QUANTIFICATION AND ESTIMATION OF ENERGY LOSSES CAUSED BY BLADE ICING USING SCADA DATA AND PRE-CONSTRUCTION METEOROLOGICAL MASTS IN THE NORDIC REGION

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ABSTRACT

In cold climates, the energy production of wind turbines may be significantly reduced by ice accretion on the blades. Understanding the impact of icing on turbine performance and accurately predicting these at the pre-construction stage of projects is a significant challenge for developing and operating wind farms in cold climates.

DNV GL has assessed data from 18 operational wind farms located in Sweden, Norway and Finland, along with data from more than 60 meteorological masts also located in the region. From these datasets, DNV GL has investigated relationships between icing and geography, climatological characteristics, and, in the case of the meteorological mast data, the type of equipment used.

Analysis of the operational data has been undertaken to assess the energy loss due to degradation of the aerodynamic performance of the blades, and the energy loss due to shutdown of the turbines. This analysis found that at the majority of sites, the loss due to turbine shutdown is negligible, and that the turbines continue operating during icing events. Icing losses were nevertheless found to exceed 10% of annual production at some sites. Additionally, inter-annual variability of icing was seen to be high, (65% for a site with 5% annual mean loss) but was seen to decrease with an increase in mean annual icing loss.

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 in the coastal Norwegian sites and those in Finland, suggesting that different icing climates exist in these areas. From this polynomial relationship, an icing map of Sweden has been developed which applies this function to the topography of the country and an assumed 100 m hub height, and provides a powerful empirical method for estimating icing losses at proposed wind farms.

From the analysis of pre-construction meteorological data, a linear relationship between sensor altitude and the accumulated number of annual days of icing at the sensors was found for the masts located in Sweden, yet again no such relationship was observed at the Finnish or Norwegian masts. From this, it follows that the correlation between sensor icing in pre-construction data and energy loss in operational data is non-linear. A methodology that predicts the energy loss due to icing based on the square of the days of icing observed in the pre-construction anemometer data is presented. The results are then validated, giving a powerful tool, which is independent of project location, for predicting icing losses at proposed wind farm sites.

Finally, a strong relationship between temperature, relative humidity and the occurrences of anemometer icing in pre-construction data was observed, leading to the creation of matrices of these parameters. This relationship has been used to develop a long-term adjustment methodology, which can be applied to the energy loss prediction based on site measurements, using reference temperature and relative humidity data sources.

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 one additional year of data from some of these wind farms, an additional 8 wind farms located in Sweden, Finland and Norway, along with the analysis of over 60 meteorological masts located in the Nordic region.

2 METHODOLOGY

2.1 Analysis of the production data

Data from 18 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.

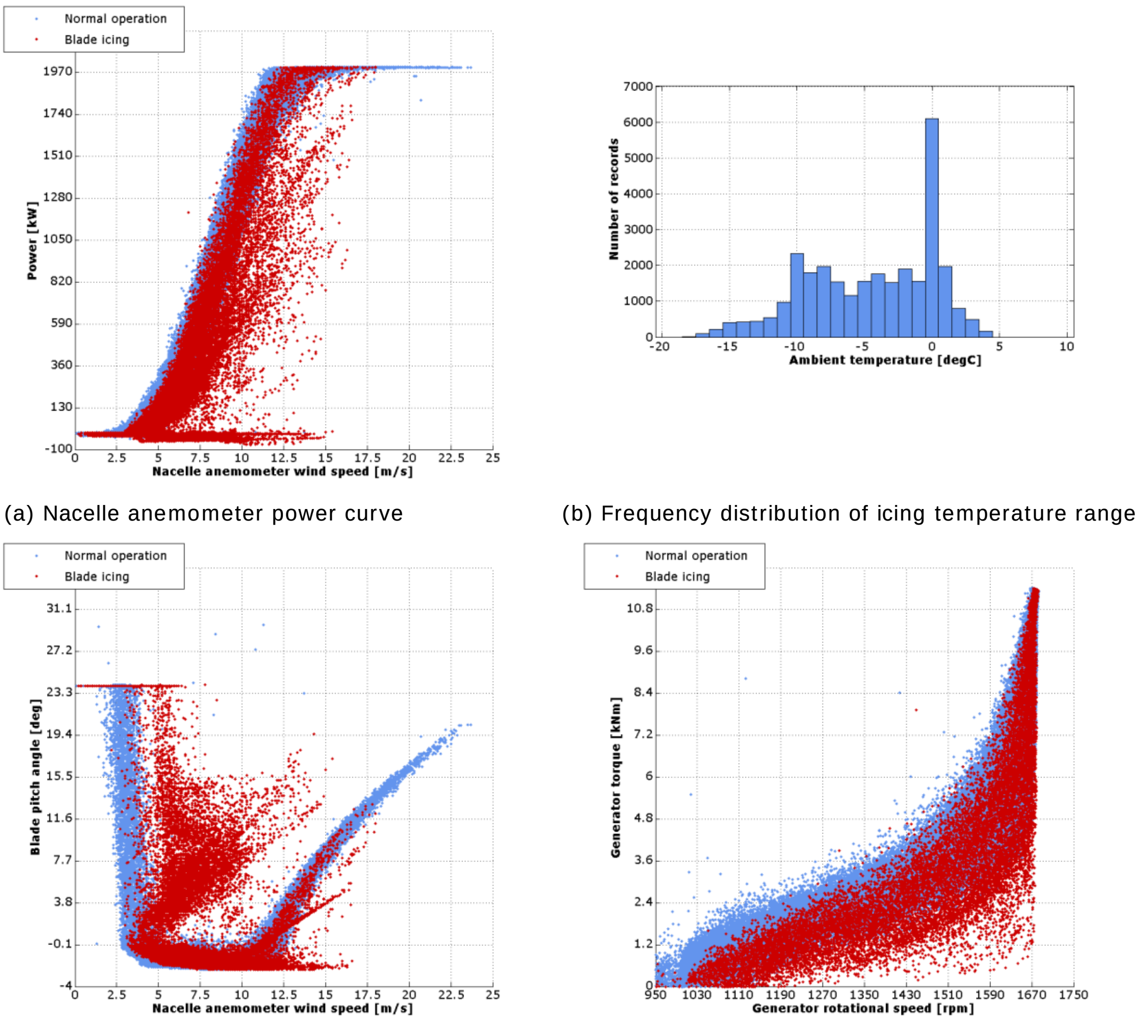
Based on the above analysis, each 10-minute record in the SCADA database was ‘flagged’ as being associated with either ‘available to operate’, ‘un-available due to icing’ or ‘un-available due to non-icing’.

