Site assessment for a type certification icing class

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1. Introduction

Icing climate has recently received much attention thanks to commonly favorable wind conditions and mostly low populated areas. On the other hand, the structural safety and reliability of wind turbines can be affected as well as the economic efficiency [1]. Present international guidelines and standards [2], [3] focus on the structural safety under normal climatic conditions, but consider icing effects only to a limited extend. A consortium among research institutes (VTT, Fraunhofer IWES, TechnoCentre éolien), wind turbine manufacturers (Senvion) and certification bodies (DNV GL) has started the international research project IcedBlades to improve the reliability of wind turbines under icing climate conditions [5]. The results, as the aerodynamic and structural modelling of blade icing with respect to wind turbine loading, have already been included in the new edition of IEC 61400-1 [4] (under development). However, especially site assessment for icing conditions is described only to a very marginal extend in all guidelines and standards. Site assessment is essential to judge whether a specific site showing icing conditions requires turbines with icing class type certification or not. Presently, DNV GL is developing a recommended practise for the certification of wind turbines under icing conditions.

2. Objectives

This publication intends to describe the required site assessment for icing conditions, based on different procedures. The icing duration is the main parameter to judge whether a specific site showing icing conditions requires turbines with icing class type certification or not. For wind turbine fatigue loads the icing duration may be of significant importance. The icing intensity as well as wind turbine extreme loads due to icing have been found to be negligible in general [1]. Based on this, the site conditions can be connected to the type certification icing class, as being proposed in [1].

3. Approach

According to [7] different icing durations can be determined: Meteorological icing is the period during which the meteorological conditions allow ice accretion; instrumental icing is the period during which the ice is present/visible at a structure and/or a meteorological instrument. For a wind turbine the rotor icing duration is of main interest. This is the period during which ice is present at the rotor blade. Rotor icing can be conservatively set equal to the instrumental icing duration. Different approaches to determine the different icing durations are described and evaluated in this presentation for the example site “Rödeser Berg”. The reference site of Fraunhofer IWES is located in an icing relevant area in the middle of Germany, at 385m ground height above sea level, where a 200m meteorological mast is installed. The mast is equipped with more than 40 meteorological and wind sensors that provide detailed information about atmospheric conditions, see Figs.1 and 2.

