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WHITE PAPER

How to accurately detect ice on wind turbines for a cost- and time-efficient operation?

- Performance characteristics of different ice detection systems.
- Proof of increase in AEP based on real data from operating wind turbines.
- Regions where an ice detection system can achieve the greatest benefits.

How to accurately detect ice on wind turbines for a cost- and time-efficient operation?

Highlights

- Rotor blade icing causes losses in energy production due to standstill.
- With state-of-the-art ice detection system, the standstill can be reduced. But not all systems have the same performance characteristics.
- With real-life data from operating wind turbines, we can show that rotor vibration-based ice detection systems outperform instrument icing systems and help to increase AEP.
- We also demonstrate that the greatest benefits can be achieved in regions with many short-term ice events during winter times.

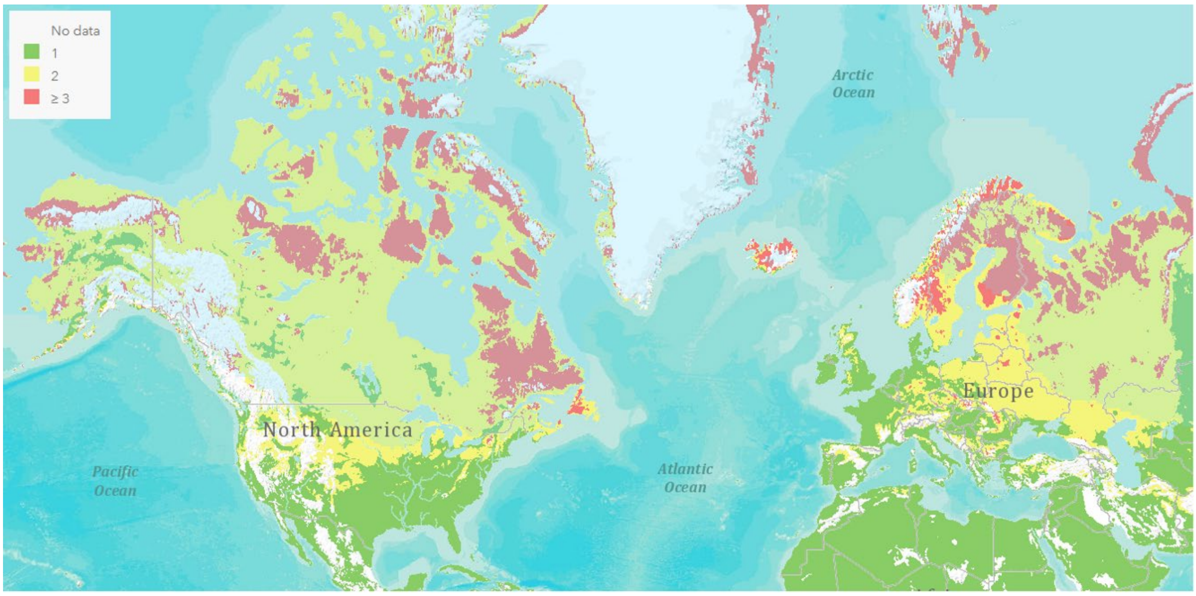

Figure 1 Wind Power Icing Atlas (WIceAtlas) of North America and Europe showing IEA ice classes (from http://virtual.vtt.fi/virtual/wiceatla)

Rotor blade icing – a serious issue for wind turbines

On average, wind turbine operators in Europe are struggling every year with a five-digit loss of earnings in euros. Ice detection systems can help to mitigate this situation.

The investment in such a system usually pays for itself within the first two to five years. Some of these ice detection systems also offer added functionalities, such as rotor blade condition monitoring or control of rotor blade heaters.

Ice mitigation is important in all areas that can be regarded as Cold Climate. The International Energy Agency (IEA) regards all areas or regions as Cold Climate where you can observe frequent atmospheric icing or periods with temperature below the operational limits of wind turbines[1]. All relevant areas in *Figure 1* colored yellow or red fall under this definition.

Within Cold Climate areas there can be either Low Temperature Climate (LTC) and/or Icing Climate (IC), as shown in *Figure* 2. Areas that have periods with temperatures below the operational limits of standard wind turbines are defined as LTC regions, whereas areas with atmospheric icing are defined as IC regions.

