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ICING AT ST. BRAIS AND MONT CROSIN

Consequences of icing for the operation and power production of wind turbines in the Jura Mountains

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The authors solely are responsible for the content and the conclusions of this report.

Contents

1 Goals of the project

Swiss Federal Office of Energy SFOE has set focus points to investigate icing on wind turbines within their research programme "Wind energy". This research project aims at addressing these focus points by studying the following questions at two sites in the Jura Mountains: St. Brais (from 2009 to 2015) and Mont Crosin (from 2014 to 2015):

- Installation of webcams for **monitoring of the icing conditions** on the nacelle and on the rotor blades. This monitoring will be extended to the Mont Crosin site.

- Assessing the **icing frequency** at St. Brais and Mont Crosin as well as typical temperature and wind conditions leading to icing. Findings from the alpine site Gütsch will be included for completion. The results will be compared with the Swiss icing atlas.

- Evaluation of different **methods for ice detection** on the rotor blades of the wind turbines at St. Brais:
  - Comparison of the actual power production with the theoretical power curve
  - Temperature and relative humidity
  - Moog/Insensys rotor blade monitoring system.

- Assessing the efficiency of the **Enercon blade heating** based on the webcam images at St. Brais: Determining the energy consumption required, the efficiency at removing ice, assessing cost and benefit, comparison of different operation modes of the blade heating and power losses with and without rotor blade heating.

- Field studies of **ice throw** at St. Brais and Mont Crosin. Comparison with previous results from Gütsch.

2 Installations

The rotor blades of the wind turbine and the sensors on the nacelle were monitored with a webcam. This webcam, a Mobotix M12 network camera with dual optics, was installed in 2009 on one wind turbine at St. Brais. The second turbine was equipped with a camera in 2012. In 2014, a webcam was installed at a turbine at the Mont Crosin wind farm. Figure 1 shows the installation at one of the turbines at St. Brais.

In 2010, one turbine at St.Brais was equipped with instruments for measuring temperature and relative humidity. The wind turbine WEC 1, that was to be installed at St. Brais, was equipped with the Moog/Insensys rotor blade ice detection system at the Enercon workshop in Aurich in 2009.

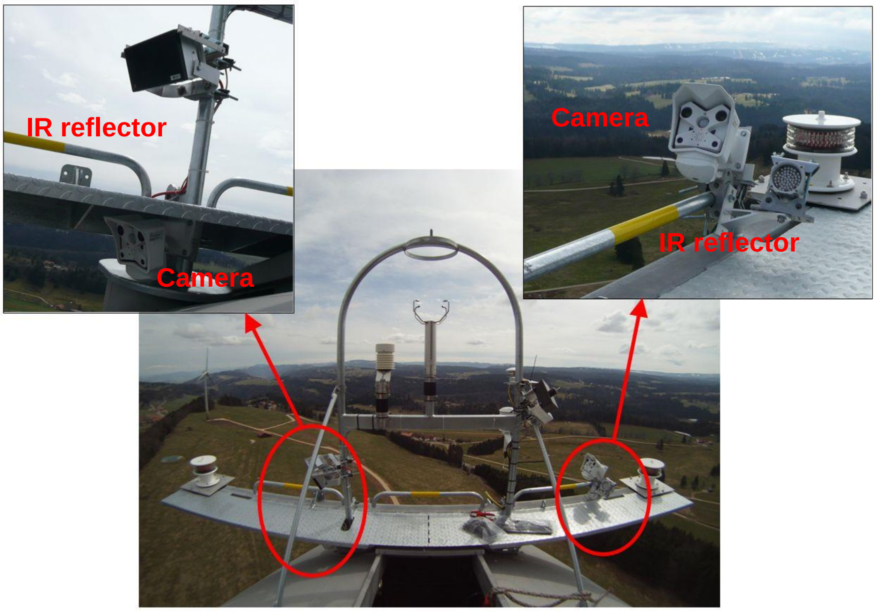

Fig. 1: Cameras and IR reflectors installed on the nacelle of a wind turbine at St. Brais. Left: The camera aimed at the rotor blade. Right: The camera aimed at the sensors.