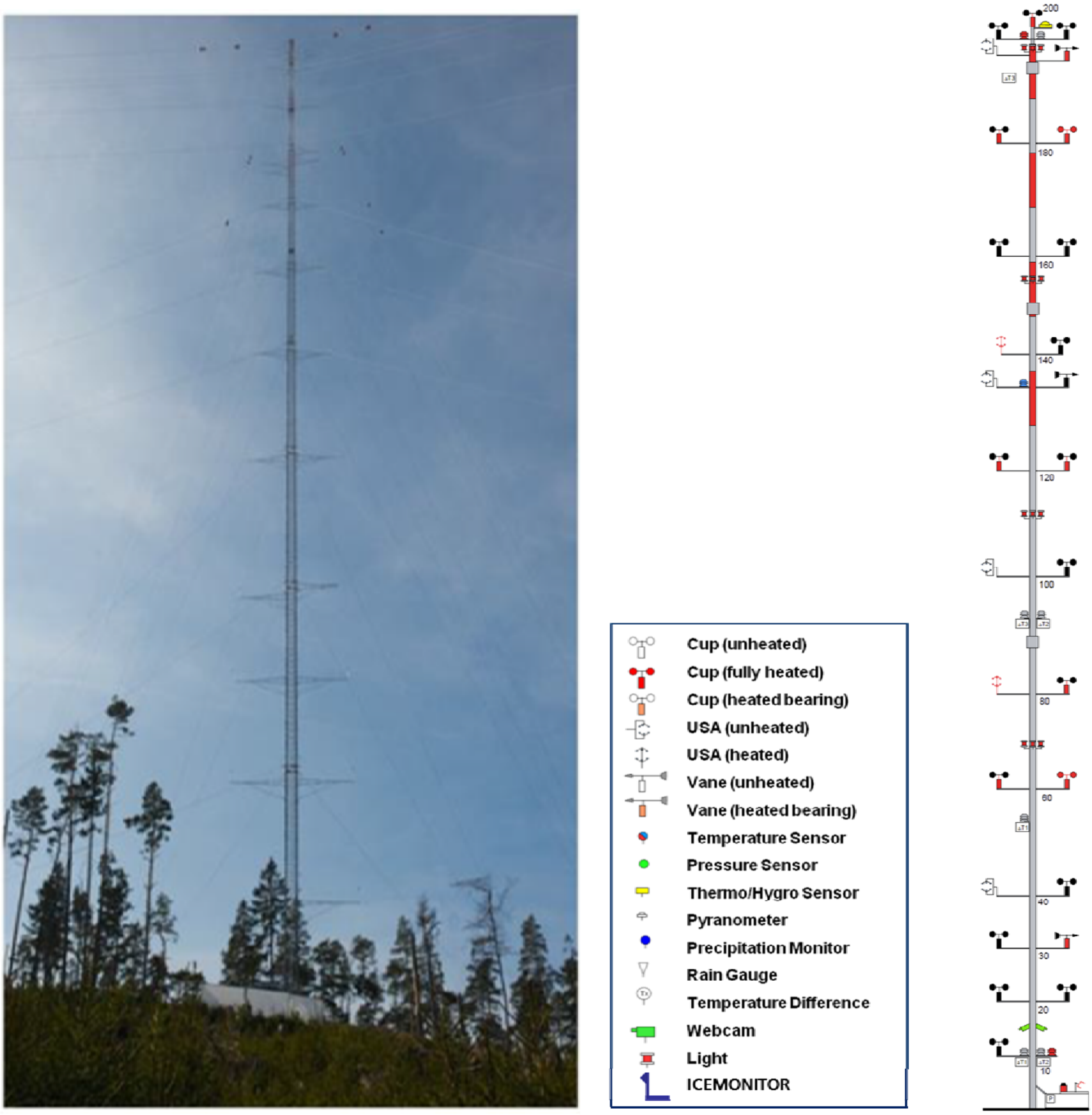

Fig. 1: Met mast Rödeser Berg and sensor locations

Four general approaches are used to estimate the icing duration:

1. Measurements of instrumental icing using ice sensor ICEMONITOR and camera installed on the met mast, based on manual evaluation.
2. Measurements of instrumental icing at several heights between 60m and 200m with double anemometry technique using heated ultrasonic and unheated cup anemometers, and using additionally temperature and humidity data. This approach combined with manual camera verification is used as reference for other approaches.
3. Measurement of meteorological icing from the mast using air temperature, relative humidity and wind velocity data

   3.1 and application of machine learning procedures, developed with the Rödeser Berg data [8],
   3.2 and application of machine learning procedures as for 3.1 and additionally application of a ceilometer
   3.3 application of boundary conditions for air temperature and relative humidity as found in 3.1 (no application of machine learning procedures and ceilometer)
4. Application of different icing atlases.

The above listed approaches are applied to one example site “Rödeser Berg”. The approaches are compared to each other. Requirements for the necessary data acquisition and its quality are listed.

Fig.2: Top view of Iced met mast with ice sensors, camera and anemometry, middle icing intensity

4. Results

Figure 3 displays the results of the approaches 1 to 3.3 for one example time series of four days in winter 2014/2015. Figure 4 shows the camera image for the central date 13/02/2015. Table 1 lists all determined icing durations.

Approach 1: Measurement of instrumental icing using ice sensor and camera

Data from the camera (upper plot, magenta crosses) has been manually evaluated and is used as reference value. Icing observed by the camera is indicated by the light blue bar “instrumental icing”. The ice sensor ICEMONITOR (upper plot, red line) shows an ice built up over one and a half days, followed by a sudden drop. This was caused by shift off of a big part of the ice package from the rotating cylinder of the sensor. Due to the accuracy of at