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 2-1 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.
- Seasonal icing loss profiles have been derived using the Swedish production data by assuming a generic production profile for a typical wind farm, the monthly icing losses observed and the relationship found between altitude and production loss.
- 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 60 meteorological masts throughout Norway, Sweden and Finland 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 5 years. In the dataset over 450 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 5 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.
- The trend in icing with respect to sensor height above ground has been investigated by considering masts with 3 or more measurement levels equipped with sensors of the same type. The quantity of data affected by icing at each level has been compared to assess any trends with height.
- 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, and further validated on a seasonal basis along with an assumed production profile.

Correlations have been undertaken at a number of masts between the percentage of time iced and the average temperature and relative humidity. These correlations were undertaken on a range of averaging periods; monthly, 5 daily, daily and 6 hourly. 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 geography

Figure 3-1 shows the correlation between hub height altitude (or elevation) and the annual icing loss for all wind turbines analysed in the dataset. As shown, 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 thought to be due to a secondary correlation between altitude and latitude resulting from Sweden’s topography (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 15% at the sites with the highest altitude.

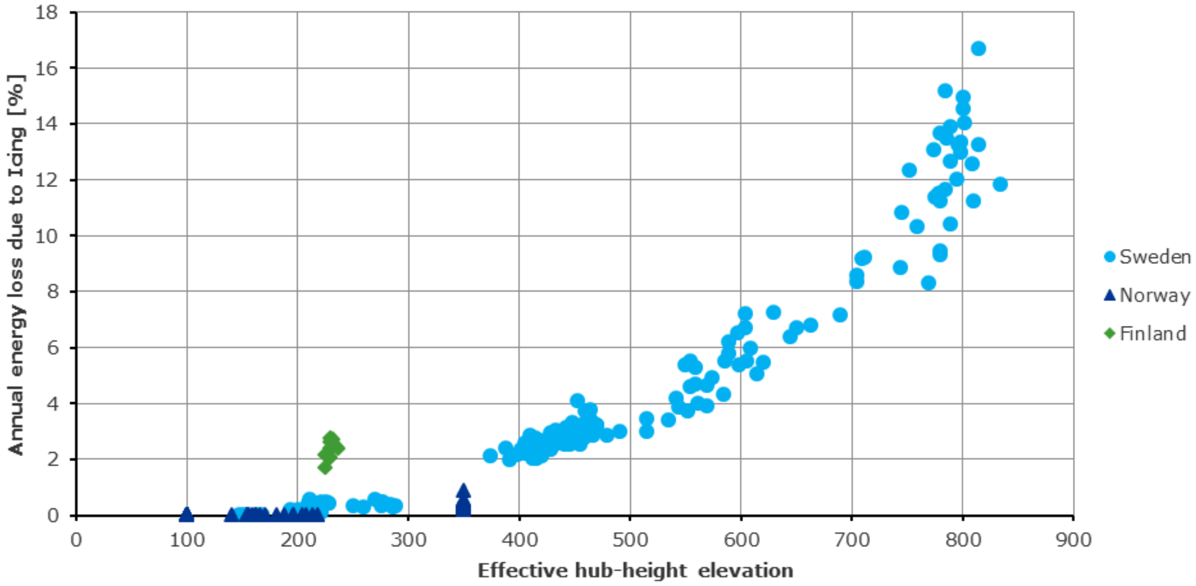


Figure 3-1 Annual production icing loss Vs hub height altitude for each of the wind farms analysed

In Figure 3-1 it can be seen that 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 other factors are the major drivers for icing 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. For regions where these factors are not influential, such as the majority of Sweden, icing losses appear to correlate well with altitude.