3 Icing conditions

3.1 Icing frequency

The following terminology is used to describe icing on structures:

- **Meteorological icing**: The period when meteorological conditions allow for an active build-up of ice
- **Instrumental icing**: Duration of the technical disturbance of an instrument or a wind turbine due to icing; the period when ice is present on an instrument
- **Incubation time**: The delay between the start of meteorological icing and the time when ice starts to build-up on an instrument (start of instrumental icing)
- **Recovery time**: The delay at the end of meteorological icing and the moment when the instrument or the wind turbine is ice-free again and can retake operation.

Figure 2 illustrates the above definitions in case of an anemometer.

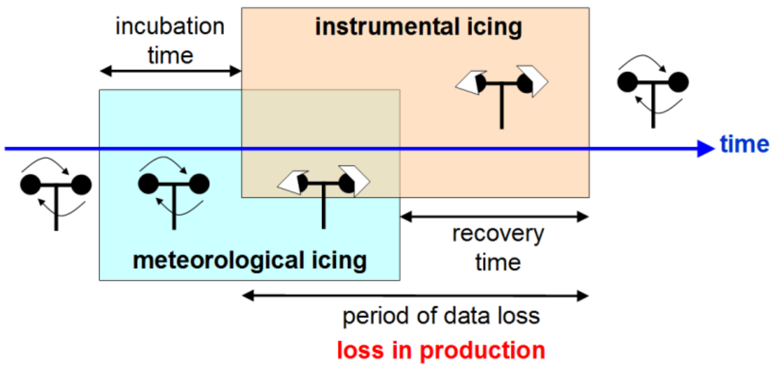

Fig. 2: Description of icing phases (meteorological icing, instrumental icing, incubation time and recovery time) of structures.

To gain information of the frequency of meteorological and instrumental icing, the images of the camera aimed at the sensors were manually evaluated. For simplicity, the first appearance of ice on the instrument was interpreted as the beginning of both meteorological and instrumental icing. This means that the incubation time was assumed to be zero. The period when an active growth of ice was observed was defined as meteorological icing. The moment when no more ice was observed on the instrument was defined as the end of instrumental icing.

Table 1 and Figure 3 give an overview of the results.

Tab. 1: An overview of the icing events at St. Brais, Gütsch and Mont Crosin.

	Meteorological icing	Instrumental icing
Gütsch 2009/10	130 h / 5.4 d	674 h / 28.1 d
St. Brais 2009/10	276 h / 11.5 d	997 h / 41.5 d
St. Brais 2010/11	247 h / 10.3 d	853 h / 35.5 d
St. Brais 2011/12	96 h / 4 d	454 h / 19 d
St. Brais 2012/13	538 h / 22.3 d	1,610 h / 67.1 d
St. Brais 2013/14	285 h / 11.9 d	868 h / 36.2 d
St. Brais 2014/15	199 h / 8.3 d	1,449 h / 60 d
Mont Crosin 2014/15	122 h / 5.2 d	1,389 h / 57.9 d

The icing frequency at the sites shows clearly that the duration of the meteorological icing events (active ice accretion) is significantly shorter than that of the instrumental icing events (persistence of ice). This difference is central for activation of blade heating. The heating can be activated to melt the ice after the meteorological icing has ceased, thus allowing for a faster restart of the operation because it is not necessary to wait until the end of instrumental icing.

The mean duration of meteorological icing over the six winters observed is 274 hours or 11.4 days (3.1% of the year) at St. Brais. This number is relatively close to the value of 9 hours a year at 100 m above ground based on the Swiss icing atlas (www.wind-data.ch). The mean duration of instrumental icing over the six winters is 1,038 hours or 43 days a winter (11.8% of the year).