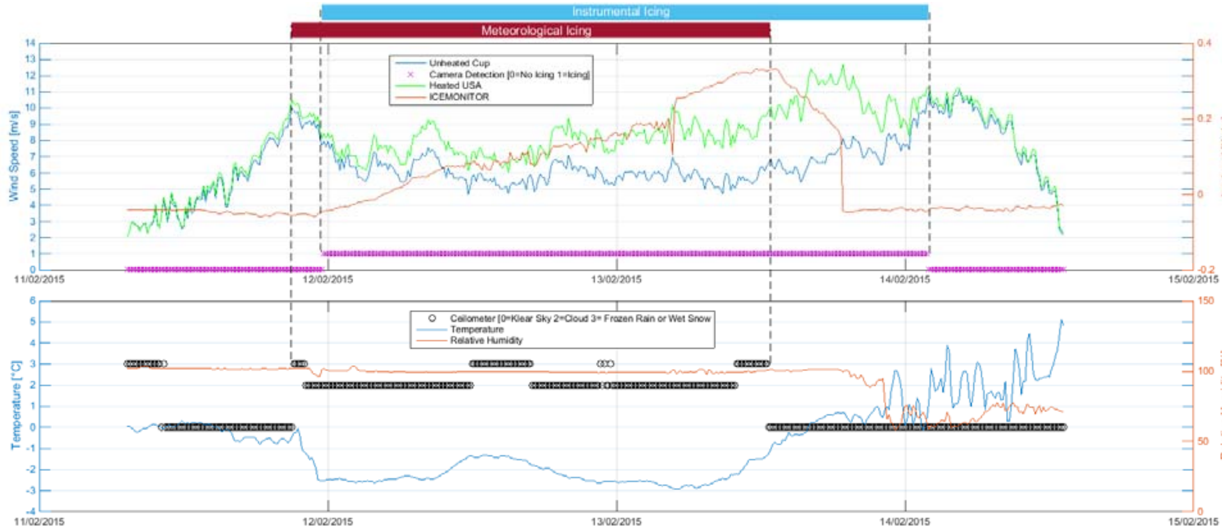

Fig. 3: Example time series for approaches 1 to 3.3

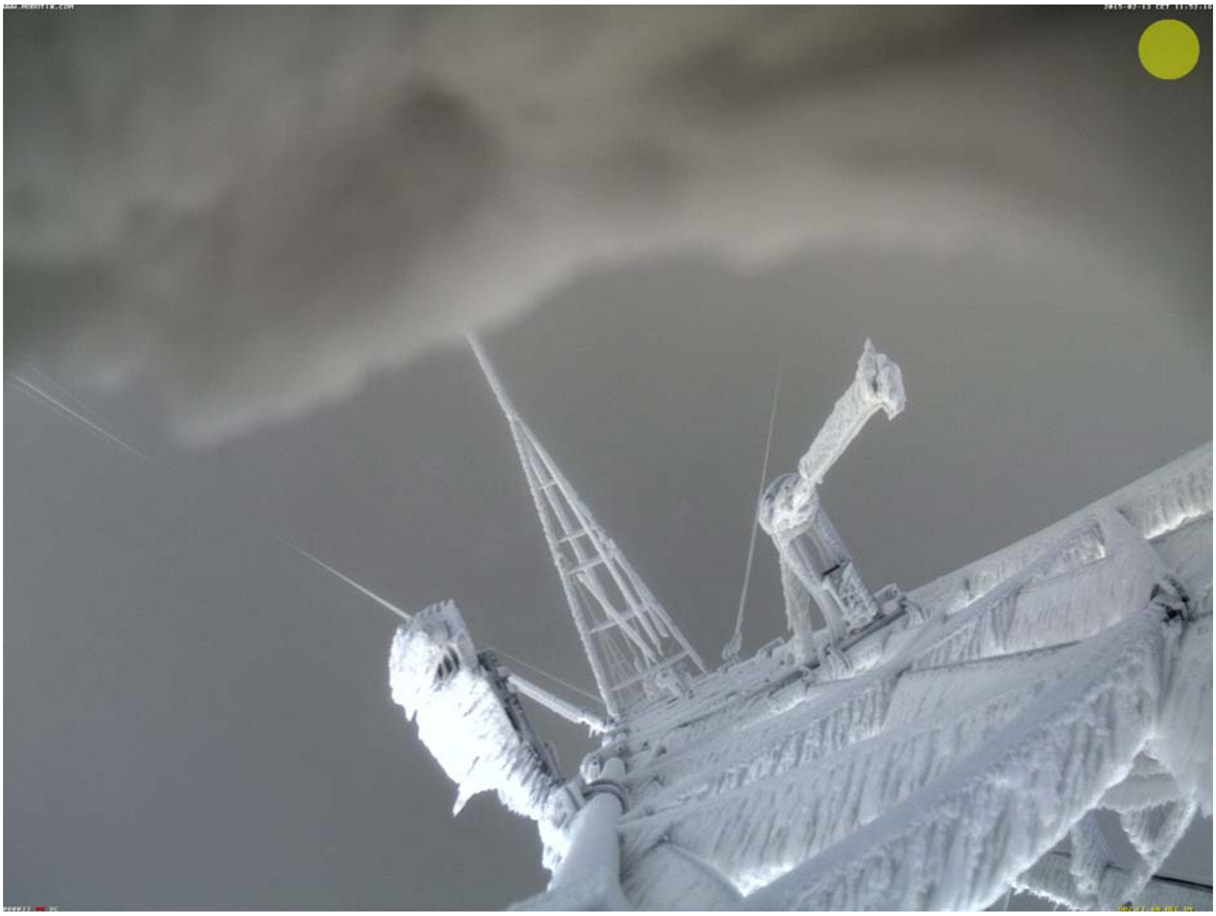

Fig. 4: Camera image on 13/02/2015 with high icing intensity

least +-50g light ice built up on the sensor was not detected. Additionally, the heating was not always capable to keep the bearing ice free that can lead to false results (fluctuation and negative values).

Approach 2: Measurement of instrumental icing using double anemometry
Instrumental icing was determined by a measured difference between the heated ultrasonic anemometer used as reference (upper plot, green line) and the unheated cup anemometer (upper plot, blue line). The instrumental icing causes a partial or full blockage of the rotating cups. The minimum value for the measured difference between heated and unheated anemometer was determined to +0.5m/s, being at least twice the sum of the two uncertainty ranges of both anemometers, here ±0.1m/s each. Sufficient and reliable power supply for the heated anemometer must be ensured also (and especially) under harsh winter conditions. Additionally, the maximum temperature (lower plot, blue line) was determined to +2°C and for the start of the instrumental icing (appr. first two hours) the relative humidity (lower plot, red line) was determined to be minimum 95%. The relative humidity can later drop significantly below 95% while the instrumental icing still remains, see last few hours of indicated “instrumental icing” where the relative humidity drops even below 70%. This approach of double anemometry measurements of instrumental icing was verified by the camera observations. Figure 5 shows the instrumental icing durations for the four observed winters 2012/13 to 2015/16 at met mast heights from 10m to 191m above ground level (agl). The first winter was comparable harsh, with up to 770h of instrumental icing at 191m, while the following three winters showed between 150h and 280h of instrumental icing there. The strong vertical gradient, as most distinct for winter 2012/2013, might be caused by