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.

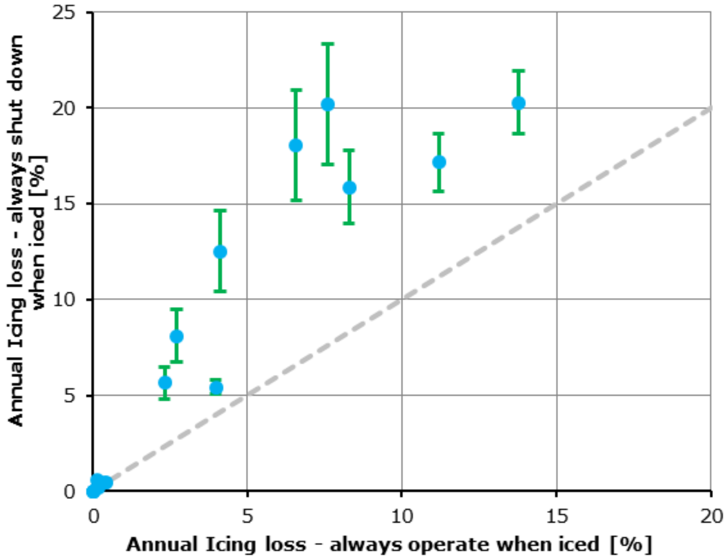


Figure 3-2 Observed annual icing loss (always operate when iced) Vs estimated annual icing loss (always shut down when iced)

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. 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 icing losses in operational wind farms

Figure 3-4 below shows the inter-annual variability (IAV) of icing losses as a function of the mean ice loss for all wind farms with 3 or more years of data. 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%.

This trend supports anecdotal evidence that in regions where cold temperatures and wintery conditions are common, there is relatively high certainty that following winters will experience similar conditions. By contrast, regions with fewer episodes of wintery conditions and cold temperatures will expect greater variation between years.

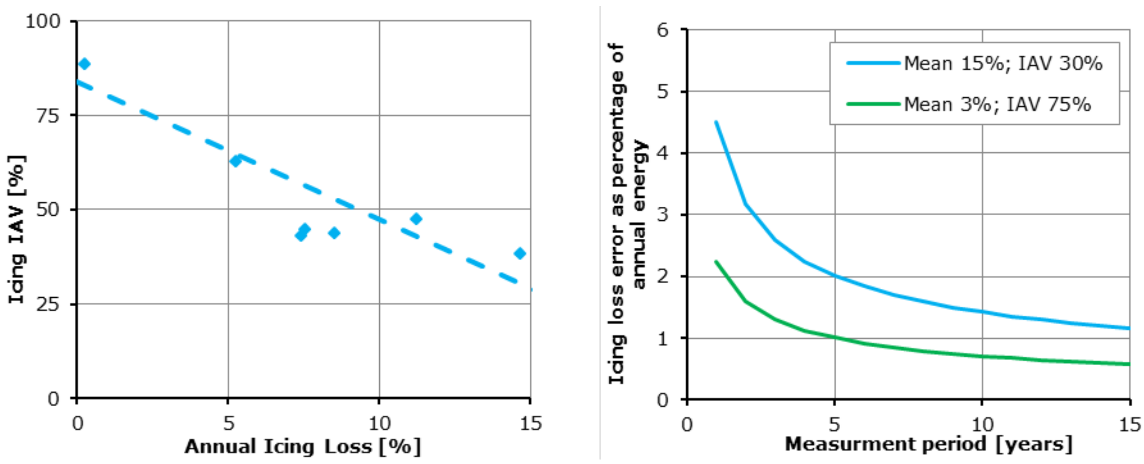


Figure 3-3 Inter-annual variability of production loss as a function of mean annual loss and the resulting expected error in icing loss predictions based on short measurement periods

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, highlighting the need for measurements of this length. Secondly, even if the long-term average loss is known, future energy losses may vary significantly from this, even when averaged of 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:

- The non-heated Thies 1st class, Vector A100 Series, NRG #40 and Risø P2546A anemometers were observed to ice to a similar degree. This result is anticipated given the similar design of these anemometers, however despite the large dataset, the exact number of comparisons is small and therefore uncertainty remains in this result.
- Partially heated anemometers, where only the shaft bearings are heated and not the cups, are believed to be affected by ice as frequently as non-heated anemometers. This is believed to be due to ice accretion on the anemometer cups causing a noticeable change in the response of the anemometer, even when the shaft remains ice free due to the heating.
- There can be clear advantages in equipping a mast with fully heated cup anemometers, as data loss due to icing can be reduced by as much as 80% relative to unheated anemometers. However, the benefit of fully heated anemometers is inconsistent, which is believed to be caused by either power supply issues or the different effectiveness of sensor heating at sites with different icing intensities.

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

- Wind vane and cup anemometer icing are not well correlated, with significantly reduced icing at wind vanes. It is thought that during light icing events where an anemometer may be caused to slow due to ice build-up on the cups, the wind vane will still be able to accurately indicate the wind direction even if affected by ice. The reduced sensitivity of wind vane icing therefore leads to significantly reduced down time. Secondly, ice accretion rates on vanes may be lower than on cup anemometers due to their smaller frontal area and reduced rotation.

