.

3.2.3. Inter-annual variability of anemometer icing

The anemometer icing IAV has a similar general trend to the one observed in the production data, although the reduction in variability with an increase in mean icing is greater, being less than 10% at masts with greater than 90 days of anemometer icing per year.

3.2.4. Predicting long-term icing losses from mast data

The observations made in both the analysis of production and mast data with respect to altitude in Sweden suggest a non-linear relationship between anemometer icing and turbine energy loss due to icing. This non-linear relationship is explained in the following way:

- From anemometer measurements, only the duration of icing is available, not the load of ice;
- At a wind turbine, it is not only the duration of icing that determines production loss, but the ice load on the turbine, assuming that the turbine remains operational during icing events.

Therefore, the following equation can be used to describe the energy loss.

$Energy\ loss\ due\ to\ icing\ = time\ spent\ iced \times severity\ of\ icing$ **Equation 1**

The time spent iced, is given in the anemometer data. The severity nevertheless must be inferred as being proportional to the time spent iced. It is assumed that short icing events will produce less ice load than longer icing events. Therefore the following equation is found:

$Energy\ loss\ due\ to\ icing = k \times time\ spent\ iced^2$, where k is an empirical constant **Equation 2**

Equation 2 is applied to the monthly average percentage of anemometer icing and averaged using the expected monthly energy production to give an annually representative mean. This method has been applied to the masts in the Swedish dataset in order to validate it against the Swedish production data using altitude. Figure 3.6 presents the result of this.

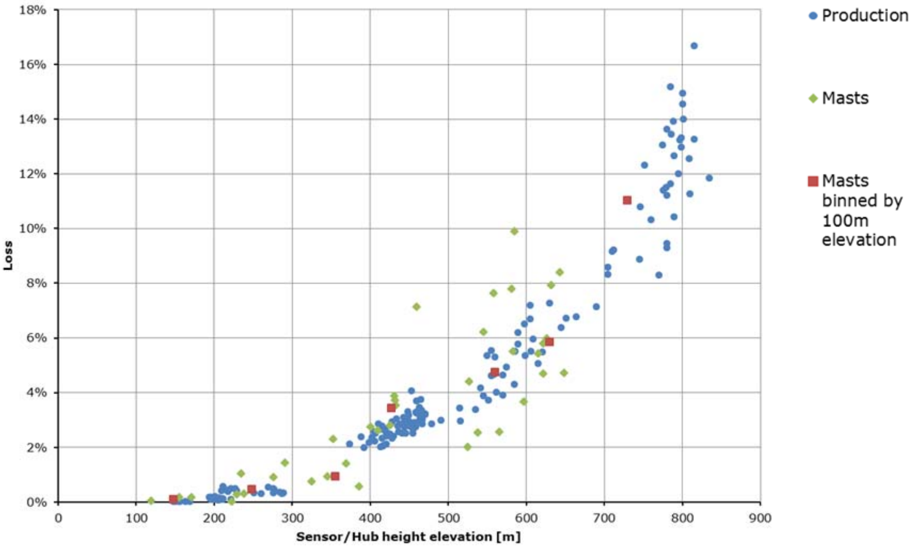


Figure 3.6 Actual and predicted icing losses in Sweden vs hub/sensor altitude

As the above figure shows, the method accurately tracks the production data trend, particularly when binned into 100 m elevation bins (red squares).

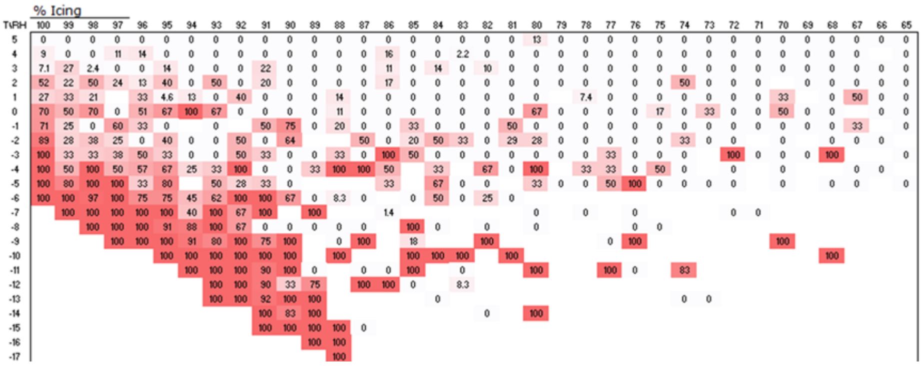
The method depends on icing observed in on-site unheated cup anemometer data and not on altitude. The method is therefore applicable even for sites where altitude is not the main driver for icing.

3.2.5. Long-term correction of icing loss predictions

A method to extrapolate historical icing events has been developed in order to assess the “iciness” of the measured period with respect to the long-term expectation. Correlations between the level of icing and either temperature or relative humidity yielded inconsistent results. That is due to icing being a function of both of these, rather than either individually. Therefore a matrix description of icing has been derived.