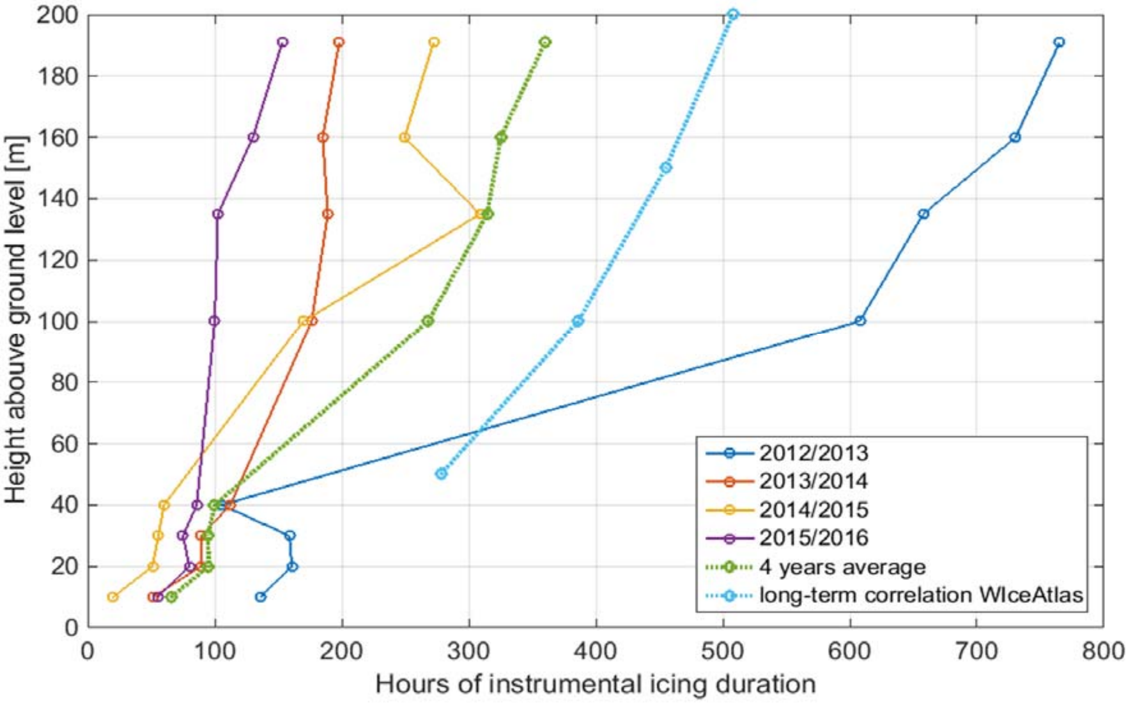

Fig.5: Instrumental icing duration for four winters 2012/2013 to 2015/2016 at different met mast heights and according to WIceAtlas data

shadowing effects from the surrounding forest with tree heights of approximately 40m to 50m agl. Another interesting aspect of Fig.5 is the partially reverse vertical gradient, showing decreasing icing duration for increasing height agl (as in winter 2013/2014 at 140m to 160m agl). The reason is probably a limited vertical cloud thickness, where the upper met mast sticks out of the cloud.

Approaches 3.1 to 3.3: Meteorological icing measurements

The determination of the icing duration based on meteorological data has the advantage, that already existing and rather easily to acquire measurements from weather stations can be used, as e.g. wind speed, relative humidity and temperatures. For this data set, a machine learning algorithm has been developed to learn the occurrence of icing at Rödeser Berg based on wind speed, relative humidity, temperature. The verification data set for the learning part were again the camera observations. As a consequence, approaches 3.1 and 3.2 determine the instrumental icing duration by using meteorological data. Since a large part of the available data set had to be used to train the algorithm, only roughly two months could be used to apply the procedure. The accuracy of the icing duration was estimated to 90% for this approach 3.1, which is considered to be good. The instrumental icing duration was determined to 135 h/a for winter 2015/2016 and 693 h/a for the harsh winter 2012/2013 by applying the accuracy of the of the machine learning algorithm on the results of approach 2. However, the results are probably fairly site specific. For a general statement on the transferability to other sites, more testing on this procedure has to be done. For details see [8]. More general methodologies for the meteorological icing duration have also been developed, using additional weather parameters as e.g. cloud base height, liquid water content and medium volume size [7]. In Fig.3 the output of a ceilometer is given (lower plot, black circles), indicating clear sky (level 0), rain (1), clouds (2), frozen rain or snow (3). However, for typical wind turbine application with blade tip heights up to 200m or 300m the ceilometer worked not very stable. For approach 3.2 additionally the ceilometer data were used as input to the machines learning algorithm. For this purpose the ceilometer data differentiated only between clear sky (0) and not clear sky (1, 2 or 3). This increases the estimated accuracy to 98%. The instrumental icing duration was determined to 147 h/a for winter 2015/2016 and 755 h/a for the harsh winter 2012/2013.