The small total number of ultra-sonic anemometers available in the dataset, together with the large number of different models, 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 3-6 shows the correlation between sensor altitude and the number of days of icing for 5 regions (southern, central and northern Sweden, Finland and Coastal Norway). The graph shows a linear increase with altitude for some regions, namely those in Sweden. By contrast, the masts in Finland do not show a trend with altitude, and show significantly higher icing relative to masts at similar altitude in Sweden. In Norway, the masts show less icing and again no strong correlation.

Furthermore, Figure 3-6 highlights that within a single region, for instance central or northern Sweden, the level of icing varies greatly with the change in altitude. This shows that latitude or longitude themselves are not strong drivers in determining the level of icing.

The number of Finnish masts and their period of measurements are low and so elevated uncertainty remains in the above graph. However, sensor icing appears to be more frequent in Finland than in Sweden for sites at the same altitude. It is thought that continental influences play a significant role, as temperatures during winter are often lower in Finland than in Sweden. In addition, as 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].

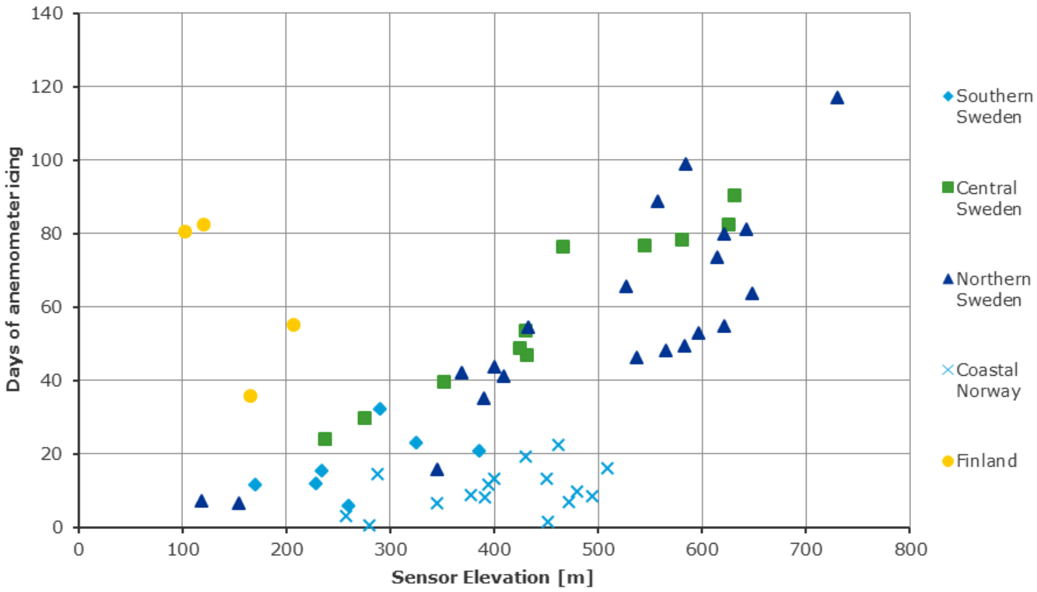


Figure 3-4 Sensor icing as a function of altitude

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.

No clear trend in the amount of icing with respect to height above ground has been found. It was observed that in the majority of cases, no significant variation in icing with respect to height above ground was present. A small number of instances showing an increase in the amount of icing with height were observed, yet very few instances showing a decrease. It is noted that independent cleaning of heights can be difficult if parallel sensors are only available at the primary measurement height, leading to uncertainty in these results.

An increasing trend in icing with height would be expected due to the temperature lapse rate and an increase in wind speed with height, which would increase the rate of water droplet impacts and therefore ice accretion on the surface of an object. It is recommended that trends in icing with respect to height above ground should be investigated at sites where the mast height is significantly lower than the proposed hub height.

3.2.3 Inter-annual variability of anemometer icing

Figure 3-7 overleaf shows the inter-annual variability (IAV) of icing. Different colours represent datasets with different measurement periods. As seen, IAV can be as high as 50% for a typical central Swedish site with approximately 40 days of anemometer icing a year. Estimating post-construction icing losses based on short periods of anemometer measurement can therefore be challenging.

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. This again highlights the need for long measurements periods, particularly at sites with an expected medium to low icing level.