The winter-to-winter variability in icing frequency is very large. In the winter 2011/12, only 96 hours of meteorological icing was observed, whereas in the following winter 2012/13 over five times more icing was observed with a total duration of 538 hours (see also Fig. 3). This shows that observing icing frequency during one single winter is not sufficient to reliably assess icing losses at a potential site for a wind park.

Based on the mean icing frequency the St.Brais site can be associated to the IEA icing class 3[1] with an average annual production loss of a wind turbine of 3-12%, depending on the set-up and operating mode.

Tab. 2: Overview of the icing events at the sites St. Brais, Gütsch and Mont Crosin.

IEA icing class	**Meteorological icing [% / yr]**	**Instrumental icing [% / yr]**	**Production loss [% of annual production]**
5	>10	>20	>20
4	5-10	10-30	10-25
3	3-5	6-15	3-12
2	0.5-3	1-9	0.5-5
1	0-0.5	0-1.5	0-0.5

The comparison with Gütsch shows that the icing climate in the Jura Mountains strongly deviates from a high alpine site. Icing at Gütsch starts approximately one month earlier in autumn and lasts 1-2 months longer in spring. The periods of meteorological icing are shorter than in Jura, but the instrumental icing periods last longer.

The icing conditions at both sites in Jura, St. Brais and Mont Crosin, are fairly similar in the winter 2014/15 with 8.3 and 5.2 days of meteorological icing and ca. 60 days of instrumental icing, respectively.

[1] IEA Task 19, RECOMMENDED PRACTICES FOR WIND ENERGY PROJECTS IN COLD CLIMATES, Edition 2011

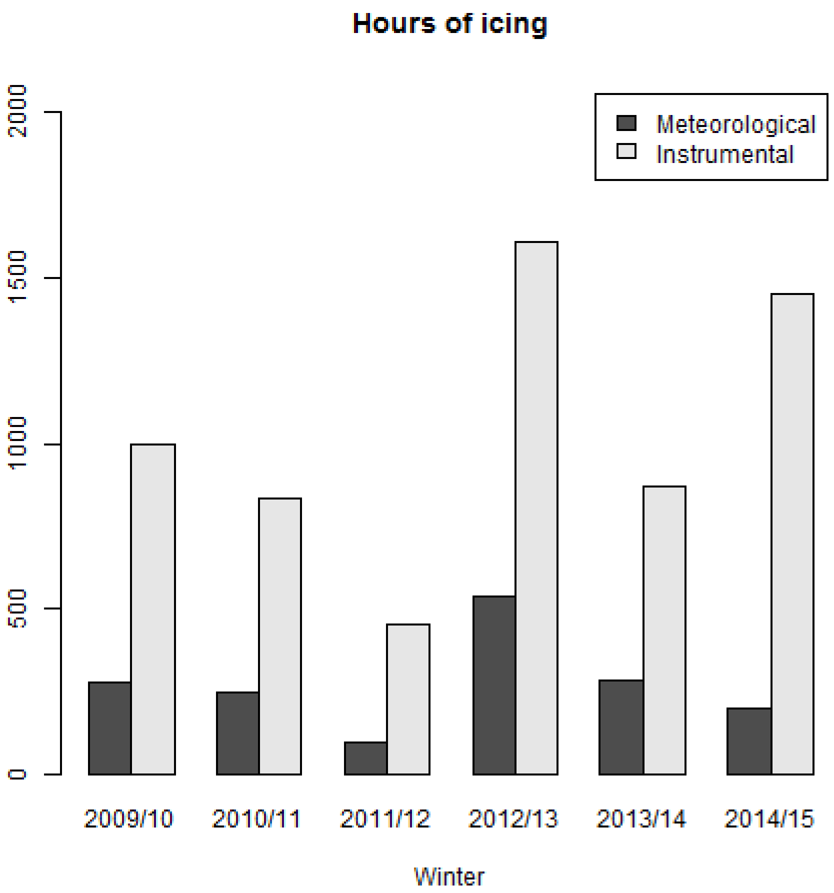

Fig. 3: The hours of meteorological and instrumental icing during the six winters measured at the St. Brais wind park site.

