MSc Program
Renewable Energy in Central and Eastern Europe

Technological and operational perspectives for the planning and operation of Wind Turbine generators under Cold Climate Conditions

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **MICHAEL LASSAGER**, hereby declare

1. that I am the sole author of the present Master's Thesis, "TECHNOLOGICAL AND OPERATIONAL PERSPECTIVES FOR THE PLANNING AND OPERATION OF WIND TURBINE GENERATORS UNDER COLD CLIMATE CONDITIONS", 89 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 16.11.2018

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Abstract

In the last decades wind energy became a cornerstone in the integration of renewable energy sources to the electrical energy production mix all over the world. The continuous development and integration of wind energy projects led more and more to project sites in remote and complex areas. The first wind energy projects in the Alpine Area were realized in the early 2000 years.

Next to the challenging logistical and infrastructural issues during the construction period the operators of the wind energy projects faced the highly underestimated issue of the influence of atmospheric icing.

Due to safety reasons, the Wind Turbine Generators (WTGs) had to be stopped and the staff of the operator had to wait, till the ice on the WTGs was melted by higher ambient temperatures. After a successful observation of ice-free rotor blades, the WTG had to be started on site, manually. Due to missing technologies of effective ice detection systems and efficient deicing systems the economical losses were enormous.

The author of the Master Thesis has made a research on the background information – starting from the political framework in the European Union and Austria, to wind energy technology in general and a deep understanding of the cold climate conditions.

For the planning of wind farms, the author exemplifies the calculations and studies that assess the risk of ice throw and create a corresponding park layout and risk concept.

The author has analyzed the available technologies for ice protection systems, divided into 2 main categories: active de-icing (involving energy consumption) and passive.

Also, the author examined the importance of the risk analysis in order to identify potential events that can negatively impact persons, assets and the environment, and to implement control measures during the operation phase that eliminate or reduce the potential risk-related consequences.

During the case study, the author analyzed the evolution of different technologies and strategies for the operation, risk management and economy of a given area in the Eastern Alps in Austria.

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1. Introduction

In the last year’s most of the WTG suppliers, as well as specialized technology providers offered integrated ice detection and/or deicing systems with various techniques to support the investors or operators of the wind energy projects to increase the electrical energy production and to decrease the Long Run Marginal Costs.

The feedback from the market from supplier’s side is that they are constantly developing their systems and are supporting the operators in increasing their productivity and safety. On the other side, the operators believe the detection and anti-icing systems are not efficient enough and there is space for improvements.

The author of this thesis, who is since 10 years active in the wind energy business, identified a gap between the operators′ lack of information and understanding of the available technologies and the supplier’s overview on the wind energy market needs.

Next to this actual market situation, it is quite difficult for the authorities, responsible for the authorization of construction and operation of a WTG, to follow the rapide technology development. Their main objective is the safe operation of the WTG, they must rely on different certifications for different components. The author will try to support with this Master Thesis all involved parties and to show that a comprehensive de-icing concept, is not just the result of the selection of the best components but particularly a result of a process, which starts already in the very early planning of a wind park project.

But also, due the massive changes in the renewable energy market in the European Union (EU), by turning away in several countries (e.g. Germany) from fixed feed in tariff models for the delivered renewable energy to a public tender system, we see decreasing market prices. The investors and operators of WTGs will not just put more and more pressure on the WTG technology suppliers to decrease the investment costs but will also focus more than in the past on the optimization of the energy production output.

The core objectives of the Master Thesis are to define which measures should be taken during the planning and operation phase of a wind energy project, to avoid economical losses and to minimize safety risks during the operation of the WTGs under cold climate conditions and to bring the relevant demands of the operators to the suppliers, making available the already existing technologies for the operators.

In order to achieve the objectives, the author follows the next steps:

1) introduce the theoretical foundations on the physics of ice and icing effects
2) an overview of available technologies for the operation of WTGs under cold climate conditions from detection systems as well as deicing systems
3) show on a concrete project, how the above measures could be implemented and latest technologies could be used to reduce the safety risk for material and people as well as to optimize the AEP

The methodology of this Master Thesis is based on three main pillars

- Literature review: the main literature in the context of this master thesis is going to be screened and the most important findings summarized to give the reader an overview about state-of-the-art knowledge
- Expert interviews: international WTG suppliers, technology providers as well as wind energy project operators have been contacted for interviews

Assessment of the latest authorization processes in Austria, most of the time Environmental Impact Assessments and the connected technical reports and studies for the construction and operation of WTG projects in Alpine areas.

2. Background information

2.1 Political framework in the European Union and Austria

It was agreed between governments during the United Nations climate change conference in Paris, COP 21, that there is an immediate need to increase our global response to climate change.

The Paris Agreement is based on the Convention and focuses all the nations on a common cause: bringing together their efforts to combat climate change and adapting to its effects, while increasing the support for the developing countries in this direction.

The main objective of the Paris Agreement is to strenghten the global response to the climatic challanges, to maintain the increase of the global temperatures in this century under 2 degrees compared to the pre-industrial levels and continuing the efforts to limit the increase of temperatures up to 1,5 grades Celsius. Aditionally, the agreement aims to consolidate the capacity of the countries to face the impact of the climatic changes. In order to reach these objectives, there will be used financial resources, a new technological frame and consolidated framework, supporing the developing and most vulnerable countries.

The Republic of Austria ratified as one of the first EU countries the Paris Agreement and since 04th of November 2016 it is legally in force.

The common defined goals are as following:

- Limitation of the increase of the average global temperature under 2°C compared to the pre-industrial level and to step up efforts to limit it under 1,5°C
- Building up a balance between anthropogenic Green House Gas Emissions (GHG) and the reduction of GHG in the second half of the 21st century
- Increase the ability to meet the obligations, for more climate resilience and reduction of GHG to adapt to the impact of the climate change
- The compatibility of global cash flows with the target of reduction of GHG as climate resilient developments

The GHG – emissions of Austria have been decreased between 2005 and 2016 from 92,7 Mio tons $CO_{2\ equivalent}$ per year to 79,7 Mio tons $CO_{2\ equivalent}$ per year. Since 2016 the GHG – emissions are slightly increasing again.

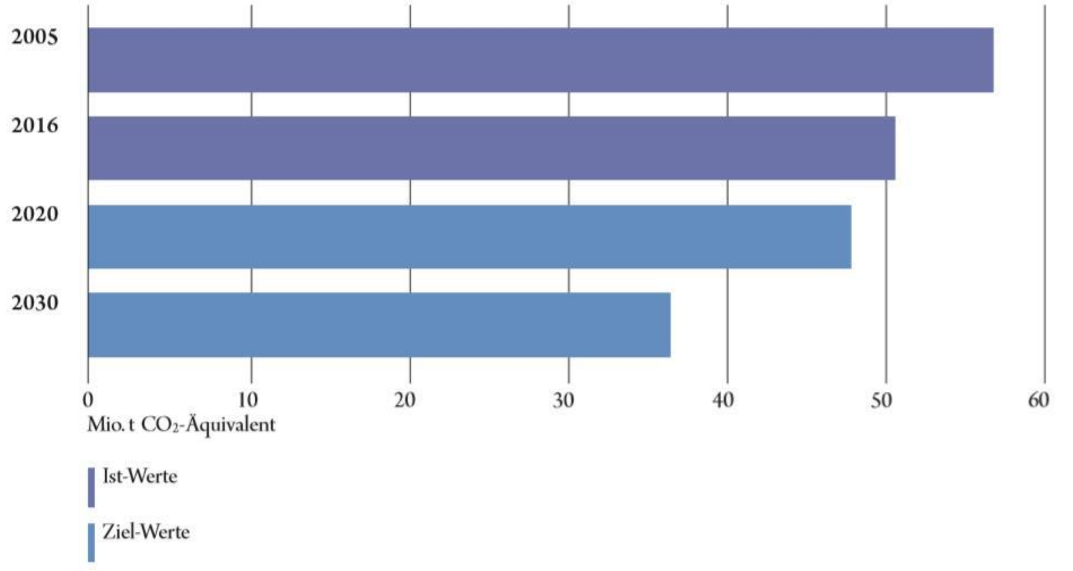


Figure 2.1 GHG emissions Austria target, Source: Umweltbundesamt, 2018

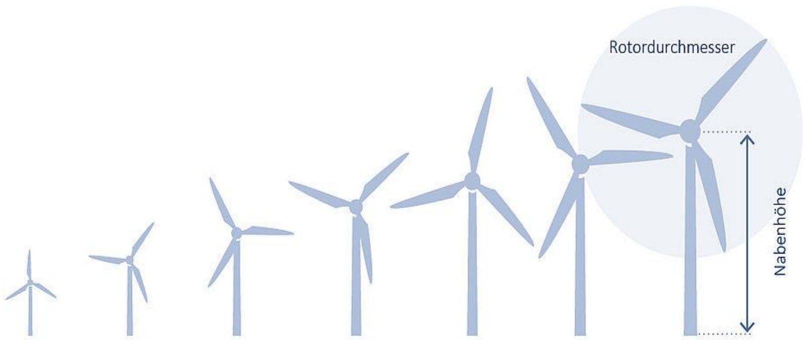
According to the actual plan of the Austrian government stated in the #mission 2030 from June 2018 the target for 2030 is the reaching of 36,4 Mio tons $CO_{2\ equivalent}$. Through a mix of different measures in all energy sectors, like production of electricity and heat or mobility this target shall be reached.

One of the targets is to reach in 2030 a production of electricity generated out of 100% renewable energies, therefore the Austrian Energy agency calculated an additional demand of renewable energy production of 29,2 TWh. However the political discussion will lead finally to this or other numbers and however the mix between the different renewable energy technologies will look like, there will be an increase of additional installation of new wind turbine generators and the repowering of existing ones.

2.2 Wind energy technology

The wind turbine uses wind energy - more precisely the power contained in the wind and converts it with the wind turbine first into mechanical and then via a generator into electrical energy.

The efficiency of a typical wind turbine is currently just under 50 % at the design point. The system is designed for the energy supply, which does not focus on the maximum power, but on the optimal energy yield. This means that the system must adapt to the changing wind conditions. Among other things, grid integration is at the center of development for modern plants and wind farms. Today, the wind farm must contribute to a stable and secure power supply in terms of security of supply.