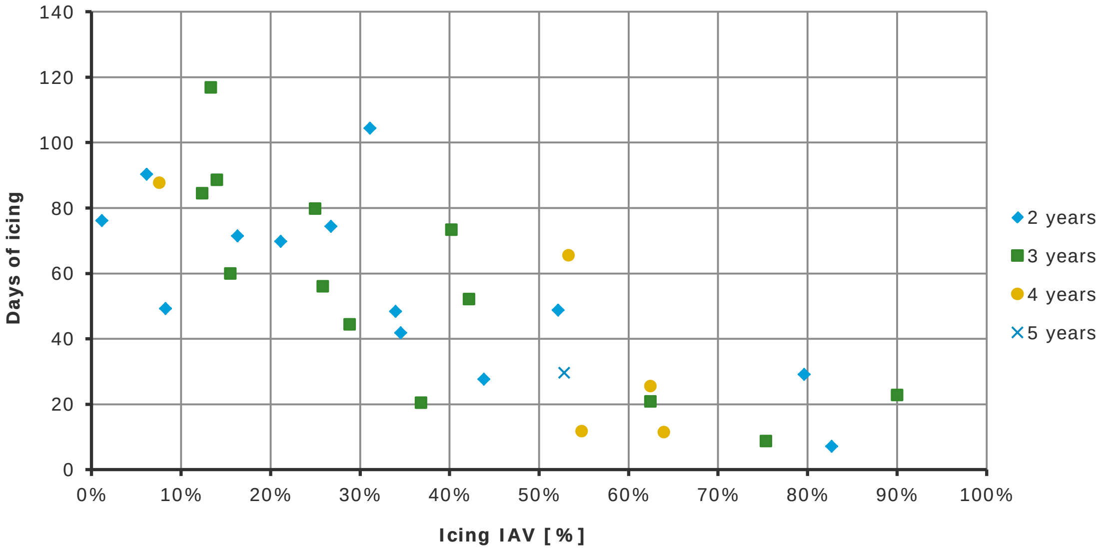


Figure 3-5 Inter-annual variability of sensor icing as a function of the mean days of icing

3.3 Predicting long-term icing losses from pre-construction data

In developing a robust methodology for predicting post construction icing energy losses from pre-construction data, the observations made in both the analysis of production and pre-construction data with respect to altitude in Sweden have been used. These are:

- Annual energy loss due to icing in production data correlates non-linearly with altitude, for the Swedish dataset;
- Anemometer icing correlates linearly with altitude, for the Swedish dataset.

These properties 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 at operational turbines.

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

As mentioned, the first input, the time spent iced, is given in the anemometer data. The severity nevertheless must be inferred as being proportional to the time spent iced giving the following:

- At sites with little icing, the ice load is assumed to be low;
- At sites with lots of icing, the ice load is assumed to be high.

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.

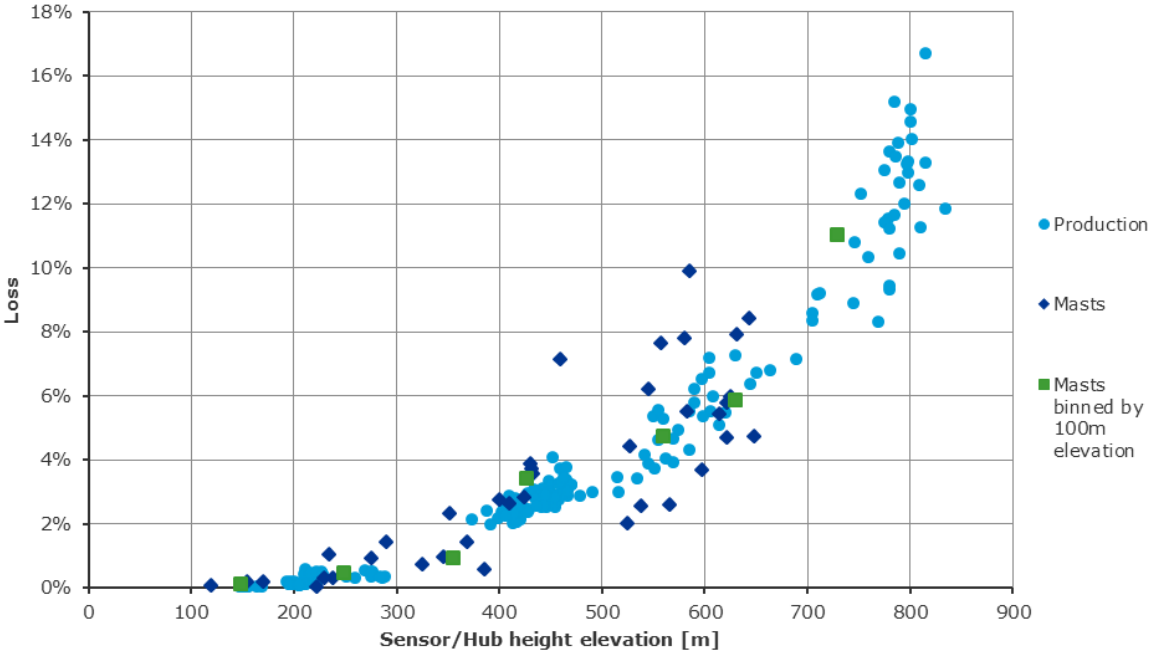


Figure 3-6 Actual and predicted icing losses in Sweden vs hub/sensor altitude

As the above figure shows, the method accurately tracks the production data trend, particularly when binned into 100 m elevation bins (green squares). The method matches the low level of loss at low elevations and the high level of loss at high elevations, and creates the same polynomial shape as the production data.

Although the method has been developed based on the Swedish data analysed here, it is thought that the underlying principles are generic and applicable to other icing climates where turbines are typically not shutdown until the performance loss is very high. 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, such as sites in Finland, Coastal Norway or Swedish Lapland.