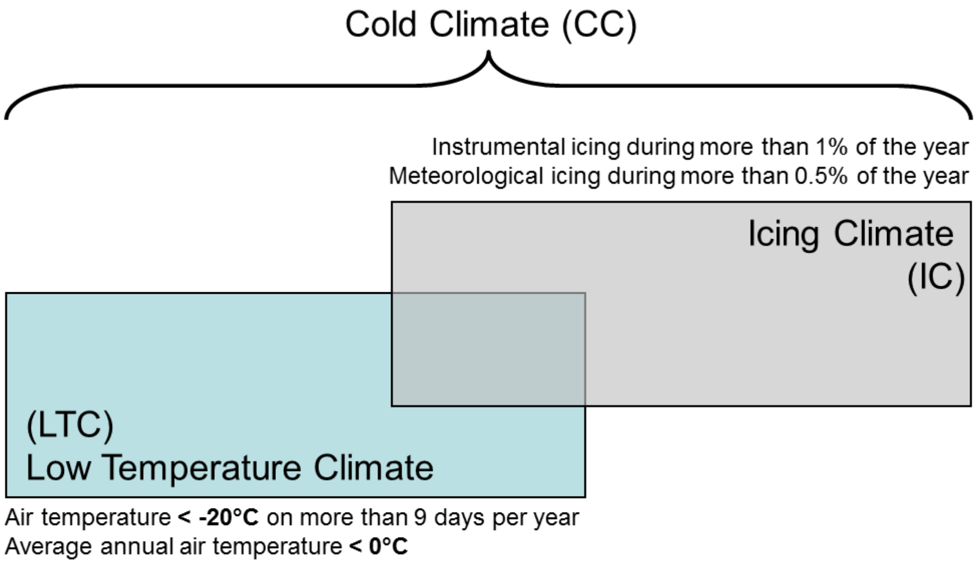

Figure 2 Definition of Cold Climate, Low Temperature Climate, and Icing Climate (IEA Wind Task 19, 2017)

When it comes to operating wind turbines, the Icing Climate conditions are the most relevant as they are linked to the presence of ice on instruments for more than 1% of the year.

Ice on wind turbines causes hazards due to ice fall and ice throw. Ice fall occurs when ice is falling off directly from a wind turbine, which cannot be avoided in icing conditions. The mitigation strategy here is to make sure that no persons enter the ice fall risk area. In practice, this is mostly done by signs around wind turbines.

Ice throw occurs when ice is thrown away by a wind turbine in operation. Depending on the weight of the ice and the rotation speed of the wind turbine, ice can be thrown away several hundred meters[2]. This fatal risk leads to different regulations limiting the operation of wind turbines under icing conditions. Operators therefore need to choose a solution that meets the authority's requirements.

Icing can also potentially lead to wind turbine failure due to loss of structural integrity[3] caused by load imbalances.

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[1] IEA Wind Task 19, 2017
[2] Bredesen, Rolv Erlend (2017): Icethrow from Wind Turbines - Assessment and Risk Management, IEA Wind Task 19, Winterwind 2017
[3] Engineering F2E Fluid & Energy (2020): Risk Assessment: Loss of Structural Integrity. https://f2e.de/en/services/risk-assessment-loss-of-structural-integrity

Choosing the right Icing Strategy

Depending on the turbine location there are different strategies to mitigate the risks of ice throw during turbine operations. All these strategies require an ice detection system that allows different operation modes during winter times.

De-icing

When you choose a de-icing strategy, the turbine is typically stopped as soon as ice is detected, and it can only be restarted when there is no more ice on the rotor blades.

For a de-icing strategy you can choose two different ice detection methods: a "discreet" ice detection method that will not give you any information on the amount of ice (e.g., power curve analysis), or detection method with continuous measurements.

Power curve is the most common ice detection method, where additional sensors could achieve more accuracy.

When ice is detected, the de-icing procedures are set in motion. Generally, there are two different de-icing procedures available:

- Hot air de-icing, where hot air is blown inside the blade heating the blade up from the inside
- Electrical de-icing, where heating mats integrated in the leading edge of the rotor blades are heated up for de-icing

The main purpose of the ice detection system in this strategy is to detect if there is any ice on the blades and to decide if the de-icing procedure has been successful.