	1980	1985	1990	1995	2000	2005	heute
Max. Nennleistung (kW)	30	80	250	600	1.500	3.000	7.000
Max. Rotordurchmesser (m)	15	20	30	46	70	90	130
Überstrichene Rotorfläche (m²)	177	314	707	1.662	3.848	6.362	13.273
Max. Nabenhöhe (m)	30	40	50	78	100	105	150
Max. Jahresenergieertrag (MWh/a)	35	95	400	1.250	3.500	6.900	15.000

Figure 2.2 Comparison of wind turbines, Source: Enercon, 2010

Technical development: Increased performance of wind turbines

In recent decades, the technical development and thus the growth in size of wind turbines have developed rapidly. The wind turbine currently in use in Germany has a rotor diameter of approximately 90 meters, a nominal power of 2.5 MW and a tower height of between 80 and 130 meters, depending on the location. Large systems are about twice the rated output and diameter. Thus, the nominal power has increased tenfold in the past ten years, the rotor diameter and the hub height have doubled.

Components of Enercon E-115 E2

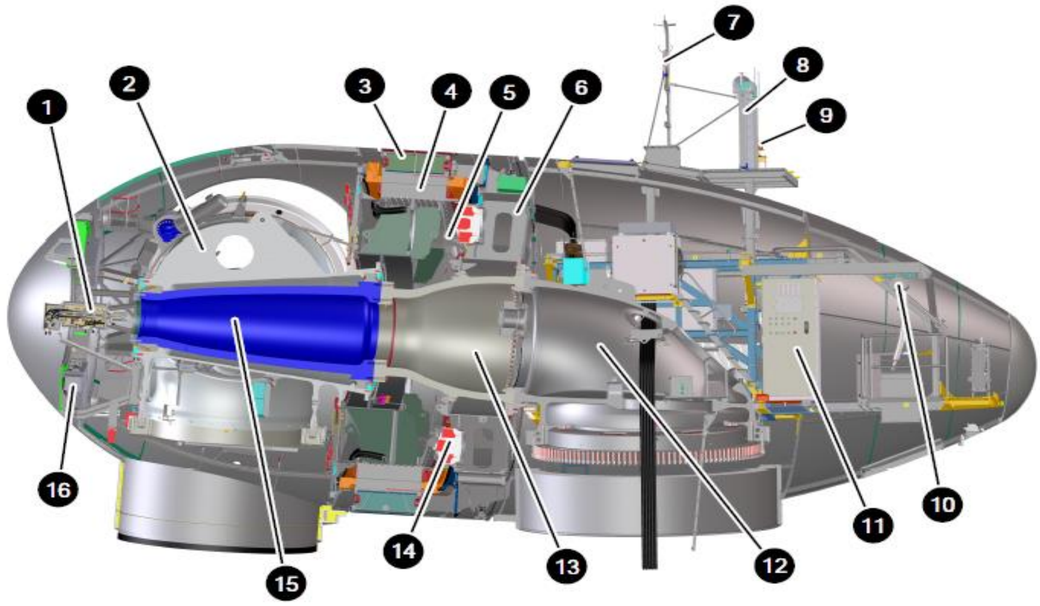


Figure 2.3 Nacelle section, Source: Enercon, 2010

1 slipring transmitter	9 firing (optional)
2 rotor hub	10 cargo winch
3 Generator stator	11 Nacelle control cabinet
4 generator rotor	12 machine carrier
5 rotor brake	13 spigot
6 stator carrier	14 generator fan (6x)
7 Wind gauge with lightning rods	15 journals
8 Recooler Generator-Stator	16 BV module (blade adjustment module)

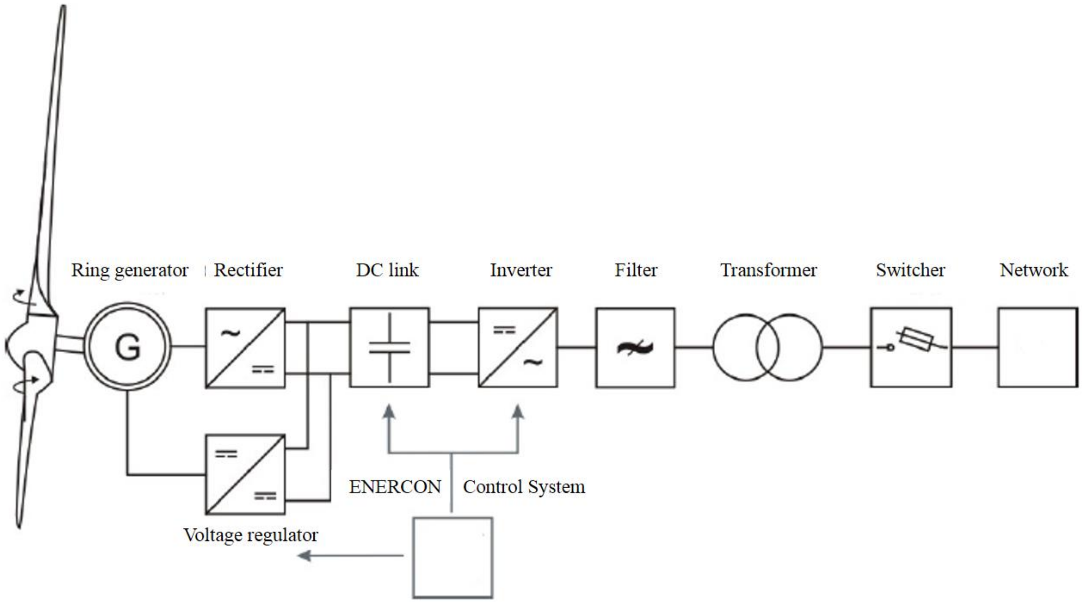


Figure 2.4 Simplified electrical diagram of an Enercon wind turbine, Source: Enercon, 2010

Energy conversion

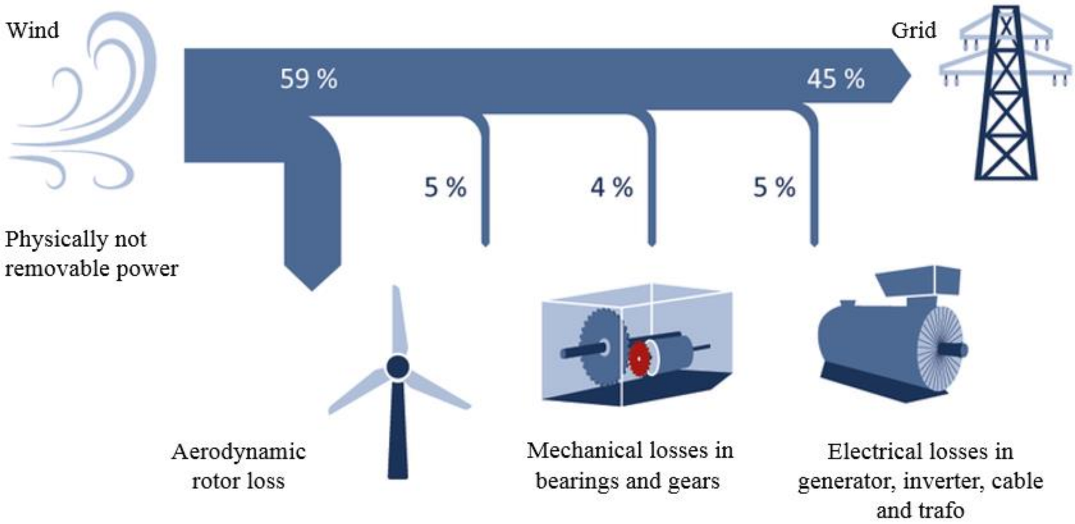


Figure 2.5 Energy conversion, Source: Enercon, 2010

Wind energy is the kinetic energy of moving air (from Greek kinesis = movement). In the conversion into electrical energy by a wind turbine, the energy of the wind must first be converted via the rotor blades into mechanical rotational energy, which then supplies electrical power via a generator. The transformation of the kinetic energy of the wind into electrical energy, like all energy transformations, is subject to energetic "losses". This means that physically no more than 59% of the power can be taken from the wind (see law of Betz). In addition, aerodynamic losses due to friction and turbulence on the rotor blade are added. Approximately another ten % losses are caused by friction in the bearings and gearbox, as well as in the generator itself, in the drives and cables as electrical losses.

Kinetic energy

Every moving mass m (body, liquid or gas) contains kinetic energy E_{Kin}. It is equal to half the mass of the body times the square of the velocity v. For wind turbines, the moving mass is the air that flows through the rotor surface.

$$E_{Kin} = \frac{1}{2} * m * v^2$$

Energy and performance

The air flow, also called mass flow, which flows in a certain time through the rotor surface of a wind turbine, is:

$$m = A * p * v$$

The power P is equal to the energy E per unit time. Thus, for the performance of the wind results:

$$P_{Wind} = E = \frac{1}{2} * m * v^2$$

Since the air flow rate is proportional and the energy of the wind is dependent on the square of the wind speed, the power of the wind depends on the cube of the speed.

$$P_{Wind} = \frac{1}{2} * p * \pi * R^2 * v^3$$

Thus, the decisive factor for the performance of the wind is its speed. If the wind speed increases by 3 times, the power will increase by 3x3x3 = 27 times. The density of the air has a linear influence on the performance. Cold air is denser than warm air, thus providing a wind turbine at the same wind speed e.g. at -10 ° C about 11% more energy than at + 20 ° C. Since the density of the air is also dependent on the ambient pressure, high and low pressure areas as well as the altitude of the location have an influence on the yield of a wind turbine.

Mechanical performance

On the rotating shaft of the rotor, the mechanical power Pmech is determined by the product of torque M and rotor angular velocity Ω or speed n:

$$P_{Mech} = M * \Omega = M * 2\pi * n$$

Electrical power

The driven generator converts mechanical power into electrical power, which is determined by the product of current I and voltage U. Here is the law of induction, which describes the coupling of electrical and magnetic quantities. In the case of the generator, the induced voltage results in an electrical conductor moving in the magnetic field as an effect. In the case of the motor, the force on a current-carrying conductor in the rotating magnetic field is the result.

Figure 2.6 ENERCON E-115 E2 general overview, Source: Enercon, 2010

2.3 Cold climate condition

Cold Climate (CC) is defined as a region that has frequent atmospheric icing or periods with temperatures decreasing below the operational limits of standard IEC 61400-1 ed3 for wind turbines. CC conditions may have an impact on project implementation, economics, and safety.