3.3.1 Seasonal icing distribution

The method described above is undertaken on a monthly basis. The distribution of icing events is important in determining the overall loss due to the following reasoning; a site where all icing occurs in one month will derive a higher annual icing loss than a site where the icing is spread over more months, even if the total days of icing is the same. This is because the severity of icing if it occurs in one event is expected to be higher than if it is spread over the season, and this is captured using the squared relationship. Furthermore, the proportion of energy expected from each month must be considered; a site with a flat production profile will obtain a lower annual energy loss than a site with a high proportion of available energy during winter.

Due to these considerations, the method has additionally been validated on a monthly basis, as presented in Figure 3-7 overleaf.

In Figure 3-7, the energy loss profile derived from operational data (blue areas) has been derived by defining an average profile from all data in Sweden, and scaling this to the annual average for different altitudes as given in the correlation in Section 3.1.1. This profile is therefore valid only for Sweden and where the correlation with altitude is strong. The anemometer derived profiles (lines) have been defined from the binned dataset presented in Figure 3-6.

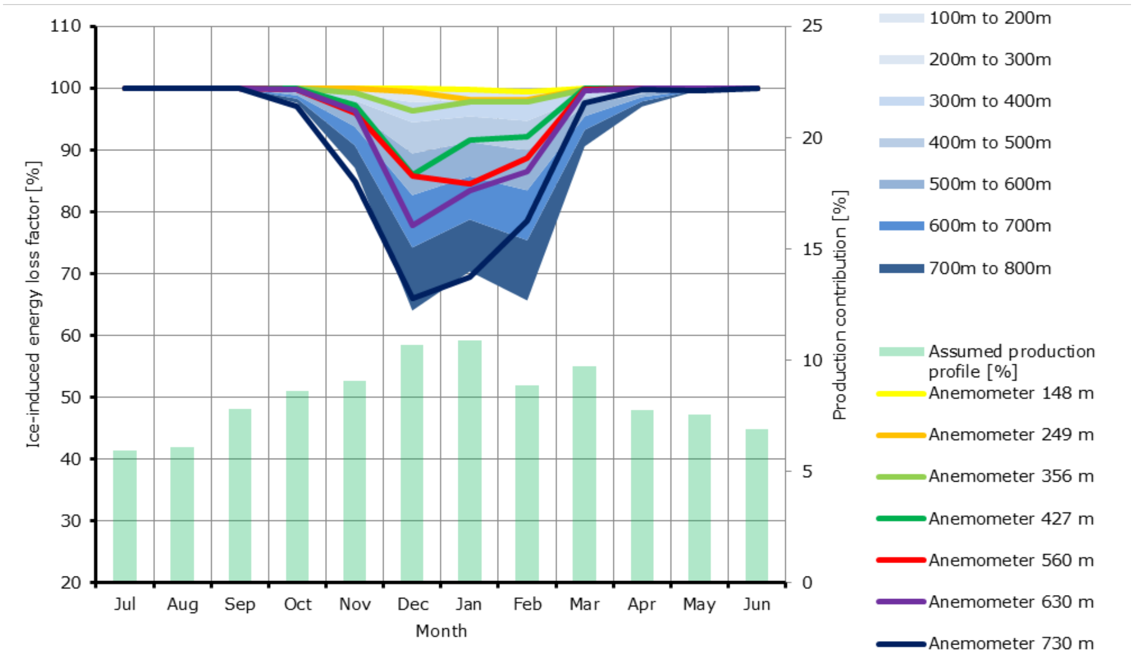


Figure 3-7 Seasonal production profile with both predicted (lines) and observed (areas) monthly ice induced energy losses for the Swedish dataset

The profiles show the winter months of December, January and February as having the greatest energy loss, with the remaining months seeing much reduced icing losses. There is uncertainty in the exact shapes of the profiles, particularly in the reduction in observed energy losses in January compared with those in December and February. It is however apparent that these 3 months suffer the majority of the energy losses due to icing, and that these also coincide with the most energetic periods of the year.

Figure 3-7 shows a good general agreement in term of shape and magnitude between the monthly observed losses and the predicted losses based on the anemometer data, for different altitudes.

3.3.2 Long-term correction of icing loss predictions

As shown in Section 3.1.3, the variability of icing between years is high. Therefore 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 on a range of averaging periods. It is thought that this 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 3-8 overleaf shows an example of a matrix of anemometer icing frequency as a function of temperature and relative humidity. The value inside each box reflects the percentage of occurrence of icing for the corresponding conditions. Blank boxes indicate such conditions never occurred during the measured period.