Anti-icing

The further north the turbines are installed, the more certain it is that there will be ice on the blades. For these turbines, anti-icing strategies are more suitable.

Anti-icing strategies aim to prevent ice to aggregate on the blades by preheating the rotor blades in the right moment. It is therefore very important to detect an upcoming ice event at a very early stage.

The power curve method, however, is not sensitive enough to do this, and therefore a more sensitive ice detection method is needed. Rotor blade ice detection systems offer here an advantage as they detect ice already in the aggregation phase before the impact of icing can be recognized in the power curve.

Ice detection

Many wind turbines are installed in high population density areas, where there are different regulatory requirements for operating turbines under icing conditions.

To optimize the operation time for these turbines, rotor ice detection systems offer the best solution and make a real difference in the annual energy production (AEP) output of wind turbines. We describe this in the *Comparison of instrument icing and rotor vibration-based ice detection system based on field data* chapter below.

Technical solutions for ice detection

There are different ways to detect ice on wind turbine blades that differ on a technological level and serve different needs. To choose the right ice detection system for the specific site and use, it is necessary to understand how ice is building up on the turbine blades.

In the incubation phase, we can observe a change in the meteorological conditions that allows for ice to build up. To get the right conditions for ice to grow on the rotor blades, low temperature, sufficient wind, liquid water content and droplet distribution on the surface is needed. This can occur locally like within fog or clouds in combination with low temperatures and wind.

In the accretion phase, ice is building up quickly on the rotor blades. This phase typically lasts several hours. The turbine operation itself can affect the severity of the ice event. As spinning rotor blades travel through larger air volume, they pick up undercooled droplets, which then form ice on the leading edge of the blade.

In the persistence phase, the ice level is relatively stable on the rotor blades until it decreases in the ablation phase to the end of the ice event. In the ablation phase ice can fall off the turbine or, if the turbine is operating, ice throw can occur. There can also be an overlap of the persistence phase and the ablation phase depending on meteorological conditions and duration of the ice event.

Ice detection system can capture these icing phases by measuring ice on the turbines. As there are different technological approaches to measure ice, the results can also differ.

Extensive comparisons between the different types of ice detection systems, as well as a direct comparison of the most important competitors in the field of ice detection and the performance of the ice detection systems can be found in publications from Meteotest[4][5] and Nergica[6].

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[4] Meteotest (2016): Evaluation of Ice Detection Systems for Wind Turbines, VGB Research Project No. 392, Vol. 41, Bern, Switzerland. https://www.vgb.org/vgbmultimedia/392_Final+report-p-10476.pdf.
[5] Meteotest (2019): Intercomparison of Blade-Based Ice Detection Systems, *Winterwind 2019*
[6] Nergica (2019): Rotor- Mounted Ice Detectors. Performance Assessment, Assessing the Performance of Turbine Rotor Ice Detector Systems | An overview - Nergica

Power curve-based systems

Systems based on power curves offer the advantage that no additional hardware needs to be installed. Ice detection takes place based on the power curve of the wind turbine, which the manufacturer provides. The system detects ice on the rotor blades by analyzing deviations of the current power from the expected power of the system.