3.2 Wind conditions during ice accretion

Figure 4 shows the dependence between the meteorological icing and local wind conditions. In the winter 09/10, the meteorological icing took place mainly during wind conditions from the sector north-east and at wind speeds between 3 and 5.5 m/s. No meteorological icing was observed at wind speeds higher than 12 m/s. Some meteorological icing took place during winds from west-southwest or west-north west but these cases were rare. This picture was confirmed by the following winters.

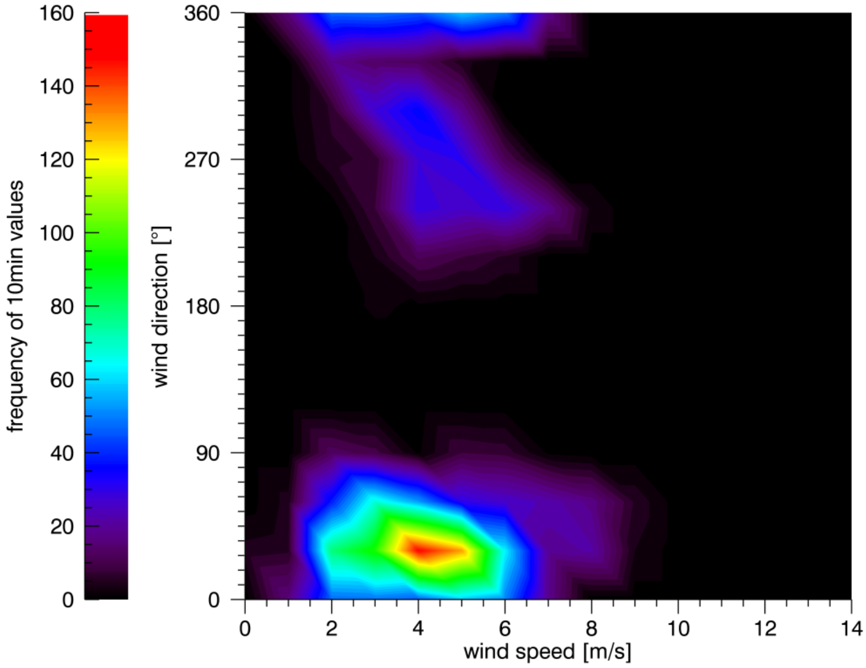

Fig. 4: Frequency distribution of meteorological icing as a function of wind speed and wind direction.

4 Ice detection

4.1 Power curve

Enercon routinely uses the method of comparison between the actual and the theoretical production according to the power curve for detecting ice on wind turbines. At St. Brais, this method was capable of detecting all icing events between December 2009 and May 2011 that were observed on the webcam images.

4.2 Temperature and relative humidity

An Enercon instrument to measure temperature and relative humidity was installed on the nacelle of the WEC 1 at St. Brais. This data were analysed during the winters 2009/10 and 2010/11.

Figure 5 shows a scatter plot of temperature and relative humidity. The data shows that saturation is not achieved at temperatures below -7°C. This is due to the definition of the World Meteorological Organisation WMO, where the measurement of relative humidity is based on saturation vapour pressure of water[2]. This, however, is not valid for temperatures below 0°C because the saturation vapour pressure is smaller over ice than over water. This leads to a positive bias in saturation vapour pressure at temperatures below the freezing point so that saturated air cannot reach the relative humidity of 100%.

Figure 5 shows values measured during icing events in pink. Icing was observed to take place at St. Brais in winter 2009/10 at temperatures until -13°C and at relative humidity between 90 and 100%.