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. 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. 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

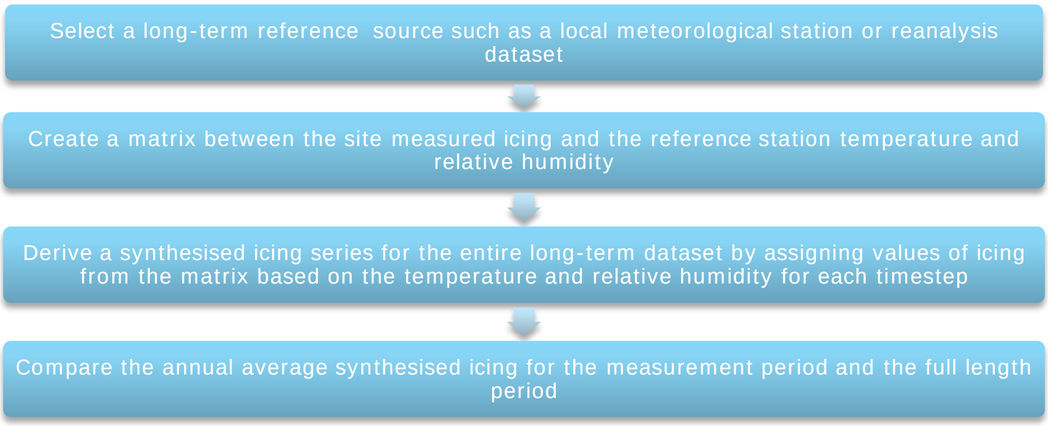
T\RH	100	99	98	97	96	95	94	93	92	91	90	89	88	87	86	85	84	83
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	9	0	0	11	14	0	0	0	0	0	0	0	0	0	16	0	0	2.2
3	7.1	27	2.4	0	0	14	0	0	0	22	0	0	0	0	11	0	14	0
2	52	22	50	24	13	40	0	50	0	20	0	0	0	0	17	0	0	0
1	27	33	21		33	4.6	13	0	40	0	0	0	14	0	0	0	0	0
0	70	50	70	0	51	67	100	67	0	0	0	0	11	0	0	0	0	0
-1	71	25	0	60	33	0		0		50	75	0	20	0	0	33	0	0
-2	89	28	38	25	0	40	0	0	50	0	64			50	0	20	50	33
-3	100	33	33	38	50	33	0	0	50	33	0	0	33	0	100	50	0	0
-4	100	50	100	50	57	67	25	33	100	0	0	33	100	100	50		33	
-5	100	80	100	100	33	80		50	28	33	0				33		67	0
-6	100	100	97	100	75	75	45	62	100	100	67	0	8.3	0		0	50	0
-7		100	100	100	100	100	40	100	67	100		100			1.4			
-8			100	100	100	91	88	100	67	0	0	0	0	0		100	0	
-9				100	100	100	91	80	100	75	100		0	100		18		
-10						100	100	100	100	100	100		100			100	100	100
-11							100	100	100	90	100	0		0	0	100		0
-12								100	100	90	33	75		100	100	0		8.3
-13								100	100	92	100	100					0	
-14										100	83	100						
-15										100	100	100	100	0				
-16												100	100					
-17													100					
-18														100				
-19																		

T\RH	82	81	80	79	78	77	76	75	74	73	72	71	70	69	68	67	66	65
5	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
3	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	50	0	0	0		0	0	0	0	0
1	0	0	0		7.4	0	0	0	0	0	0	0	33		0	50	0	0
0	0	0	67	0	0	0	0	17	0	33	0	0	50	0	0		0	0
-1	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	33		0
-2	0	29	28	0	0	0	0	0	33	0	0		0		0	0	0	
-3	0	0	0	0	0	33	0	0	0		100	0	0	0	100			0
-4	67	0	100		33	33	0	50	0		0		0			0	0	
-5	0		33	0	0	50	100	0	0	0	0		0		0	0		0
-6	25	0																
-7			0		0		0				0	0						
-8	0		0				0	0										
-9	100					0	100						100					
-10		100													100			
-11			100			100	0		83									
-12																		
-13									0	0								
-14	0		100															
-15																		
-16																		
-17																		
-18																		
-19																		

Figure 3-8 Icing occurrences matrix, by bin of temperature and relative humidity

The matrix given in Figure 3-8 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. The procedure for undertaking the long-term correction using matrices is given in the flow chart overleaf.

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. Correlations between the reference source and site are therefore critical and are undertaken before any long-term correction is made.



An illustration of the result of the method is presented in Figure 3-9 overleaf, which gives the synthesised monthly average icing for the entire dataset along with the trends in monthly average temperature (blue) and relative humidity (red and green, where the green or modified signal attempts to adjust the humidity values below zero to be representative of the relative humidity with respect to ice, and thereby result in 100% relative humidity at saturation below 0°C).

Figure 3-9 shows a significant variation in icing between months and between consecutive years, as given by the 12 month rolling average. The graph shows predicted historical periods of low icing, such as the 2007-2008 winter at this site, and those such as the years 2009-2011 with higher icing. 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.