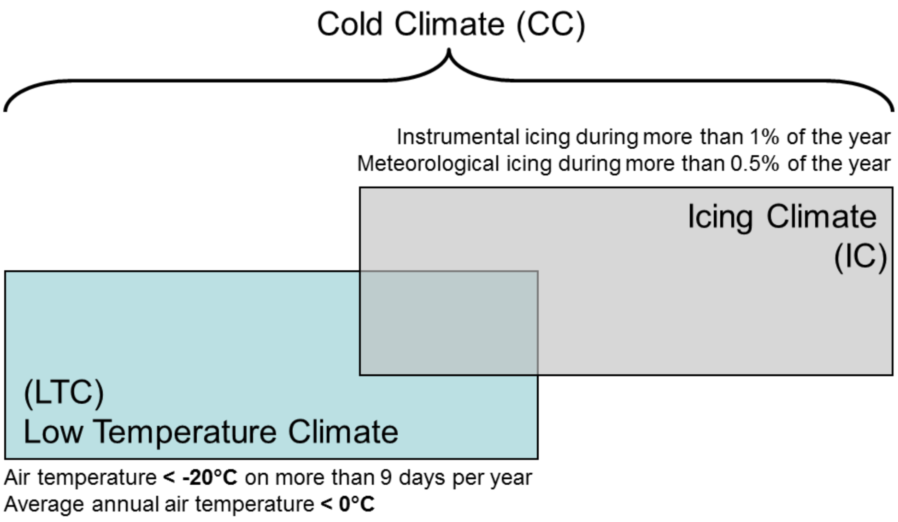


Figure 2.7 Definition of Cold Climate, Low Temperature Climate and Icing Climate, Source: IEA Wind Task 19 - Available Technologies report of Wind Energy in Cold Climates, 2016

Low Temperature Climate (LTC) regions are represented by areas that have periods with temperatures decreasing below the operational limits of standard wind turbines. Areas with atmospheric icing are called Icing Climate (IC) regions.

To understand the influence of cold climate on the operation and performance of wind turbine, the International Energy Agency (IEA) launched task 19 "Wind energy in cold climates" in 2001.

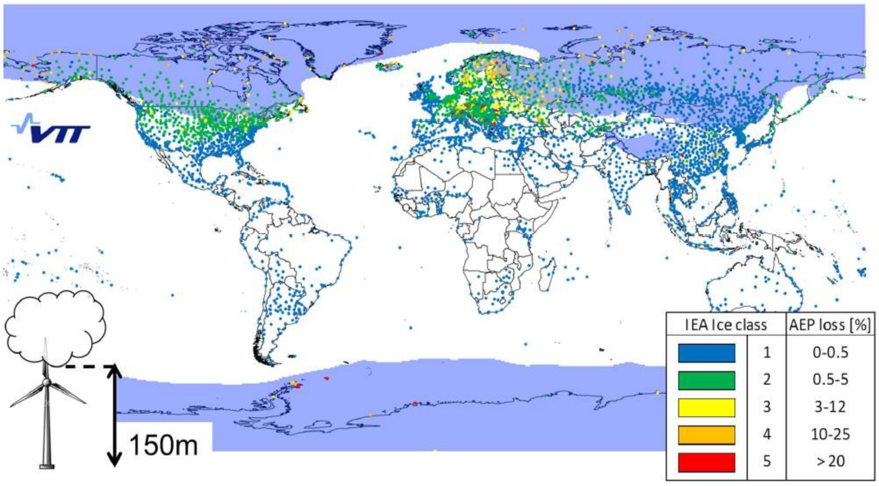


Figure 2.8 IEA Ice class classification, Source: VTT Technical Research Centre on Finland Ltd, 2016

There are regions where the WTGs are facing only atmospheric icing or low termperature, but there are also areas where both atmospheric icing and low temperature events can occur.

Even if a site is located in a Low Temperature Climate, in an Icing Climate or is facing both situations, it is still classified as a Cold Climate site.

In February 2017, the Task 19 workgroup of IEA draws the latest global icing map. The aforesaid icing map not only shows the distribution of global icing regions, but also the ice class and AEP (Annual Energy Production) loss.

2.3.1 Icing climate

Atmospheric icing is defined as the period of time where atmospheric conditions are present for the accretion of ice or snow on structures that are exposed to the atmosphere. Atmospheric icing can have an impact on the WTG. Usually it has the form of in-cloud icing (as rime ice or glaze) and/or precipitation (like drizzle, wet snow or freezing rain).

IEA Icing Climate site classification

Table 2.1 Evolution of an icing event, Source: Task 19 Wind Energy in Cold Climates, International Energy Agency (IEA), 2017

IEA Ice Class	Meteorological Icing	Instrumental Icing	Reduced Production
	% of year	% of year	% 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	<1.5	0 - 0.5

Besides the various types of atmospheric icing, the ice can be:

Rime ice: The water drops from clouds or fog, which are cooled, can be transported by the wind. When these droplets hit a surface, they freeze. If the droplets are small, soft rime is formed, but if the droplets are bigger, hard rime is formed. Rime ice growth is asymmetrical, located only on the windward side of a structure, and it can occur at temperatures down to -20°C. Rime ice growth typically occurs at higher temperatures than -20°C.

- Glaze ice: Glaze ice can apprea due to freezing rain, freezing drizzle, or wet in-cloud icing. It forms a smooth, transparent, and homogenous ice layer which is stronlgy adhesive. It usually appears between temperatures of 0 to -6°C. It's density is higher compared to rime ice. It occurs when warm air is melting the snow and forms rain drops, which fall through the freezing air to the ground. Wet in-cloud icing may appear when the surface temperature is close to 0°C. During glaze ice formation, the water drops hitting the surface do not freeze entirely. This layer can move due to wind and gravity.
- Wet snow: represents melted snow crystals that have a high liquid water content. These crystals are highly adhesive to the surface of an object. Wet snow accretion, appears at temperature is between 0 and +3°C.EA Ic

Atmospheric icing can have the following effects on a wind energy project:

- Icing affects wind measurements, leading to data loss and increased measurement uncertainty.
- Heavy ice loads can cause the collapse of measurement towers that were not dimensioned for the CC site conditions.
- Ice on the wind turbine blades may increases the noise levels of a wind turbine.
- Potential ice throw from the blades of a wind turbine is a safety issue.
- Ice on rotor blades leads to icing related production losses.
- Energy yield calculations for sites with icing condition have an increased uncertainty compared to standard operation conditions.
- Due to the ice on WTG blades, there can be imbalances in aerodynamic and mass. Over the time, this can increase the loading of components, and the WTG life time can be reduced.

- The mainenance and service is more difficult in case of icing.
- Depeding on the structures, instrumens and WTGs exposure, an icing event can be described with the following:
  - Meteorological Icing: The period when the meteorological conditions (such as temperature, wind speed, droplet distribution, water characteristics) allow accumulation of ice.
  - Instrumental Icing: The period during which ice is present/visible on a structure and/or a meteorological instrument.
  - Rotor Icing: The period during which ice is present on the rotor blade of a wind turbine. In case of rotor icing, the incubation and ablation times are shorter compared to instrumental icing. There is significant difference between the duration of rotor icing for a wind turbine at stand still in comparison to a wind turbine under operation.
  - Incubation is defined as the period between the meteorological icing and the instrumental/rotor icing. It depends both on the surface and the temperature of the structure.
  - Accretion: The time when ice is growing (active ice formation).
  - Persistence: The total time duration when ice remains on a structure (no ice growth).
  - Ablation: The time when ice is being removed from the structure through natural means. Ablation comprises melting, erosion, sublimation, and shedding of ice. This represents the time between the end of meteorological icing and the end of instrumental/rotor icing.

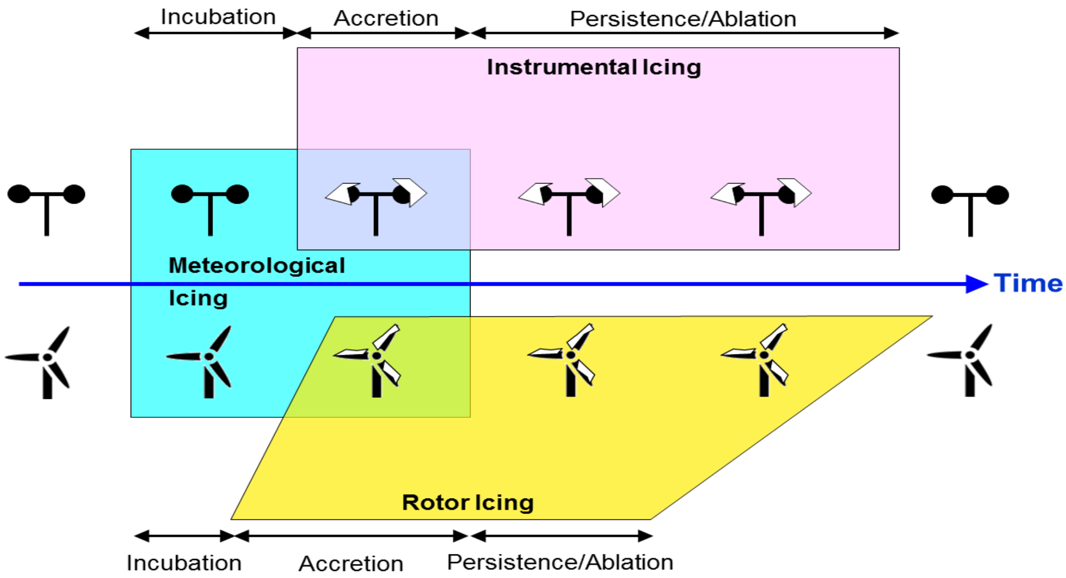


Figure 2.9 Definition of Meteorological Icing, Instrumental Icing, Rotor Icing, Incubation, Accretion, Persistence, and Ablation, Source: Task 19 Wind Energy in Cold Climates, International Energy Agency (IEA), 2017

More detailed description of the icing conditions:

- Icing Intensity: Ice accumulation on a specific time on a structure [cm/hour or g/hour]
- Ice Load: Ice mass accreted on a structure [kg/m]

2.3.2 Low Temperature Climate

Low temperature climates (LTC) are most common in polar regions, and are often associated with high pressure systems that lead to clear skies and a corresponding increase in radiation from the surface to the atmosphere. However, they can also be located in areas of high elevation, in the middle latitudes. Most regions that experience very low temperatures are also located either far from coastlines, or along coasts that freeze during the winter.

LTC can lead to the following effects on a wind energy project:

- Materials of the WTGS and its components are usually influenced by low temperatures.