[2] WMO/CIMO: Guide to Meteorological Instruments Observation, Chapter 4, Annex 4.A, Item 17

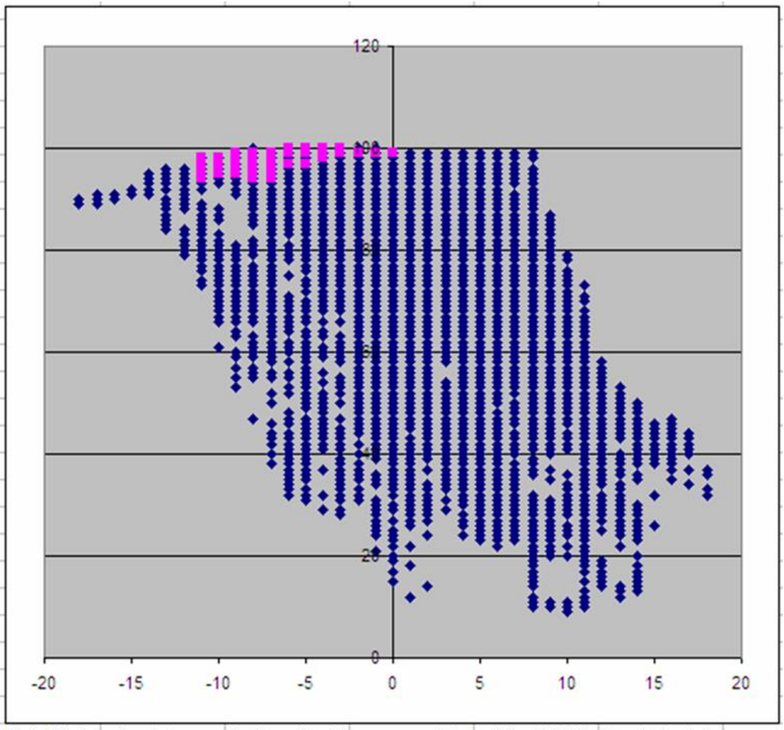

Fig. 5: Blue: The relationship between temperature and relative humidity at St. Brais during the winter 2009/10. Saturation is not reached at temperatures below ca. -7°C. Pink: Measurements made during icing events.

A commonly used definition of icing is the threshold of air temperature below the freezing point and relative humidity above 97%. The bottommost row in Figure 6 shows the periods when these conditions were fulfilled.

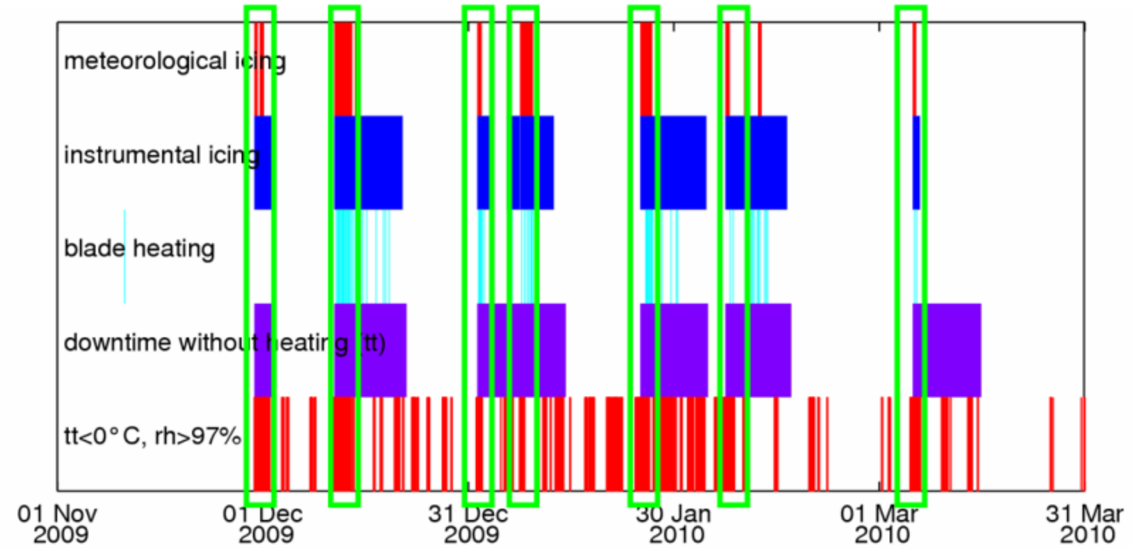

Fig. 6: Periods when air temperature was below the freezing point and relative humidity was above 97% (bottommost row), compared with instrumental icing. The green boxes mark the periods with meteorological icing.