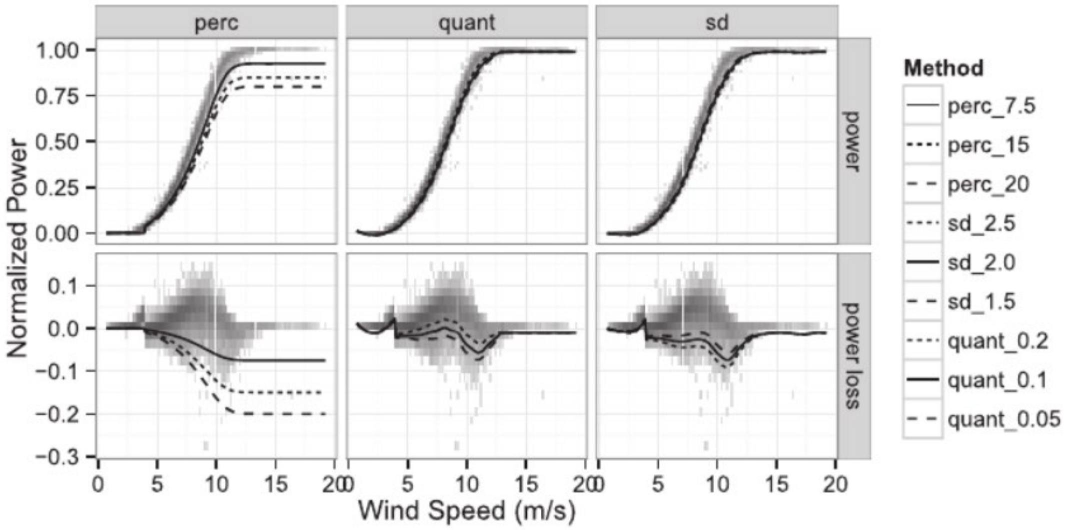

Figure 3 Examples for power curve ice detection methods. The top row shows wind speed versus power, the bottom row shows wind speed versus power difference. The methods shown are flat percentage (perc), standard deviation (sd) and quantile (quant)[7]

The measurement is quite accurate during the build-up phase as the system generates a standardized power curve with a deviation gradient. However, there is no measurement during standstill as the measurements take the power generation as a reference. For this reason, the legislator often requires further detection systems in addition to those based on power curves.

[7]Davis, N., Byrkjedal, Ø., Hahmann, A. N., Clausen, N-E., and Zagar, M. (2016): Ice detection on wind turbines using observed power curve. Wind Energy, 19(6), 999–1010. https://doi.org/10.1002/we.1878

Instrument icing systems

Instrument icing systems are based on the nacelle of the wind turbine. Anemometers, ultrasound measurements, or meteorological data, such as humidity, are used to check whether icing is occurring and whether the turbine should be shut down.

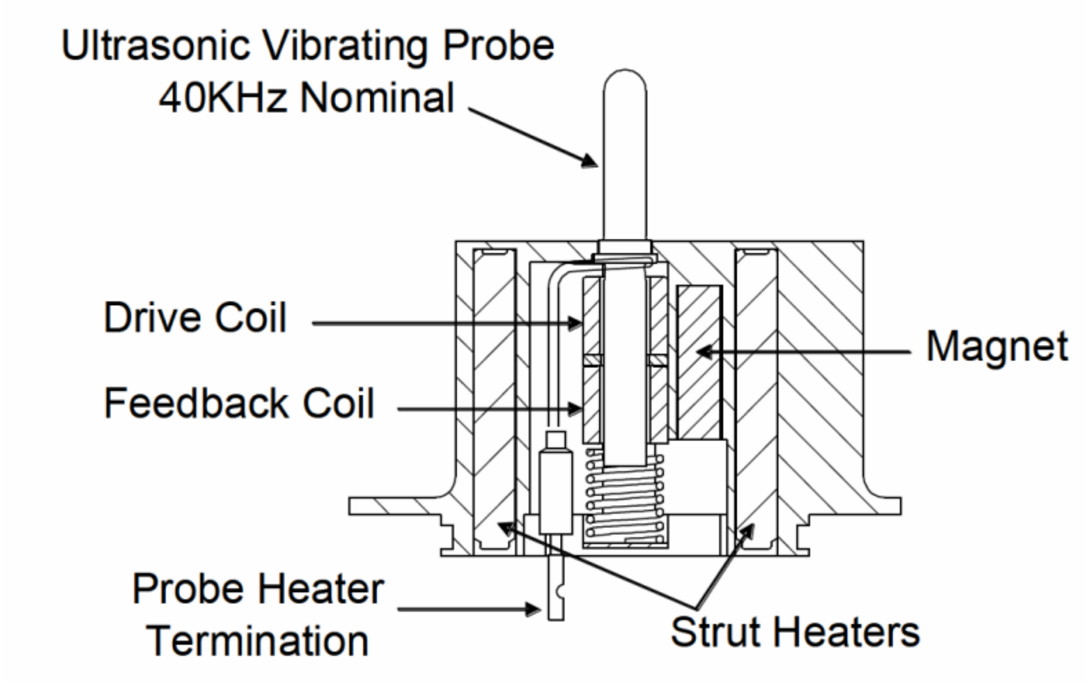

Figure 4 Example for an ultrasonic ice detector. In an icing environment, ice get collected on the sensing probe. The added mass causes the frequency of the sensing probe to decrease. The ice load depends linearly on the induced frequency shift. The sensor software monitors the probe frequency shift and detects this decrease.