- High air density leads to higher energy densities, which needs to be considered in the control of the wind turbine.
- Maintenance and service under low temperature conditions take more time.
- Cold start of a wind turbine can be more difficult at low temperatures.
- Oils and lubricants can lose their viscosity.
- Heating of the components increases a wind farms internal energy use, reducing the energy it can provide to the grid. (Source: Task 19)

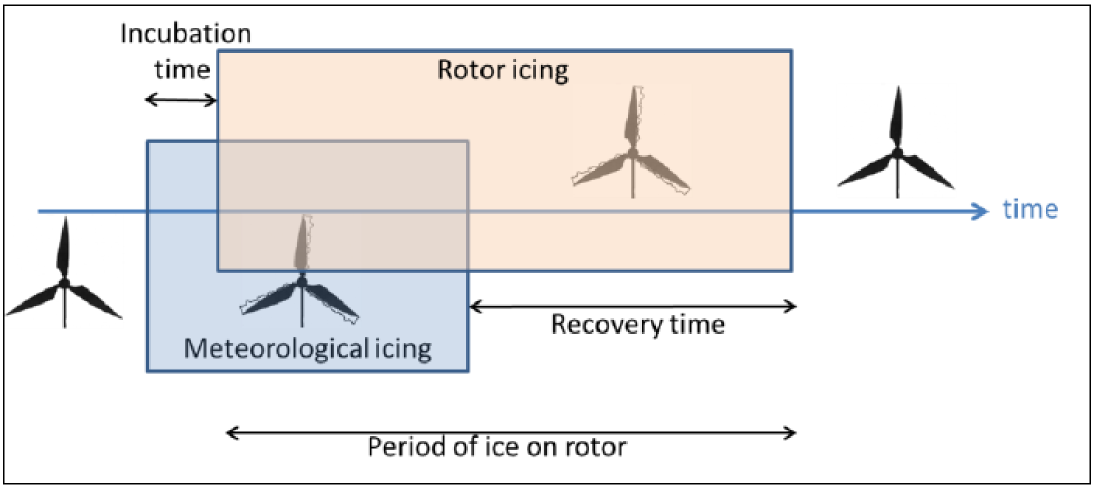


Figure 2.10 Stages of Meteorological Icing, Instrumental Icing, Rotor Icing, Incubation, Accretion, Persistence, and Ablation, Source: Task 19 Wind Energy in Cold Climates, International Energy Agency (IEA), 2017

2.3.3 Icing effects

Downtime

Unless there is installed an ice mitigation equipment, wind turbines must be stopped in order to prevent mechanical damage. This corresponds to huge power losses for wind farms with frequent icing events, taking into account that the effect on wind turbines is up to four times the duration of the meteorological icing event. Downtimes vary from several days up to weeks, due to the ice on the blades. Usually the icing events are frequently associated with high wind speeds, and this makes production losses much more impactful. A statistical study conducted in Germany, in 2005, showed that downtime is the biggest impact of an icing event.

Aerodynamic loss

The impact of ice shape on the airfoils is frequently referenced in the literature. It generally increases the roughness and damages the profile of the airfoil, leading to significant loss of performance. Also the convective heat transfer coefficient is modified. Depending on factors such as intensity, duration and frequency of icing events, annual production losses can be between 0.005% and 50%. Each icing event has the potential to reduce the wind energy production by 15 – 30 %. There have been developed power curves for wind turbines affected by ice accretion by using field measurements and/or models. Specific 3D power curves describe energy as a function of wind speed and ice load, and make a comparison between losses due to icing and actual energy production. These comparisons prove that there is still considerable uncertainty of the actual power generation losses.

Shorter life expectancy

When the WTGs blades are covered in ice, they become unbalanced, in addition to increasing the load on the components. Despite the fact that the wind turbines are designed to support heavy loads according to safety standards, component fatigue may reduce their operational life. The effects are such as:

- Additional ice causes higher deterministic loads.
- Asymmetric masses will cause unbalance.
- Ice accretion increases the vibrations.
- In case of the small WTGs with light rotor blades, there can be a change in the normal frequencies of the blades, causing resonance to appear.

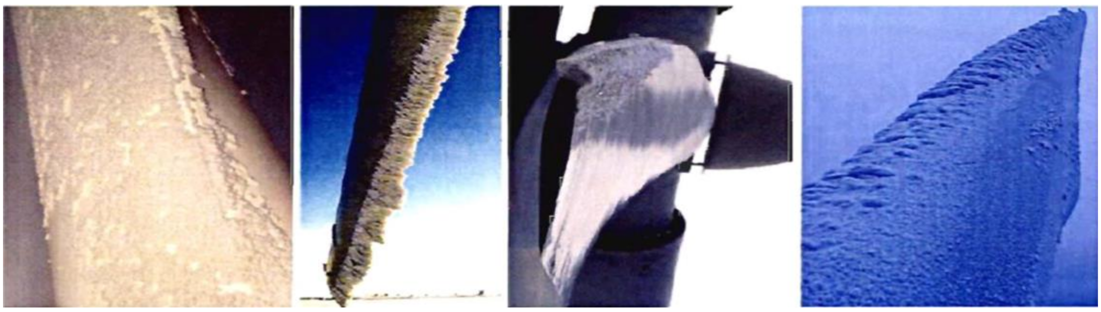


Figure 2.11 Airfoil shape altered by ice; Source: Système électrothermique de dégivrage pour une paled′éolienne: simulations ensoufflerie réfrigérée et impact sur la puissance produite.Université Du Québec À Rimouski, Mayer C, 2007

Secondary effects

The secondary but not less important effects are:

- Safety risks: pieces of ice from rotating blades can be projected at a distance depending on their weight and the blade velocity. It is a major safety risk for for the residents and employees, and for neaby roads and facilities.
- Overload due to delayed stall: ice accretion can delay the aerodynamic stall, which increases energy production. The peak of energy might damage the electrical components as they are not designed for the excessive amount of electrical power. Overloads also increase the stresses on the mechanical compo nents (gearboxes,blades) and can cause their deterioration.
- Increased noise his excessive amount of electrical power.

2.4 Planning phase

Different consulting companies and WTG suppliers started in the early 2000 years to investigate the field of icing reasons and effects. Target was not just to get a better understanding also to have a chance to implement the right measures in the planning phase, in the operating phase and to improve the known technologies.

2.4.1 Basis / General

One of the first known studies is the so called „Ice throw study Gütsch", which is Ice Throwing in Practice September 16, 2011 René Cattin, Enercon E-40.

The Swiss company Meteotest has observed on the Gütsch above Andermatt in the Swiss Alps a wind turbine with 46 m hub height and a rotor diameter of 40 m for several years with respect to ice accumulation on the rotor blades. A measurement of the ice pieces was conducted and documented.

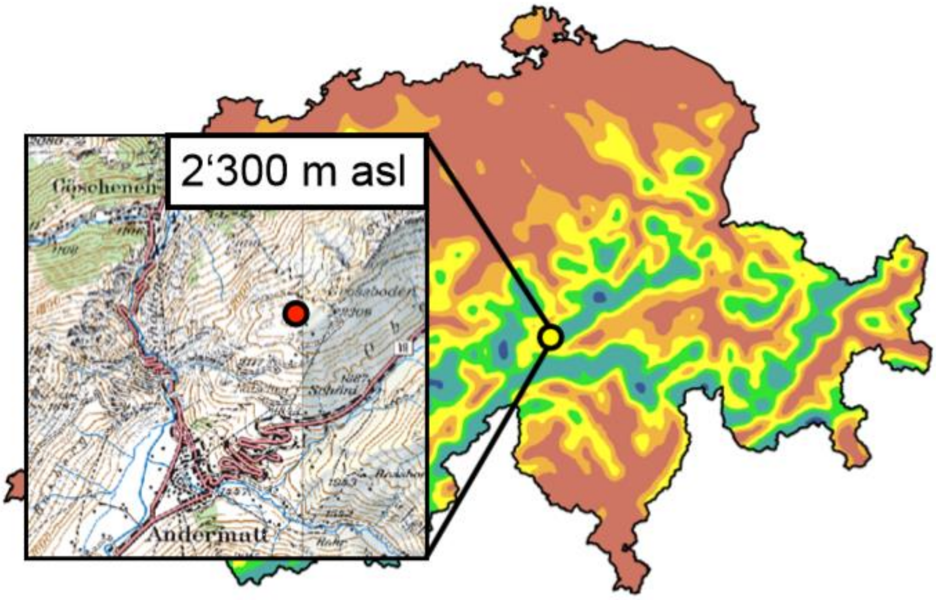


Figure 2.12 Wind turbine in Andermatt, Source: Ice Throwing in Practice, René Cattin, 2011

During 1 year, there were recorded approximately 7 days of meteorological icing, approximately 30 days of instrumental icing and approximately 150 days below freezing. After each icing event, the area of the system was examined locally.

All pieces of ice found were recorded and classified taking into account the distance, the angle to WTG, size, weight and type of ice (hoar frost, clear ice, wet snow).

Figure 2.13 Samples of ice, Source: Ice Throwing in Practice, René Cattin, 2011

Figure 2.14 Icing conditions, Source: Ice Throwing in Practice, René Cattin, 2011.

During 2005 – 2009, there was observed that icing can also occur during summer. The maximum recorded distance for ice throwing was 92m (2.25 rotor diameter), with 50% of the ice pieces landing in the area of the rotor. Out of the maximum weight of 1.8 kg, all of the heavy pieces of ice (> 600 g) landed in the area of the rotor.

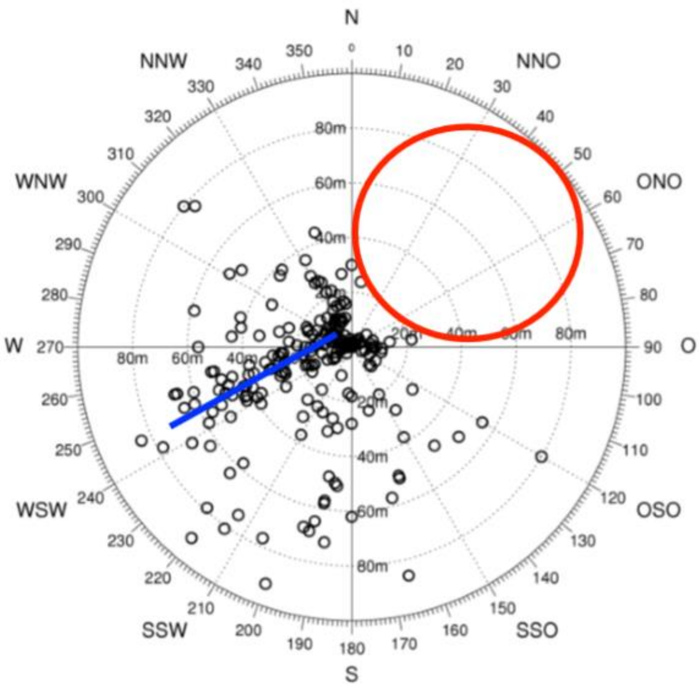


Figure 2.15 Hits of ice according direction from the WTG, Source: Ice Throwing in Practice, René Cattin, 2011