Figure 3.7 shows an example of such matrix. The value inside each box reflects the percentage of occurrence of icing for the corresponding conditions.

As shown, icing can occur at temperatures slightly above freezing, and it occurs more frequently in a band of conditions, typically between saturation and 4% to 5% below saturation[1]. As seen, there are some occurrences of icing outside the band referred to above, these are likely to be episodes of instrumental icing [2], however the occurrences of these is low.



% Icing

T\RH	100	99	98	97	96	95	94	93	92	91	90	89	88	87	86	85	84	83	82	81	80	79	78	77	76	75	74	73	72	71	70	69	68	67	66	65
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	9	0	0	11	14	0	0	0	0	0	0	0	0	0	16	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
3	7.1	27	2.4	0	0	14	0	0	0	22	0	0	0	0	11	0	14	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	52	22	50	24	13	40	0	50	0	20	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0		0	0	0	0	0
1	27	33	21		33	4.6	13	0	40	0	0	0	14	0	0	0	0	0	0	0	0		7.4	0	0	0	0	0	0	0	33		0	50	0	0
0	70	50	70	0	51	67	100	67	0	0	0	0	11	0	0	0	0	0	0	0	67	0	0	0	0	17	0	33	0	0	50	0	0		0	0
-1	71	25	0	60	33	0		0		50	75	0	20	0	0	33	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	33		0
-2	89	28	38	25	0	40	0	0	50	0	64			50	0	20	50	33	0	29	28	0	0	0	0	0	33	0	0		0		0	0	0	
-3	100	33	33	38	50	33	0	0	50	33	0	0	33	0	100	50	0	0	0	0	0	0	0	33	0	0	0		100	0	0	0	100			0
-4	100	50	100	50	57	67	25	33	100	0	0	33	100	100	50		33		67	0	100		33	33	0	50	0		0		0			0	0	
-5	100	80	100	100	33	80		50	28	33	0				33		67	0	0		33	0	0	50	100	0	0	0	0		0		0	0		0
-6	100	100	97	100	75	75	45	62	100	100	67	0	8.3	0		0	50	0	25	0																
-7		100	100	100	100	100	40	100	67	100		100			1.4						0		0		0				0	0						
-8			100	100	100	91	88	100	67	0	0	0	0	0		100	0		0		0				0	0										
-9				100	100	100	91	80	100	75	100		0	100		18			100					0	100						100					
-10						100	100	100	100	100	100		100			100	100	100		100													100			
-11							100	100	100	90	100	0		0	0	100		0			100			100	0		83									
-12								100	100	90	33	75		100	100	0		8.3																		
-13								100	100	92	100	100					0										0	0								
-14										100	83	100							0		100															
-15										100	100	100	100	0																						
-16												100	100																							
-17													100																							

Figure 3.7 Icing occurrences matrix, by bin of temperature and relative humidity

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[1] It is noted that measurements of relative humidity are typically calibrated according to WMO/CIMO (World Meteorological Organization/Commission for Instruments and Methods of Observations) standards, where saturation vapour pressure is always calculated with respect to water, rather than ice, meaning that below 0˚C, 100% relative humidity cannot be reached, and resulting in the slope observed in the figure.

The matrix given above is derived using site measurements of temperature and relative humidity. In order to undertake a long-term correction, an equivalent matrix is derived using a long-term reference source of temperature and relative humidity.

In deriving the long-term correction, it is important that the reference temperature and relative humidity are representative of the conditions at the site and consistent throughout the period. An illustration of the result of the method is presented in Figure 3.8 which gives the synthesised monthly average icing for the entire dataset. There is a significant variation in icing between months and between consecutive years, as given by the 12 month rolling average. This demonstrates the value in appreciating the relative “iciness” of the site measured period with respect to long-term conditions.

There are a number of uncertainties affecting the long-term correction method and therefore the results are used indicatively at this stage.

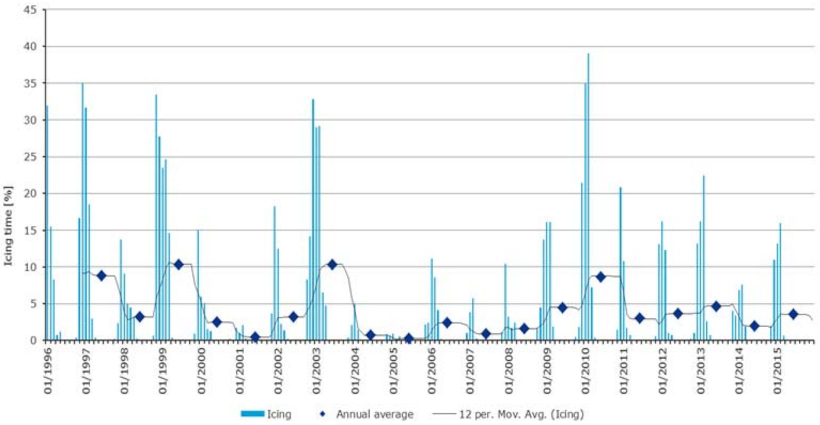

Figure 3.8 Long-term mean icing levels derived from long-term temperature and relative humidity