Since the flow conditions on rotor blades are different due to their rotational speed and higher position, the sensors must be appropriately sensitive and conservatively aligned to reliably measure ice build-up. These systems are cost-effective but do not allow for automatic restart after the icing event.

Rotor vibration-based systems

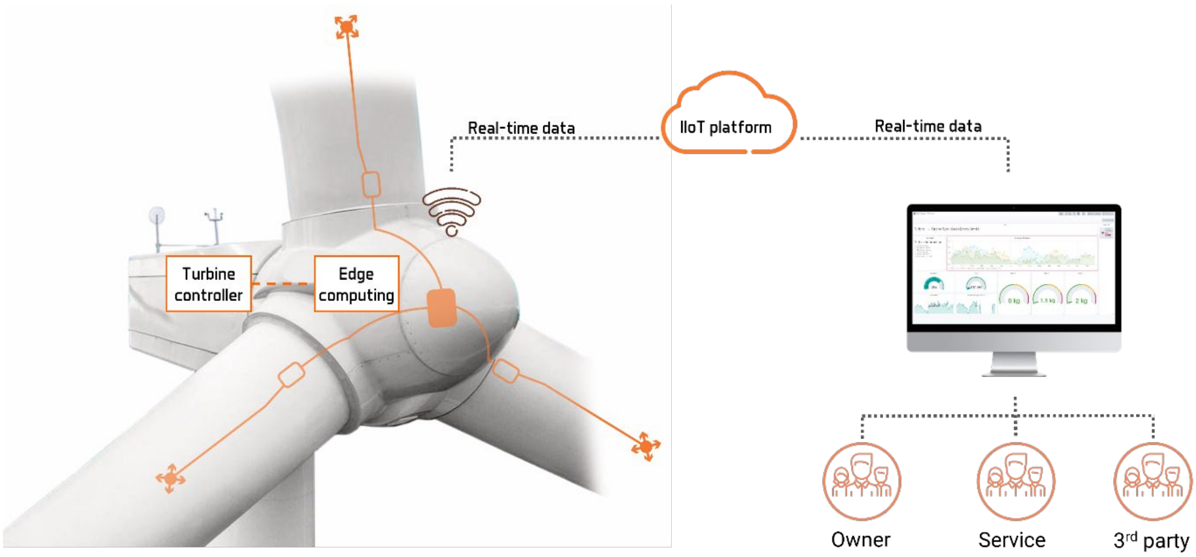

Figure 5 Setup of a rotor vibration-based ice detection system (in this case the Polytech ice detection system)

The rotor vibration-based ice detection system measures the vibration of the rotor blades and is trained for the normal, ice-free behavior of the blade. With ice building up on the rotor blade, the measured frequencies change. The system then uses this information to calculate the ice mass on the rotor blades.

These systems offer clear advantages over the two methods already mentioned. Vibration measurement using vibration-sensitive sensors in the rotor blade ensures time-exact, autonomous control of the wind turbine, as the sensors measure the risk of icing and the actual icing directly on the vibration behavior of the rotor blade.

The largest manufacturers of wind turbines rely on fiber optics for the sensor technology in the blade as these are insensitive to electromagnetic interference (lightning strike) and have an extremely high robustness and cycle stability.

Comparison of instrument icing and rotor vibration-based ice detection system based on field data

Description of the analysis setup

For the analysis we used data from turbines installed globally and equipped with a Polytech ice detection system in the winter of 2017/18.

As we wanted to assess the overall performance of the system, we chose not to analyze specific regions but looked at turbines globally. The data also came from different types of turbines. We, however, did not observe any significant effects of the turbine type on the performance of the Polytech ice detection system.