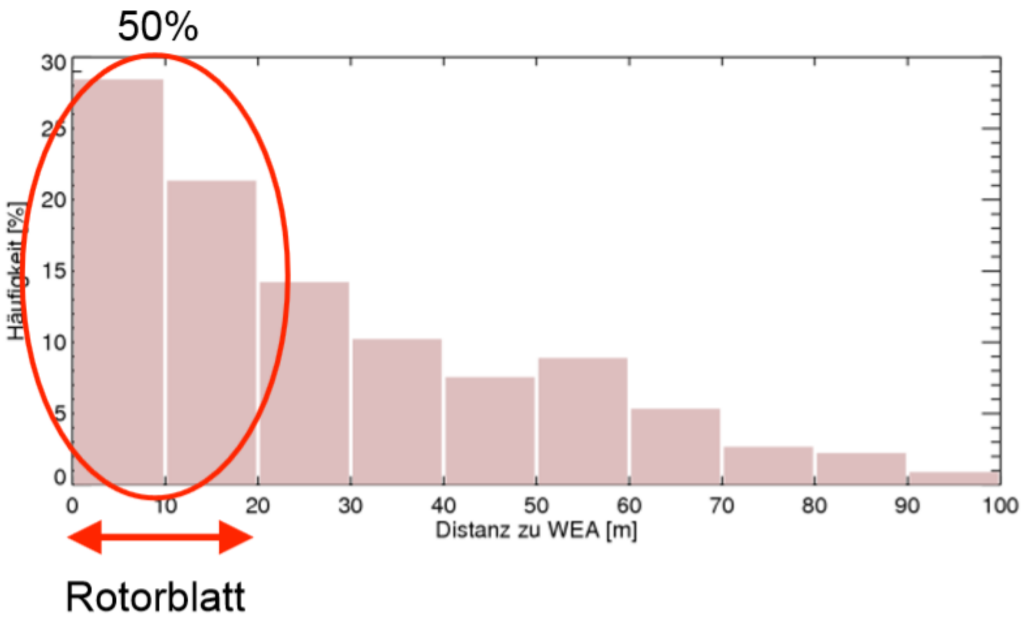


Figure 2.16 Hits with distance from WTG, Source: Ice Throwing in Practice, René Cattin, 2011

From the 2 studies result that two thirds of the pieces of ice had a weight of less than 200 g. 50% of the ice pieces were found within a radius of 20 m (rotor radius) around the base of the plant. The extremes were 1.8 kg in weight and 92 m in distance from the WTG (see (Cattin, Russi, & Russi, 2009)).

Recent studies, such as the "ICETHROWER - mapping and tool for risk analysis" study by Pöyry Sweden (see (Göransson, 2015)), confirm the results of the Gütsch study.

Within the framework of the focal points of the Wind Energy Research Program of the federal Government, this research was conducted on a project at the locations of St. Brais (2009 to 2015) and Mont Crosin (2014 to 2015).

There were installed webcams for the monitoring of icing conditions on the nacelle and on the rotor blades, aiming to extend the monitoring for the Mont Crosin site

The frequency of icing events at the sites of St. Brais and Mont Crosin was determined, as well as the typical temperature and wind conditions for ice formation. This was supplemented with the evaluations of the location Gütsch. There was also conducted a comparison with the icing map of Switzerland.

During the evaluation of different systems for ice detection on the rotor blades of the WTG at the St. Brais site, there was performed a comparison of the power curve with the actual production, obseerving temperature and relative humidity for Moog and Insensys rotor blade monitoring system

The efficiency of the blade heating was determined by evaluating the webcam images at the location of St. Brais. The required energy and cost-benefit ratio were calculated, taking into account the completeness of ice removal, comparison of different operating modes of blade heating, yield losses with and without rotor blade heating.

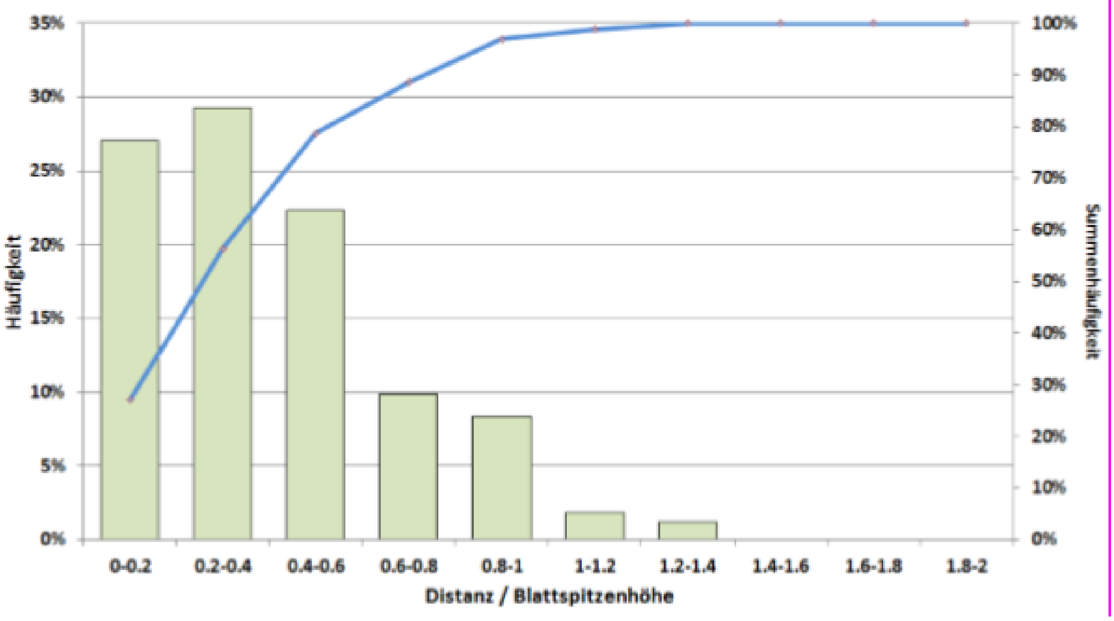


Figure 2.17 Frequency distribution of the ice pieces found (Gütsch, St. Brais, Mont Crosin) depending on distance, standardized with the blade max height of the respective wind turbine, Source: Ice Throwing in Practice, René Cattin, 2011

The analysis has shown an increased frequency of ice thrown for a distance measuring up to a blade top height for all three locations. For longer distances the observed frequency decreases significantly. The risk radius for ice throw according to the frequently used the formula for calculating risk: 1.5 * (rotor diameter + hub height) for the three investigated locations is in the range of 1.9 to 2.0 x blade max height and was never reached during the field studies.

When planning and operating wind farms under icing conditions, the risk of ice throw must therefore be assessed in each case and a corresponding park layout and risk concept has to be worked out.

Based on the meteoroligical studies, first analyses can be made and the risk, frequency and distance of ice throw can be calculated. These analyses are then implemented in planning and authorization process.

For most of the approvals for a wind energy project, in EU – member countries an Environmental Impact Assessment (EIA) has to be carried out. The project applicant must submit an environmental impact declaration to the authority together with the application for approval and the documents required by the administrative regulations for approval of the project. In some countries the Ice Fall Risk Assessment has to be part of the Environmental Impact Assessment

These reports are based on different assumptions and also equipped ice detection systems. The datas of wind measurement campaigns carried out in the project area are used as input data for the calculation of the fall widths and their directional distribution.

The ice fall models calculate, based on the meteorological conditions at the location as well as the characteristic data of the wind energy plant (hub height, rotor diameter), the trajectory of a piece of ice from its appearance until the impact on the earth. With the aid of a time series of wind speed and wind direction, the frequency of impact of the ice pieces around the system can thus be determined. For each available time series, a simulation is performed.

For the calculation, it is assumed that a piece of ice has no or hardly no velocity at the time of dropping (blade stands still or in taillspin mode) and it occupies a random position on a rotor blade. From the time of detaching, the piece of ice is subject to gravity and air resistance as well as the energy of the wind, which deflects it from its orbit. The calculation of the trajectories is done using coupled equations of motion with drag coefficient, the adjusted air density and including a wind profile of wind speeds present in the project area altitude.

For ice fall simulations, the hits are counted in monitoring grid with a width of 1 x 1 m. From the simulated incidence frequencies, it can be calculated the probability with which a monitoring grid is hit by a piece of ice of a certain size.

The impact probabilities of the pieces of ice resulting from the simulation are displayed in graphic for the entire winter half year.

For the calculations, there are used parameters that characterize the dimensions of the ice piece, the height and rotor radius of the wind turbine and the meteorology at the site.

Ice-throwing model gives the specific probability of ice throw around each wind turbine of a specific wind farm. The model determines the path of millions of ice pieces, taking into account the wind speed and direction.

The wind turbine is always directed in the wind and the rotation speed is adjusted according to the current wind speed.

Typical features related to the location and WTG (like wind speed, air properties, rotor blade diameter and hub height,) are considered.

Dimensions of ice pieces

The pieces of ice found on the above mentioned Gütsch lead to a conclusion regarding the frequency distribution of the mass in an icefall event.

In order to meet this frequency distribution, a piece of ice has to be defined with fixed density value and dimensions. The dimensions of the pieces of ice are based on the actually observed icefall events:

- Weight class 0g-100g: Small piece of ice, clear ice; Dimensions 0.08 x 0.04 x 0.03 m / ice density 900 kg / m3. (86g)
- Weight class 101g-500g: Small piece of ice, hoarfrost; Dimensions 0.10 x 0.08 x 0.05 m / ice density 600 kg / m3. (240g)
- Weight class 501g-2500g: Large piece of ice, hoarfrost; Dimensions 0.50 x 0.10 x 0.05 m / ice density 600 kg / m3. (1.5 kg)
- Weight class 2501-4500g: Large piece of ice, clear ice; Dimensions 1.00 x 0.20 x 0.03 m / ice density 900 kg / m3. (5.4 kg)

The current literature assumes that a safety-relevant piece of ice has a minimum weight of 100 g-150 g. By considering a piece of 86 g, a corresponding safety buffer is installed.

According to the experience from studies on ice fall observations (for example Gütsch study (Cattin R., 2012)) [5], about 3.000 safety-relevant pieces of ice per winter half-year can be assumed. With 25 icing events per year, this corresponds to about 120 safety-relevant pieces of ice per event.

Modeling the danger area

It presents the results of the simulations of the impact probability in the vicinity of the wind turbines, incl. the data on the wind conditions in the winter period, the impact probabilities can be then calculated.

The different color ranges represent the probability per m² that at least one particle strikes. The highest hit probability is in the red area and decreases logarithmically up to the blue color. The full coloured zone can be called the risk zone.