Approach 3.3 applies only the boundary conditions for relative humidity (> 85%) and temperature (< 0°C) determined in approach 3.1 for the same data set. As a consequence, this approach 3.3 determines the meteorological icing duration based on meteorological data. This approach is presently widely used for site assessment. Here, the results can be compared to the more sophisticated ones for the site Rödeser Berg. Approach 3.3 overestimates the meteorological icing duration with 820 h/a for the harsh winter 2012/2013. Ice formation depends on four parameters: Temperature, wind speed, liquid water content in the air and water droplet size. High relative humidity is an indicator of the existence of liquid water content in the air, but information about droplet size remains unknown. Small air droplets mainly do not produce icing despite a height relative humidity. This is why the overestimation was expected [10].

Approaches 4.1 and 4.2: Icing maps

Wichura [6] (approach 4.1) presents an icing map resp. equation for Germany, based on long term weather station data, but with limited spatial resolution. For the site Rödeser Berg about 360 hours per year meteorological icing at about 10m above ground level are determined. The also given mean conversion factor meteorological to instrumental icing duration of 1.3 leads to an estimated instrumental icing duration of about 470 hours per year at 10m agl.

Figure 4 shows between 20h and 130h of instrumental icing at 10m agl and between 150h and 770h of instrumental icing at 191m agl at Rödeser Berg. The icing map and appropriate equation [6] have been generated using ground based data. Their application to heights above ground exceeding 10m agl is not possible, since effects like in cloud icing are not considered in the approach by Wichura [6]. This makes a direct comparison of [6] and Rödeser Berg data difficult for met mast heights above 10m agl.

The “WIceAtlas map” [9] (approach 4.2a) categorizes the entire land surface of the earth based on long-term data according to the IEA ice classes [7] referenced for 150m agl. For the site Rödeser Berg ice class 2 is observed, i.e. 0.5% to 3% meteorological icing (=44h to 260h) and 1% to 9% instrumental icing (=88h to 790h) per year. Based on the “WIceAtlas map” [9] an evaluation with a high spatial resolution for the site “Rödeser Berg” at different heights has been carried out for the instrumental icing duration (approach 4.2b). For 50m agl a duration of 278h/a, for 200m agl a duration of 508h/a has been determined. According to [6] and [7] icing atlases should be used only as a first approximation for the icing duration, unless a high spatial resolution is provided. Specific site conditions (e.g. exposures, sheltering) might not considered.

Conversion factor meteorological into instrumental (rotor) icing duration:
In case the meteorological icing duration is measured, a factor can be determined to convert this duration into the instrumental icing duration. Based on various long-term investigations across Europe and Northern America IEA [7] has determined this factor to 2 to 3, depending on the IEA ice class. Wichura [6] determines a factor of 1.2 to 1.7 with 1.3 as the mean

Approach and measurement height above ground level (agl)	**Meteorological icing duration (hours/year)**	**Instrumental icing duration (hours/year)**
1. IceMonitor (145m)	44 – 211 *	61 (winter 2015/16) – 296 (2014/2015)
2. Instrumental icing (double anemometry + relative humidity + temperature + camera) (191m) (reference)	107 - 550	150 (2015/2016) – 770 (2012/2013)
3.1 Relative humidity + temperature + wind speed for machine learning algorithm (135m)	96 – 495 *	135 (2015/2016) – 693** (2012/2013)
3.2 Relative humidity + temperature + wind speed + ceilometer for machine learning algorithm (135m)	105 – 539 *	147 (2015/2016) – 755** (2012/2013)
3.3 Relative humidity > 90% + temperature < 0°C (135m)	820 (2012/2013)	1148 *
4.1 German icing map (10m)	360	470
4.2 a WIceAtlas map according to IEA ice classes (150m)	44 - 260	88 - 790
4.2 b WIceAtlas map detailed (200m)	363 *	508
* this data has been determined by multiplication with resp. division by the conversion factor meteorological into instrumental icing duration of 1.4 ** this data has been determined by applying the accuracy of the machine learning algorithm on the results of approach 2		

Table 1: Comparison of all available data evaluations and calculations

value. For the examined site Rödeser Berg a mean factor of 1.4 for the examined winters 2012/2013 to 2014/2015 was determined. This was done by comparing the instrumental icing duration according to approach 2 with the meteorological icing duration according to approach 3.1 (and additionally using a ceilometer for reference) applied to the same set of data.