For a proper analysis of the ice events, we required a minimum amount of information and data points from a single turbine to consider it in the analysis. We only choose turbines with data for the whole winter season. In each dataset, we needed the information from the Polytech ice detection system as well as the signals from the instrument icing system installed.

We only analyzed data for turbines where the instrument icing system was reset after the ice event but excluded the turbines that used a deicing formula[8] for the signal of the instrument icing system. We removed all these turbines from the analysis to avoid distorting the results[9].

These considerations left us a total of 125 turbines with complete data.

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[8] In this operation mode, the turbine is reset to operation after a defined time with meteorological conditions that do not allow icing. Typically, the deicing formula takes values of external temperature and wind speed as input parameters over all phases of ice event. This information is then calculated resulting in delay interval until restart. These operation modes differ across turbine types, OEMs, countries, and occasionally regulatory requirements.

[9] For these turbines, the Polytech ice detection system was the leading system to control the turbine under icing condition. The instrument icing system, however, was not shut down, and would only reset manually or according to the deicing formula of the turbine OEM. As the Polytech ice detection system controlled the restart, there was no need to reset the instrument icing system anymore. This also meant that the signal of the instrument icing system was still present long after the ice event.

Structure of data

Figure 6 is an example of an actual icing report from a system in the field. It shows the ice curve for all three blades, the signal of the instrument icing system (in this case an anemometer), and the system availability (depicted by the "ready" line, where the low wind speed caused gaps in the system availability). Based on the measured data, the system calculates the power gain and loss during the specific icing event.

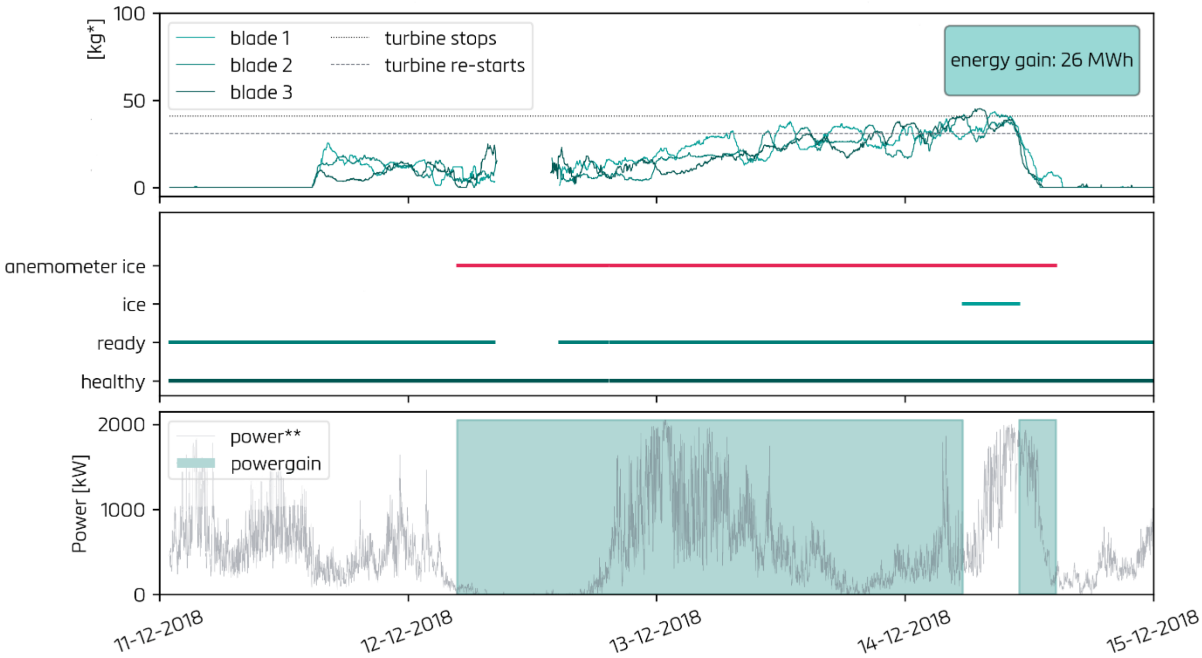

Figure 6 Polytech ice detection winter report. In this case, the turbine was able to produce 26MWh of energy more in a 4-day period with the use of a rotor vibration-based ice detection system.