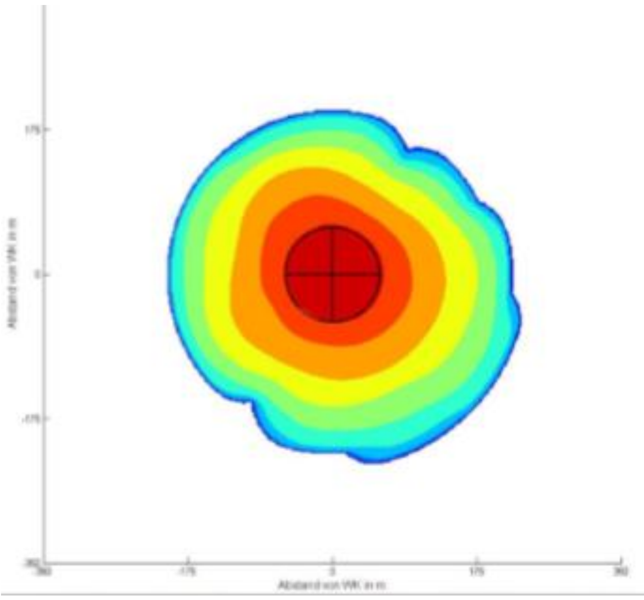


Figure 2.18 Ice hit probability, Source: Ice Throw Risk Assessment EWS-Verein, Pretul 2018

2.4.2 Risk analysis

The aim of the risk analysis is to identify potential events that can negatively impact persons, assets and the environment, and to implement control measures that eliminate or reduce the potential risk-related consequences. A risk analysis is critical for mitigating accidents and improving safety.

It is generally accepted that the most critical risk is the one affecting the integrity of persons, namely injuries or death. Thefore, it is intended that wind power plants do not significantly increase a person's risk of injuries or death.

With the aid of the calculated probability of ice throw and the maximum distances, it can be determined whether a road, a hiking trail or a trail is in the danger zone. Here we differentiate between icefall of a standing WTG or ice throw of an operating WTG.

Combined with the likelihood of a person or object near the wind turbine, the risk of getting hit by a piece of ice is determined and related to socially acceptable risks.

Since there are no risk limit values defined for ice fall for WTG, there can be used general international statistics for determining the risk of death, like the minimum endogenous mortality principle, which measures the generally accepted risk of death due to a particular technilogy.

When performing a risk analysis of icing of wind turbines, there are 2 major aspects to be taken into consideration: the probability of an icing event and the potential damage.

Probability calculation

In order to assess the probability, there must be determined which is the risk period (winter) and the lenght of exposure in the danger zone (frequency). The number of events over a time period is observed, taken into account the impact probability and the presence probability for persons.

The paths for pedestrians can be: frequently used path (20-200 people / day) - local infrastructure, regularly used trail (2-20 people / day) - accessibility to hiking destinations, occasionally used path (0,2-2 persons / day), normally unused path (0-0.2 people / day): - access roads for forestry or agriculture.

The duration of exposure represents the full period between entering the danger zone until leaving it.

Potential damage

The potential damage is assessed individually, depending on several factors, and is mainly split in 2 cathegories: impact on non-operating and operating personnel.

The risk of death is calculated for pedestrians by the probability to be hit in the head (0 ,04 m^2) and for vehicles by the probability to be hit in the windscreen (2 m^2).

According to CENELEC, 2000, the statistical risk of death of an European adolescent is 0.0002 (2 * 10-4) deaths per person per year.

Risk for non-operating personnel

In countries with a high level of technical development, it is assumed that, on average, every person is exposed to 20 technical systems, which sets the lower limit for the generally accepted risk of death at 0,00001/year for each system (CENELEC, 2000). Also, taking ingo account other aspects for the socially accepted risks, there is added a futher safety factor of 0,1. Given the senzitivity of the subject and the lack of clearly defined limits for this specific technology, it can be considered that the socially accepted risk of death of persons not belonging to the company ≤ 1 * ** * 10-6.

Risk for operating personnel

The death risk in the workplace may be higher than the risk of "involuntary" death, especially when in contact to sources of danger, such maintenance of machinery.

The accepted risk of death in the workplace must not exceed the natural risk of death, which is 50% of the MEM. Adding the safety factor of 0.1, it leads to an accepted risk of death operators ≤ 1 * 10-5.

Probability for residents

In order to assess the probability for residents, there must be determined which is the risk period (winter) and the lenght of exposure in the danger zone (frequency).

The paths for pedestrians can be: frequently used path (20-200 people / day) - local infrastructure, regularly used trail (2-20 people / day) - accessibility to hiking destinations, occasionally used way (0,2-2 persons / day), normally unused path (0-0.2 people / day): - access roads for forestry or agriculture are considered "normally unused".

2.5 Technologies for ice protection systems

In terms of energy, there are two types ice protection systems: active systems and passive systems. Active systems need an energy supply in order to operate while passive do not need energy. Ice protection systems can be used as anti-icing, de-icing, or both.

Some of the ice protection systems require stopping the wind turbine. Some of the causes are the high risck of ice projections or the WTG engine cannot support the operation of the WTG itself and the ice protection system in the same time. (Source: Ice protection systems for wind turbines in cold climate: characteristics, comparisons and analysis, 2016 Elsevier Ltd)

2.5.1 Active – de-icing

2.5.1.1 Chemical methods

Coatings can be added to chemical substances to reduce their freezing point. This way, there is created a thermal hysteresis between the melting point and the freezing point. This can be achieved using biochemical substances that leach the waterdroplets, such as antifreeze proteins. (Source: Farzaneh M, et al. Anti-icing and de-icing techniques for overhead lines. Springer,; 2008.).

There can be used freezing point depressant fluids to avoid the freezing of supercooled droplets. These fluids are already widely used to de-ice and protect aircrafts. Liquid gels are commercially available and they have the same constraints as icephobic viscous coatings. This method can either prevent the development of ice on the structure, or, by maintaining a thin film of water between on the structure, below the ice. This makes the natural elimination of ice due to gravity or wind an easier process. (Source: La flamme J, etal. De-icing techniques before during and following ice storms - volume I : main report. CEA Technologies; 2002.).

Non-water soluble liquid gels can be used to reduce ice adhesion on the surface of the blade. These gels are named icephobic viscous coatings. Given the fact that the coating requires timely application, depends on the forecasting, can be used only on limited surfaces and are mostly non-biodegradable, they can be used only for certain cases. It is considered an active technique, as a pumping system is needed in order to bring the fluid to the top of the tower, besides an automatic controller. But the fluid is considered a passive device as it requires no power to protect the blades. It means that, depending on the type of controller, it can be used in de- or anti-icing mode. This would most likely be a low-cost method, but the system has to be designed before it can be tested.

2.5.1.2 Mechanical methods

2.5.1.2.1 Direct de-icing (knocking)

Mechanical removal systems include rope access or sky lift manual de-icing and helicopter de-icing using hot liquids.

Mechanical methods involve physically breaking the ice to accelerate its separation using scrapers or the energy released by the vibration or movement of the structure. These methods are designed primarily for de-icing.

2.5.1.2.2 Indirect de-icing (vibration de-icing and ultrasonic de-icing)

2.5.1.2.2.1 Pneumatic techniques

Pneumatic methods are commonly used to de-ice the edges of small-sized aircraft wings. When there is enough ice collected, the air chambers are inflated and deflated by the flows of compressed air. (Source: Mayer C, etal. Wind Tunnel Study of Electro-Thermal De-Icing of Wind Turbine Blades. IntJ Offshore Polar Eng 2007;17(3):182–8).

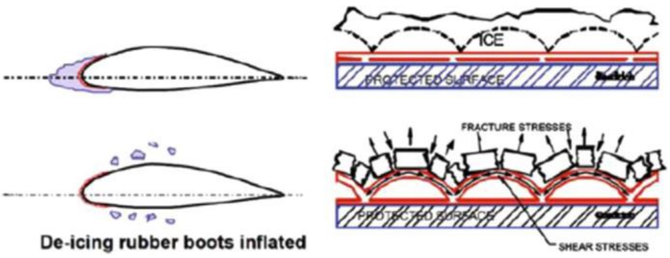


Figure 2.19 Working principle of inflated rubber boots; source: Botura G,Fisher K. Development of Ice Protection System for Wind Turbine Applications. In BOREASVI. Pyhätunturi, Finland: FMI 2003

2.5.1.2.2.2 Expulsive techniques

Expulsive methods use electro-magnetic or piezoelectric pulses to break off and eject the ice (Source: Mayer C. Système électrothermique de dégivrage pour une paled′éolienne: simulations ensoufflerie réfrigérée et impact sur la puissance produite.Université Du Québec À Rimouski,;2007). Electro-expulsive de-icing technique means placing a spiral coil near the inner face of a metallic plate.

2.5.1.2.2.3 Ultrasonic de-icing

The system behind this technique is to destroy the adhesion bonds between two surfaces. Therefore, it has a wide range of applications. The device uses ultrasonic waves that create stress at the junction of the two materials.

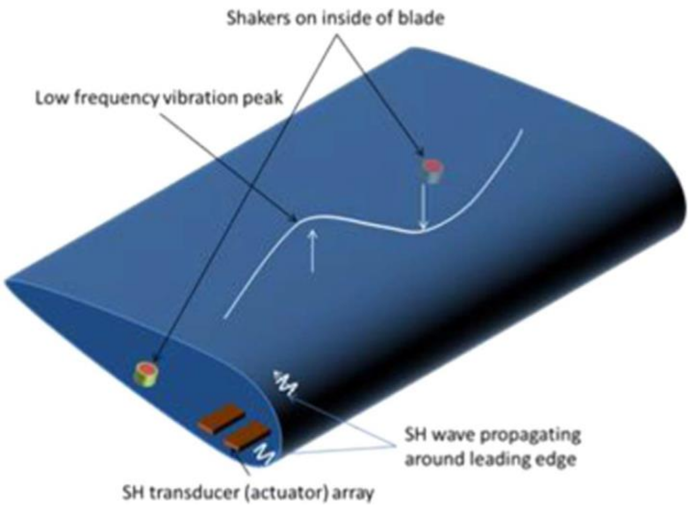


Figure 2.20 Ultrasonic de-icing technique currently being tested; source: DeIce-UT. Summary description of project context and objectives.From: ⟨http://www.deice-ut.eu/publications/⟩; 2014

2.5.1.3 Thermal methods

If the surface of interest has a temperature above the freezing point, this prevents ice to build-up. For this method it is required an external source of energy. Electrical heating elements such as metal or carbon fiber, might be subject to lightning so they need to be protected (Source: Tammelin B, et al. Icing effect on power production of wind turbines. In Pro- ceedings of the BOREAS IV Conference; 1998)

2.5.1.3.1 Hot air injection

Ice protection systems based on hot air incorporate a source of heat and a fan which circulate the hot air on the blade.