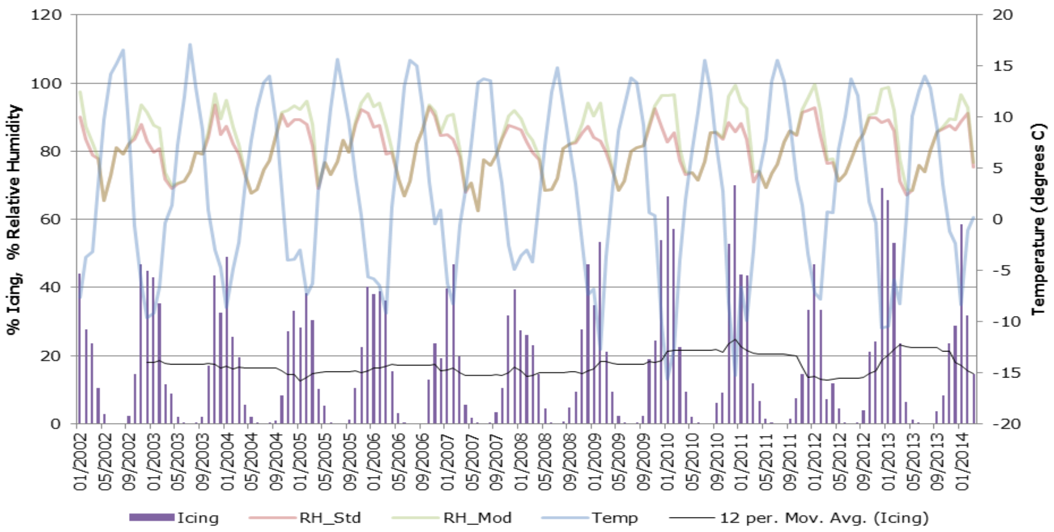


Figure 3-9 Long-term mean icing levels derived from long-term temperature and relative humidity data

3.4 Icing map of Sweden

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 100m, to derive an icing climatology (map) for an area covering most of Sweden, as presented in Figure 3-10 below.

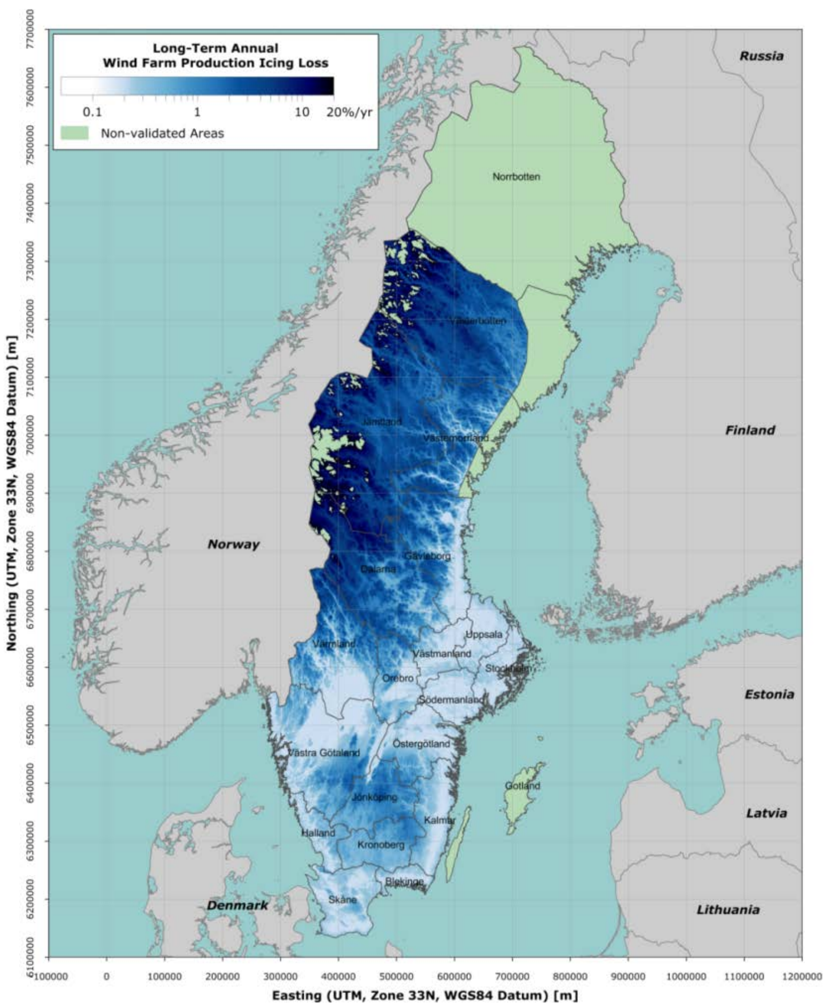


Figure 3-10 Validated icing map of Sweden derived from operational SCADA data

Some areas of Sweden, where altitude is expected to not be the only factor driving icing losses, have been excluded. For these areas and for Norway and Finland, further work is needed to investigate potential Atlantic coastal effects, effects of latitude, the influence of continental weather systems, cloud base height and other factors.

The map is considered to be reasonably representative of long-term conditions as the production data used spans over a period of at least 6 years and is spatially diverse.

4 CONCLUSIONS

Based on the results of the analysis of data from approximately 18 wind farms and 60 measurement masts located across Norway, Sweden and Finland 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.
3. The relationship between altitude and energy loss appears to be less strong in the north of Sweden and Norway, and it is thought that the relationship does not exists in Finland where the icing climate is believed to be more severe.
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 linear relationship between the days of icing and altitude has been found in the Swedish data, yet no correlation was found between altitude and icing at the coastal Norwegian masts or those in Finland.
7. 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.
8. 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 or reanalysis datasets, 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.