Obviously there is no connection between these periods and the actual icing events. These conditions are often fulfilled although no ice is observed. The combination of temperature and relative humidity can thus not be used for ice detection due to the high probability of false alarms.

4.3 Moog/Insensys rotor monitoring system

The performance of the Moog/Insensys rotor monitoring systems in detecting ice was generally positive (Fig. 7). It became apparent, though, that using the system without real-time operational data, especially the pitch angle of the wind turbine, was not without difficulty. A further analysis of the performance of the Moog/Insensys system was not possible because this data was not available for this project. Meanwhile, the production of the Moog/Insensys ice detection system has ceased.

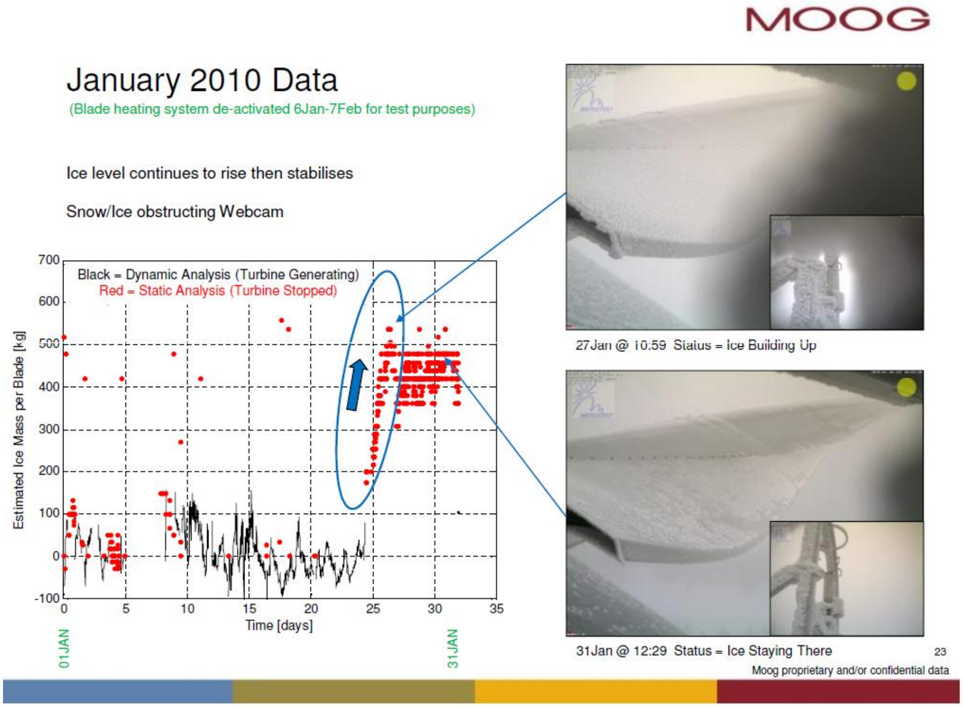

Fig. 7: Ice accretion monitored by the Moog/Insensys rotor monitoring system during an icing event in the end of January 2010.

5 Performance of the blade heating

5.1 Heating at stand-still

The blade heating of the wind turbines at St. Brais during the winter 2009/10 operated in such a way that after each detection of ice the turbine was stopped automatically. Then, the rotor blades were heated during three hours. After this heating cycle the turbine was automatically put back to operation.

During the winter 2009/10 the blade heating was activated 124 times at both turbines. The heating power used was 0.5% of the annual energy production of both turbines. The blade heating was mostly active during periods of meteorological icing. When ice no longer accreted, the blade heating was deactivated or was activated only for removing small remainders of ice.