Long term corrections:
As already seen in Fig.5, significant variations of the icing duration with factors up to five occur among different winters. The four years average shows still a factor of more than two, compared to the different winters. Based on the “WIceAtlas map” [9] a long-term averaged evaluation has been carried out with a high spatial resolution for the site “Rödeser Berg”. A very similar vertical gradient can be observed between the four years average and the “WIceAtlas map” data. A correction factor of about 1.3 can be determined, indicating that the four measured winters show a lower icing duration than what can be anticipated in the long run. Consequently, icing durations need to be measured over a longer period, covering at least 10 years. As an alternative, short term measurements (covering at least one year) must be corrected using long term correlations e.g. from nearby weather stations, airports or icing maps with a high spatial resolution. The icing map [6] provides only rough indications, due to the limited spatial resolution and lack of specific site condition consideration.

All evaluated and calculated data based on the different approaches for the site Rödeser Berg are listed in table 1. All values indicated with an asterix (*) have been calculated by multiplication with resp. division by the determined conversion factor of 1.4.

The presently drafted IEC 61400-1 edition 4 [4] recommends 750 hours/year rotor icing as long-term average for a standard icing site if no other information is available. Turbines designed according to this drafted standard [4] would fit to the site Rödeser Berg.

5. Conclusions

The following conclusions can be drawn:

- Main conclusion: Different approaches based on different data sets can be used to determine the rotor (=instrumental) icing duration of wind turbines at a given site. This rotor icing duration can then be compared with the proposed ice class for type certification [1] to judge whether a turbine with ice class certification is required for this site.
- For the investigated site “Rödeser Berg” instrumental icing durations at 50m/100m/150m agl of about 278h/386h/466h per year according to a long term correlated icing map and about 110h/268h/325h per year according to a four years average based on a measurement campaign have been determined. Yearly variations can be as large as a factor of five. The icing class for type certification according to [1] proposes to determine turbine loads with 720h icing per year, while up to 168h icing per year are covered by the standard (ice free) wind turbine class under certain conditions. Since the blade tips of modern wind turbines collect ice easily at heights of 150m and above, the site “Rödeser Berg” would require an ice class type certified wind turbine according to [1].
- ICEMONITOR can show high failure sensitivity, camera observations were highly reliable (approach 1).
- The recommended setup to determine the instrumental icing duration is the use of double anemometry with one heated ultrasonic anemometer and one unheated cup anemometer (approach 2). Sufficient and reliable power supply for the heated

anemometer must be ensured. Air temperature and relative humidity are measured as well. The recommended boundary conditions are:
   - The difference between heated and unheated anemometer (at the same mast height) must be at least twice the sum of the two uncertainty ranges of both anemometers; shadowing effects from the mast must be avoided.
   - The temperature must be below +2°C and the relative humidity must be above 95% at start of the instrumental icing.
- The application of approach 3.1 (use meteorological measurements of temperature, wind and relative humidity data as input to machine learning algorithms) has the advantage to be able to apply standard data from nearby weather stations. These machine learning procedures seem promising [8], but may be very site specific. Therefore, more investigations in this area are required.
- Using the meteorological measurements without the algorithms and applying the determined boundaries of the measured values (approach 3.3) results in large overestimation of the icing duration by a factor of roughly two to three.
- Based on approach 3.1 some meteorological boundary conditions can be given for instrumental icing at the investigated site “Rödeser Berg”: The lower limit for relative humidity is 85%; above 100% relative humidity (saturation) and temperature below +3°C a very high probability exists; highest probabilities were observed between +2°C and -5°C, extreme low probabilities below -10°C.
- Icing maps provide rough estimations for icing durations. In case a high spatial resolution is provided, they can be used for long-term correlations. However, icing maps should be used only as a first approximation, since specific site conditions (e.g. exposures, sheltering) are not considered (approaches 4.1 and 4.2).
- Conversion factors from meteorological to instrumental (rotor) icing duration have been determined to 1.4, fitting well to the German icing map, and still quite well to the IEA mean conversion factor of 2 to 3.
- Strong height dependent icing profiles have been examined, showing different icing probabilities at different heights, partly caused by forest shadowing effect and limited cloud thickness.
- Icing durations can differ significantly between different winters; a long term correction is required.

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