The example visualizes a measurement period of four days. On 11st December, ice starts to build up. The rotor vibration-based system can detect this build up very accurately and stops the turbine once the predefined threshold is reached. This accurate detection results in a huge energy gain. The reason for this was that the ice build-up on the blade was below the turbine stop level for a long period of time.

The rotor vibration-based ice detection systems stopped the turbine two full days after the instrument icing (in this case the "anemometer ice") system would have. The actual ice event lasted only a few hours before the turbine was set back to operation.

Categorizing of ice events

Ice events have variable durations lasting from a few minutes up to several months in the far north. This makes it impossible to do any analysis based on the unique ice events. We therefore needed to define different ice event categories.

As we observe most of the events being rather short, we decided to go for a fixed boundary approach, where we set the categories manually.

We defined the five categories based on the length of ice events:

Category	Length of single ice event	Number of events	% of total events
1	0 – 1h	324	60.7%
2	1h – 6h	120	22.5%
3	6h – 24h	51	9.6%
4	24h – 72h	27	5.1%
5	>72h	11	2.1%

Table 1 Categories of ice events

Figure 7 shows the distribution of the ice events in the chosen categories.

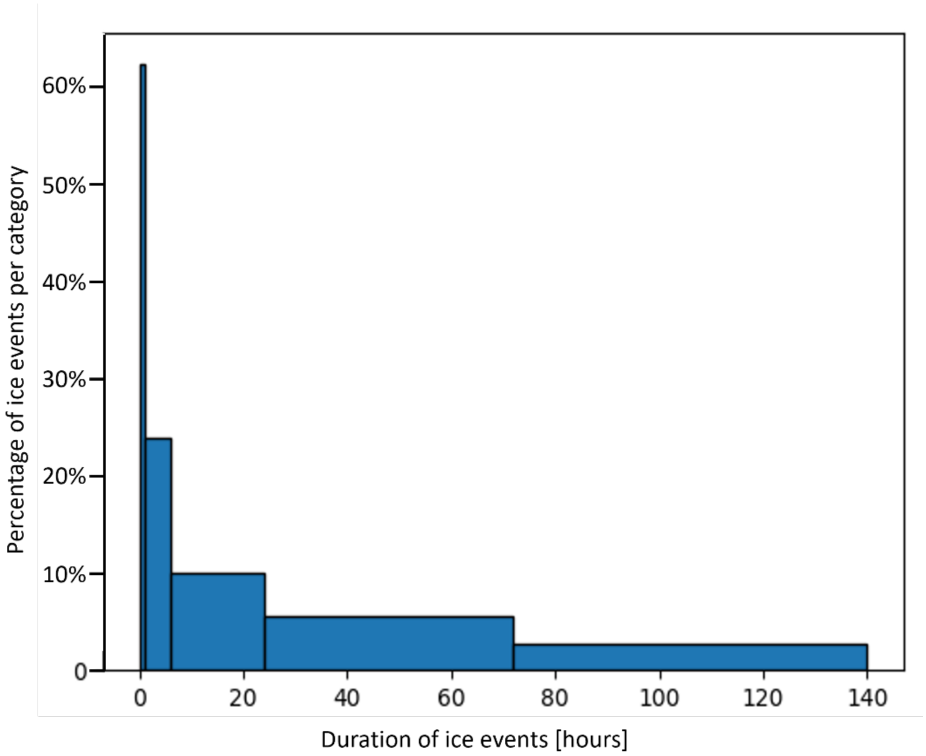

Figure 7 The distribution of ice events in the different ice categories.

Discussion

The categorization shows that most of the ice events have a short duration under 24h (92.8% of the events). This is not surprising as most of the turbines in the analysis are in areas according to IEA ice class 1 or 2. Heavy icing is not expected to occur in those regions too often[10].

In all categories there is an increase in operation times by using our ice detection system as opposed to instrument icing systems. *Table 2* outlines the average operational gains when using the Polytech ice detection system compared to instrument icing systems.