Assuming that a turbine without blade heating would be standing still during the whole period of instrumental icing, the stand-still time at St. Brais was reduced by at least a factor of 4 thanks to the rotor blade heating. This corresponds to a power surplus of 6% compared with the theoretical annual energy production of both turbines. On the other hand, having to shut down the turbine during the heating lead to a stand-still time of 7.5 days altogether for each turbine, or 3% of the theoretical annual energy production.

The blade heating was deactivated at the WEC 1 from January 6 till February 8, 2010, while WEC 2 operated normally. A comparison was made between the additional energy gain and the energy loss due to heating and the relationship between cost and benefit of the de-icing system was assessed. Three icing events were observed during the study period. Table 3 shows the begin and the end of the icing periods as well as the power production surplus of the WEC 2 during this period, compared with the energy consumed for heating. The results confirm the gain in energy due to blade heating. The energy consumed for heating during this period was approximately 6.5% of the energy gained.

Tab. 3: Heating power consumed compared with production losses due to deactivation of the heating.

Event start	**Event end**	**Production WEA 2 [kWh]**
Jan 6, 2010 6:48 pm	Jan 7, 2010 4:30 pm	3,892
Jan 25, 2010 8:01 pm	Feb 2, 2010 6:41 pm	96,608
Feb 7, 2010 11:35 am	Feb 8, 2010 8:27 pm	2,993
Production loss WEA 1		**103,493**
Energy saved due to deactivation of blade heating		-7,020
Production loss total WEA 1		**96,473**

5.2 Heating during operation

The operation mode of one turbine was changed to heating in operation in winter 2010/11. When the turbine detects a production decrease, the rotor blade heating is activated. The detection is based on a tighter threshold than while heating at standstill. The end of the heating period is detected using the power curve and meteorological parameters. If the higher threshold for production decrease is detected during heating, the turbine switches off automatically and continues to heat at stand-still.

The analysis of the data shows that in three of four cases the power production was higher when heating during operation, as opposed to heating at stand-still. The gain was between 10 and 30%. The production gain depends on the wind speed during the icing event as well as its duration. In all three cases the rotor blades were heated over a relatively long period of meteorological icing. At the time of finishing the project both turbines at St. Brais operate with heating during operation.

5.3 Preventive heating

During the winter 2011/12 the turbine WEC 2 at St. Brais operated with preventive heating. The turbine was heated during operation. The heating was controlled with the measurements of temperature and relative humidity. The turbine was shut down during strong icing events and heated at stand-still.

Analysis of the data shows that the temperature and relative humidity are not optimal parameters for triggering preventive heating. These triggers lead to an excessive consumption of heating power. Therefore the approach of preventive heating was pursued no further.

6 Ice throw

As soon as ice builds up on turbine blades it can fall down from a standing turbine or shred from a running one. This so-called ice fall or ice throw poses a danger for passers-by and service personnel. Therefore, assessing this danger is an intrinsic part of planning and operating a wind turbine under icing conditions.

A study on ice throw was carried out between 2011 and 2015 at both WEC at St. Brais. Furthermore, this study was extended to wind park Mont Crosin in winter 2014/15.

To complete the results the data of the ice throw study at Gütsch from 2005 to 2009 was included into the analysis.

The relevant questions were how often does ice throw occur, how long distances do the ice particles reach, what dimensions and weight do they have and whether differences can be distinguished between turbines depending on their operation mode. Ice particles were collected at the sites when webcams showed icing on rotor blades. Camera images were downloaded and controlled on a daily basis for this purpose.

All field studies added up, a total number of 1,000 ice particles was collected. It was not possible to differentiate between ice fall (turbine at stand-still) or ice throw (turbine in operation).