This technique was first used for Enercon wind turbines in 2009, and then for Senvion and Vestas. It is used for both anti-icing (Enercon, Senvion) and de-icing (Vestas). There are two main differences between its application on WTGs and aircrafts:

1. In aircraft, the hot air is produced by the propellant and does not need to be additionally heated.

2. In WTG, unlike the aircraft where the fan is in the middle of the wing, the electrical fan is located at the top and the hot air needs to be driven over a long distance

The system was tested at the Saint-Brais site, in Switzerland, with positive results. Nevertheless, the hot air injection system is energy consuming and that effectiveness depends on factors such as meteorological conditions and blade size. The consumption of the heating system for ENERCON E-82 and E-70 turbines is about 85 kW. At a nominal wind speed, a turbine produces approximately 96% of energy while heated. The annual production losses while the blades were heated were around 3.5%, compared to 10% when no heating. Production loss due to turbine stops was 3%, while the heating energy represented 0.5% of the annual production. (Source: Cattin R.Wind turbine blade heating – does it pay ? Meteotest 2010;2.)

When creating the device, there must be taken into account that the WTGs might be operating at high altitudes, where the air density decreases. If, for example, the air density is 10% lower than at sea level, then the efficiency of the system will also decrease by 10%. (Source: Battisti L. Wind turbines in cold climates. Springer; 2015.)

De-ice the blade with the heating film or other heating elements under the surface of blade or heat the inside of blade with hot air or other radiation sources and then the heat will be transferred to the blade surface through the casing (flow of hot air).

A fan heater installed near the blade flange heats up the air inside the rotor blades to a maximum of 72 °C.

The interior of the rotor blade is divided into sections with webs parallel to the blade axis. These webs are used to direct recirculating hot air through the rotor blade. From the fan heater, the heated air flows along the blade’s leading edge to the blade tip and then back to the blade flange between the blade's main webs. The air is then reheated and blown back into the rotor blade. This way the surfaces of the blade’s leading edge and middle segments are heated, which allows ice build-up on the blade to melt.

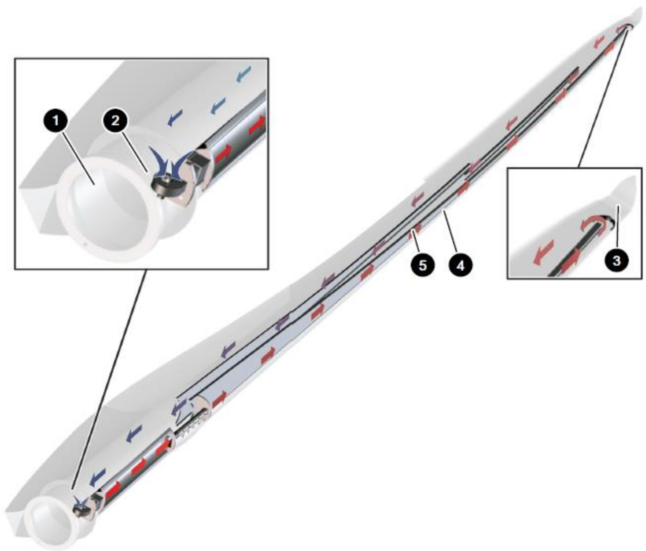


Figure 2.21 Air flow of blade heating system in E-115 E2 rotor blade, Source: Enercon, 2010

1 - Blade flange; 2 - Blade heating system; 3 - Blade tip; 4 - Leading edge; 5 – Webs

The fan heater is integrated into the earthing system of the WEC. The rotor blade shell and the GRP webs act as insulators that prevent arcing between the lightning conductor and the fan heater.

Power consumption

The wind energy converter's own power consumption increases when the blade heating system is on. The nominal power (maximum power consumption) of the blade heating system depends on the WTG type.

It is possible to limit the power consumption from the grid. However, reducing the power consumption also reduces the effectiveness of the blade heating system.

Activation of the blade heating system

Each rotor blade is equipped with its own separate heating system which includes a heating element, two safety thermostats connected in series (break contacts), radial fans and temperature sensors.

All heating elements are individually controlled so that all three rotor blades are heated to the optimum temperature.

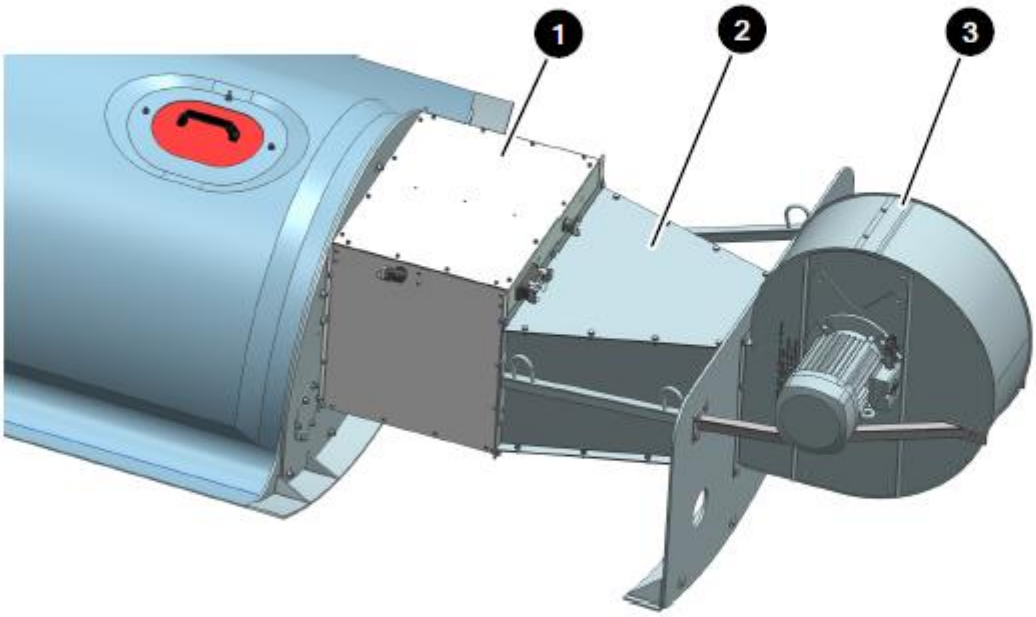


Figure 2.22 Flange-side view of E-115 E2 blade heating module, Source: Enercon, 2010

1 - Heating element; 2 - Diffuser; 3 - Radial fan

The time period for heating is limited by a given number of minutes (actual standards between 1 and 4 hours). The activation of the heating system is in most cases just allowed, when the turbine stopped, in some known cases the activation is also allowed during operation, which has to be discussed in detail with the responsible authorization and the supplier and operator of the WTG.

The switch-on point of the blade heating system is controlled by an additional tolerance range and its own counter. The additional tolerance range setting is generally not as wide as the tolerance range for switching off the WTG.

2.5.1.3.2 Resistive heaters

The resistive heaters can be configured in 3 ways, as summarized below:

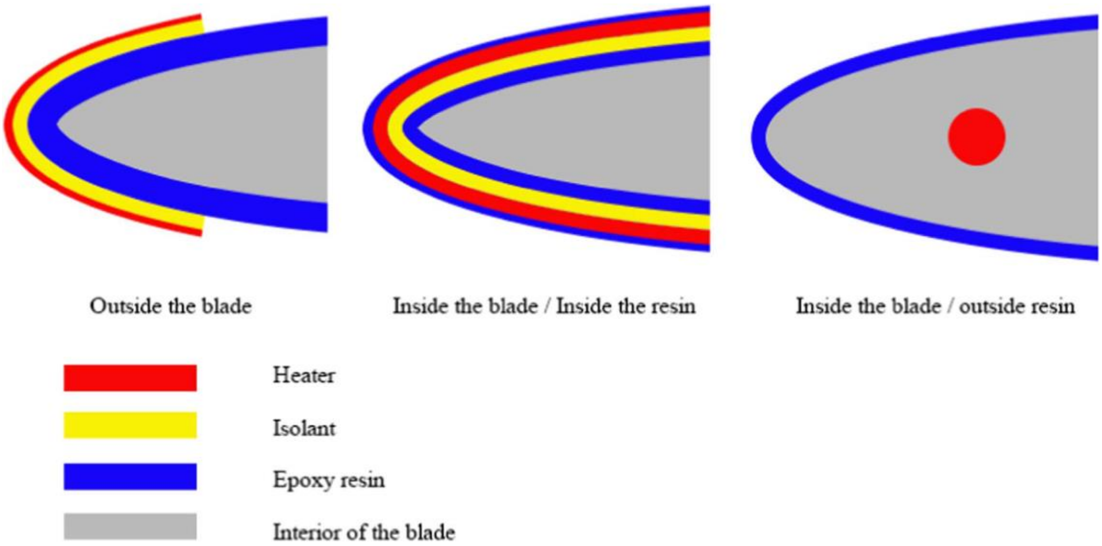


Figure 2.23 Configuration of resistive heaters, Source: Siemens, 2011

This device was installed by Siemens and Nordex in their cold climate wind turbines. The emergence of composite materials opens the way to various research. (Source: Siemens blade de-icing.Brochure de présentation; 2011; Anti-icing-Higher Yields in cold climates. Nordex .from ⟨http://www.nordex-online.com/fileadmin/MEDIA/Produktinfos/EN/Nordex_Anti-Icing_en. pdf⟩; 2015)

Electro-thermal ice protection systems are based on heating elements, typically carbon fibre, that are placed on the outer surface on the blade.

Technical details

Main materials for heating of blade

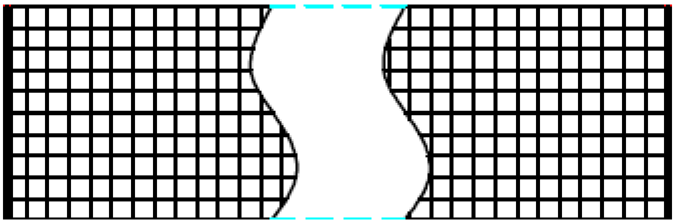


Figure 2.24 Materials for heating of blade, Source: Ice protection systems for wind turbines in cold climate: characteristics, comparisons and analysis, 2016 Elsevier Ltd

Heating part - Carbon fiber

Insulating part - Glass fiber

Power density - Customized based on the desired power, heating voltage, heating area, and density 300-700 W/m2

Thickness of heating material - Less than 1 mm

Thickness of electrode - Less than 1.8 mm

Advantages

Heat concentrating capability - The carbon fiber has excellent electrical and thermal conductivity and high thermal efficiency, and provide different heating effects for different parts based on the icing degree.