3.3. Icing map of Sweden

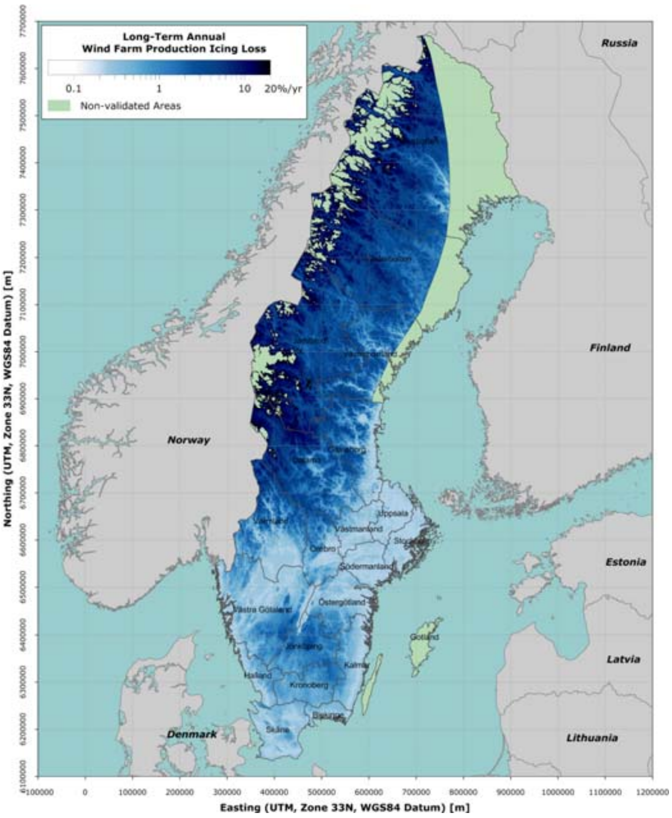

Figure 3.9 Validated icing map of Sweden derived from operational SCADA data

The relationship between hub height altitude and ice induced energy loss described in Section 3.1.1 has been used together with Sweden's topography and an assumed hub height of 100 m, to derive an icing climatology (map) for an area covering most of Sweden.

Some areas of Sweden have been excluded. For these areas and for Norway and Finland, further work is needed. The map is considered to be reasonably representative of long-term conditions as the production data used spans over a period of at least 7 years.

4. Conclusions

Based on the results of the analysis of data from approximately 20 wind farms and 70 measurement masts located across the Nordic region the main conclusions are as follows:

1. Wind turbines in the Nordic region typically remain operational during icing conditions, and thereby minimise their energy loss due to icing. Consequences to safety, noise or turbine life time have not been investigated.
2. A strong polynomial relationship between icing production loss and altitude for sites located in Sweden has been found, and used together with topographic data to derive an icing energy loss climatology for Sweden. Altitude can therefore be used as a proxy for icing loss in most of Sweden.
3. Icing climate seems to increase in severity as we move eastwardly. The slope and shape of the correlation between ice loss and altitude is likely to vary for different longitudinal areas. Further data is needed to establish this correlation and therefore an ice map of Norway or Finland has not been produced.
4. Inter-annual variability of energy losses due to icing has been shown to be high and to decrease with an increase in mean annual icing loss. The high variability highlights the need for long measurement periods, and shows that even over long periods, future energy losses may differ significantly from the historical mean. Inter-annual variability in anemometer icing was found to mirror this result.
5. Analysis of anemometer data showed unheated or partially heated cup anemometers to ice a similar amount. Fully heated anemometers offer considerable benefit in terms of reduced icing downtime; however this is inconsistent due to either power supply issues or the different effectiveness of heated sensors in different icing conditions.
6. A method has been presented and validated that converts occurrences of anemometer icing into a predicted annual energy loss due to icing. This method has also been validated on a seasonal basis.
7. A method to put icing losses into a long-term context has been developed. This is based on temperature and relative humidity data from long-term meteorological station, and matrices of frequency of icing occurrences by temperature and relative humidity.

5. References

[1] "Quantification of energy losses caused by blade icing using SCADA data, and the development of an energy loss climatology using data from Scandinavian wind farms", Staffan Lindahl, DNV GL, Winterwind 2014, Sundsvall, Sweden.

[2] "Recommendations for Meteorological Measurements under Icing Conditions" A. Heimo, R. Cattin and B. Calpini, Meteotest and MeteoSwiss, presentation at IWAIS 2009 conference, Andermatt, Switzerland.

[3] "IEA Wind Recommended Practice 13: Wind Energy in Cold Climates", IEA, Edition 2011, May 2012.