Evaluation of the data collected at St. Brais (Enercon E-82, hub height 78 m) during winters 2012/13 and 2014/15, at Gütsch (Enercon E-40, hub height 50 m) from 2005 till 2009 and at Mont Crosin (Vestas V90, hub height 95 m) during the winter 2014/15 confirms, that ice throw takes place at all three sites.

Figure 8 shows a frequency distribution of the distance of all ice particles collected at the foot of the turbine relative to the tip height of the turbine (= hub height + rotor radius) as well as the cumulative frequency distribution. The analysis shows a maximum of the distances at 0.2 to 0.4 x tip height. 75% of all ice particles collected were found within 0 to 0.6 x the tip height. No ice particles were found at distances larger than 1.4 x tip height. It is possible that ice throw occurs beyond these distances. However, the analysis is based on a fairly large number of particles, suggesting that the probability of finding particles beyond 1.4 x tip height is fairly low.

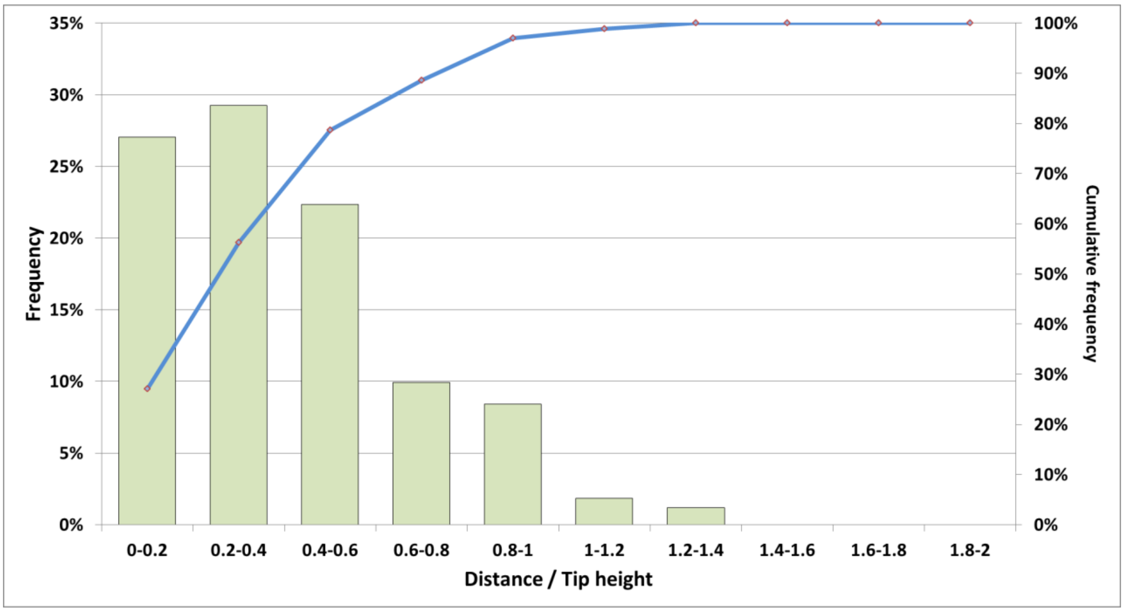

Fig. 8: Frequency distribution of the ice particles collected (Gütsch, St. Brais, Mont Crosin) depending on the distance, normalised with the tip height of each turbine.

The analysis shows an increased frequency of ice throw up to distances equal to the tip height at all three sites. The frequency observed decreases significantly at longer distances. Therefore the risk of ice throw has to be assessed for each individual wind turbine during planning and operation under icing conditions and a specific layout and risk concept has to be established.

The radius of danger of ice throw according to the Seifert[3] formula used commonly for calculating the areas of risk of 1.5*(rotor diameter + hub height) is 1.9 to 2.0 x tip height at all three sites investigated. Distances this long were never observed during the field studies.

As a result of the field studies measures were taken by the operators for minimising the risk at all three sites. These measures included warning signs, adaptation of the operating mode as well as adaptation of the situation and maintenance of hiking paths or cross country ski tracks crossing the sites.