Category	Mean additional operation time[11]
1 (0 – 1 h)	7 min
2 (1 – 6 h)	1.5 h
3 (6 – 24 h)	8.3 h
4 (24 – 72 h)	18.5 h
5 (> 72h)	98.25 h

Table 2 Gained operation time by using Polytech ice detection systems

The table indicates that the longer the icing event, the more additional operation time you get by using our rotor vibration-based ice detection system.

The gains in categories 1 and 2 are often a result of continued operation during icing conditions. In these categories, the instrument icing systems force the turbine to stop often, whereas the rotor vibration-based system did not detect ice above the predefined shut-off level.

The gains in categories 3 and 4 are a result of "interrupted ice events". We see several events in the analyzed data, where the instrument icing system stopped the turbine too early and detected ice for a longer time. Within the same period, the rotor vibration-based system detected ice-free time spans, which allowed the turbine to spin again.

In category 5, we see an additional gain of operation time of 98.3 h. This gain results from our ice detection system ending these long-term ice events much earlier than the instrument icing systems. However, as there are only a few ice events in this category, the results might not be representative.

Our analysis also showed that there are huge differences between the turbines within the same wind farm. The main reason for this turbine-specific behavior could be meteorological differences at site.

[10] IEA Wind Task 19, 2017
[11] Based on the maximum duration of ice events in this category

Conclusion

Rotor vibration-based ice detection systems are not just another feature to equip wind turbines with. They pay off in operation times, and therefore help to improve AEP for all wind turbines that are affected by ice for several days per year (See *Figure* 8). *Figure* 8 shows the Business Cases of replacing an instrument icing system by a vibration-based system for different icing situations and project types. For example, a 3.0 MW onshore turbine with 2,500 full load hours and 89 €/MWh at a site with 2.5% AEP icing losses can (on average) improve the losses by 1.6% AEP, resulting in more than 10,000 € additional revenue per year.

			1.5 MW	3.0 MW	6.0 MW
Icing loss	**Relative gain**	**Improvement potential**	**1,800 full load h 2,700 MWh AEP 92€/MWh**	**2,500 full load h 7,500 MWh AEP 89€/MWh**	**4,500 full load h 27,000 MWh AEP 108€/MWh**
1.5%	63% (8)	0.9%	25.5 MWh **2,347 €**	70.9 MWh **6,308 €**	255.2 MWh **22,708 €**
2.0%		1.3%	34.0 MWh **3,130 €**	94.5 MWh **8,411 €**	340.2 MWh **30,278 €**
2.5%		1.6%	42.5 MWh **3,912 €**	118.1 MWh **10,531 €**	425.3 MWh **37,847 €**
3.0%		1.9%	51 MWh **4,695 €**	141.8 MWh **12,616 €**	510.3 MWh **45,417 €**

Figure 8 Potential gains in AEP on wind turbines using the Polytech ice detection system

Wind farms with dominantly category 1 and 2 ice events have a huge potential to reduce their number of ice event and therefore increase operation time. As every additional hour of operation is valuable, the owner and the operator can quickly experience the financial benefits of rotor vibration-based ice detection systems. The reduction of standstill time is mainly determined by the reduction of false positive alarms from the instrument icing system and the combination with automatic restart. Field installations show that unnecessary downtime due to icing can be reduced up to 95%.

Wind farms with category 3 and 4 ice events can improve their operation times and increase their AEP by accurately detecting the start and the end of the ice events.

Regardless of the duration of ice events, rotor vibration-based ice detection systems have several advantages over instrument icing systems.

[12] The relative gain results from the average of the more than 350 systems in the field.

They offer continuous measurements and can be certified for automatic stop and restart of the turbine without any further visual inspections. And with their increased measurement accuracy, you can reduce the turbine standstills during winter times, and therefore increase your AEP. Depending on site specific conditions the system can enable for 300 MWh additional energy production and 5% gain.

“The reliability and performance of the ice detection system of Polytech overall convince in our wind farm. The systems will have paid for themselves in our wind farm already in the 2nd winter.”

Dieter Schreiber, Leader Monitoring und Innovation, Windkraft Simonsfeld AG

We at Polytech therefore recommend these state-of-the-art rotor vibration-based ice detection systems for a cost- and time-efficient operation during winter times.