Uniformity - The same heating line dissipates heat uniformly.

Self-healing - The crack of heating material doesn't affect the heating effect.

Reliability - Combined with the composite material of blade, the strength of blade can be increased. Besides, the power density can be designed based on the requirements of wind turbine.

Stability - The influence of ambient temperature on the resistance of product is negligible. Besides, the raw material has small coefficient of thermal expansion, high heat resistance and corrosion resistance, and good anti-fatigue performance.

Microwave heating

For the microwave ice protection system, there is necessary to have an external coating on the surface of the blade. The generators of the blade create microwaves that heat the coating.

In 1982, Hansman proposed a micro- wave ice prevention system which can heat impinging super- cooled water droplets byt ransmitting microwave electromagnetic energy to the droplets (Source: H., Jr, R. J. Microwave ice prevention system, Google Patents; 1982). The microwave frequency depends on the liquid water absorbtion properties. This system allows even heat distribution,consumes less energy, is easy to maintain and is not subject to lightning. There are concerns of this technique regarding its safety . There was an attempt to adapt it to wind turbines by LM Wind Power (former LM Glasfiber).

Infrared heating

Infrared heating is a technology that delivers energy to an object which is distant from the power source. Its main advantage is the fact that the energy is emitted through the air, and it does not require an of installation on the blades. Therefore, it brings no additional roughness. It can be used both for de-icing or anti-icing. The ice melts and due to heat absorption. It is well known that ice is a strong absorber of infrared radiation; therefore, in order to avoid the risk of fire, materials that do not absorb the range of radiation must be carefully selected. This process is difficult to achieve. For example, for a specific wavelength, polished aluminum absorbs only 10%, while oils absorb up to 90% of the radiations. Most of the components in the nacelle, such as lubricants and oils can quickly overheat (Source: Ryerson, C. Assessment of superstructure ice protection as applied to offshore oil operations safety: ice protection technologies, safety enhancements, and development needs, DTIC Document, 2009.). This technology requires special safety precautions.

2.5.1.4 Detecting ice

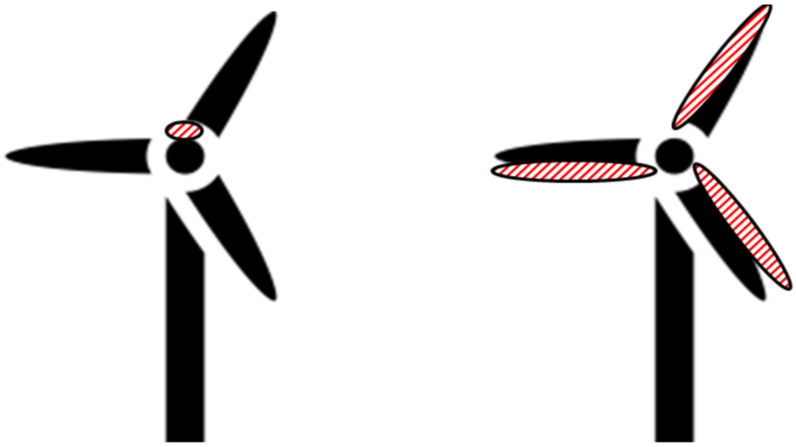


Figure 2.25 Ice detecting systems, Source: Detektion von Vereisung an Windkraftanlagen, Verbund, Dr. Thomas Burchhart, 2016

In order to overcome the effects of icing, there are required precise ice detection tools (Source: Gagnon M, Bolduc D, Ibrahim H, Dufresne M. A Parametric Analysis of Ice Protection Systems. February 11-12. Sundsvall, Suède 2014.).

Ice detection instruments can be classified in two main categories:

Indirect approach: is used to predict icing events based on general weather conditions like temperature, humidity and by means of correlation models (Source: Ronsten G, Heimo A, Kunz S, Ostrozlik M, Persson PE, Sabata J, Makkonen L. COST 727: atmospheric icing on structures, measurements and data collection on icing: state of the art. Bundesamt für Meteorologie und Klimatologie. Meteoschweiz; 2007.).

The indirect approach determines more costs and has not been proven as reliable (Source: Cattin, R. Icing of Wind Turbines, Elforsk report 12:13. Technical Report January; 2012.).

Direct approach: is using sensors that measures changes determined by the accumulation of ice (Source: Mughal U, et al. Dielectric based sensing of atmospheric ice. 39th international conference applications of mathematics in engineering and economics. AMEE13, AIP Publishing; 2013).

The main advantage of the direct approaches is that the operators know when the ice has accumulated, and they can stop the WTGs. The main disadvantage is that these approaches only detect instrumental ice, but can not be used for determining the beginning of the event (known as meteorological icing). (Source: Cattin, R. Icing of Wind Turbines, Elforsk report 12:13. Technical Report January; 2012.).

There were recorded cases when the sensors didn't detect any ice, even if the blades were completely covered. Also, there were cases when the measurements were wrong. It should also be taken into account the fact that these devices need to be protected by lightning. (Source: Homola M C, etal. Ice sensors for wind turbines. Cold Reg Sci Technol 2006; 46 (2):125–31.).

In order to determine ice accumulation parameters – like type, frequency, density – there are also capacitive and impedance techniques (Source: Mughal U, et al. Dielectric based sensing of atmospheric ice. 39th international conference applications of mathematics in engineering and economics. AMEE13, AIP Publishing; 2013).

However, aproven reliable approach is to compare the speed measurements of two anemometers, with one anemometer heated. This means additional costs for heating. Nevetheless, the sensors are reliable only when they are placed on the leading edge of the blade. The differences in energy production should be measured as well. For example, a 50% production drop generally means that the blades are covered with ice.This method is commonly used to calibrate other detection devices (anemometer) (Source: Parent O, Ilinca A. Anti-icing and de-icing techniques for wind turbines: critical review. Cold Reg Sci Technol 2011; 65(1):88–96)., and has been used successfully by Vestas and Siemens.

Ice detection using this technique can not be used when the turbines are turned off. Also, the drop in output power may be the result of other factors, such as misalignment, wind turbulence, or the activity of another turbine.

One of the most reliable methods is the detection of aerodynamic noise (Source: Mayer C. Système électrothermique de dégivrage pour une paled′éolienne: simulations ensoufflerie réfrigérée et impact sur la puissance produite. Université Du Québec À Rimouski;2007.). Ice deposits onleading edges create a small turbulent boundary layer that increases turbine noise.This method can detect very small amounts of ice and is commonly used by operators (mainly to protect themselves from flying ice).

The instruments for detecting an icing event are only reliable in specific conditions. While there are several studies underway, the only general reliable method of ice detection is visual inspection.

Detection time

Information on rotor icing is required in order to maintain safe and efficient operation of WTGs under icing conditions. Instrumental icing is not equivalent to rotor icing.

Following parameters must be taken into consideration: WTG hub height, blades structure, size and shape of the WTG in standstill or during movement, wind speed and direction, air density, vibration, accelaration forces.

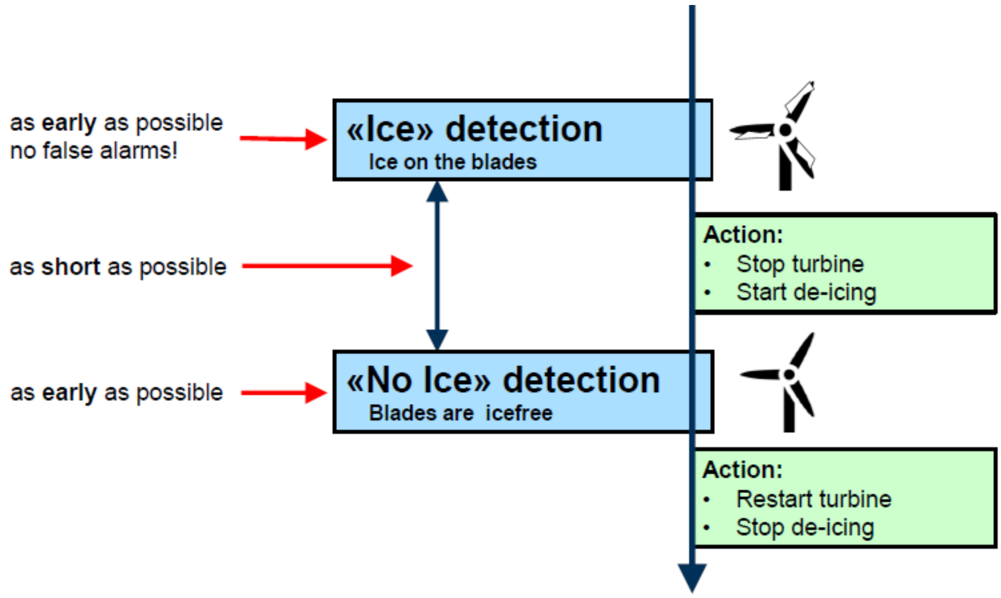


Figure 2.26 System for ice detection , Source: Detektion von Vereisung an Windkraftanlagen, Verbund, Dr. Thomas Burchhart, 2016

2.5.1.4.1 Nacelle based systems

If the rotor blades are iced unevenly, there are heavy unbalances in the rotor, which can lead to a strong acceleration of the nacelle. An electronic sensor measures permanently the acceleration of the nacelle in axial direction as well as diagonally to the axial direction. If the resulting acceleration exceeds a certain limit, the turbine controller stops the WTG immediately. Additional safety is provided by a mechanical vibration switch resp. second electronic vibration sensor. If triggered, this safety switch stops the WTG using the safety system, independently from the operating control.

In all cases, an error will be generated code, which describes the reason of the turbine shut-down.

The sensor may use ultrasonic to detect ice on a special sensor wire. As soon as the system detects ice, it will send a digital signal to the turbine's control system. This signal remains active, depending on the settings of the sensor, for about 15 minutes. Then, the sensor will heat the wire, thus removing the ice layer.

After that, the sensor checks again, if a new ice layer has been formed. This test interval takes about 30 – 45 minutes, depending on the settings of the sensor. However, it is difficult to notice, if the sensor will react again after a short time or not. Thus the time will be measured after the last activation of the sensor and this will be shown in the visualization in minutes. If the displayed time exceeds 45 minutes, it is safe to assume that there is no ice anymore on the turbine. Only then it is reasonable to visit the turbine in order to check if there is ice or not. (Source: Measures to detect ice on Vensys wind energy converters, 2016)

Overview of existing nacelle based detection systems

Temperature/ Relative humidity

This system allowes detecting temperature < xx°C and relative humidity> XX %, but does not represent icing. It can show relative humidity of ten measured wrongly below 0°C. The droplet distribution is neglected. The cost is < 5’000 €.

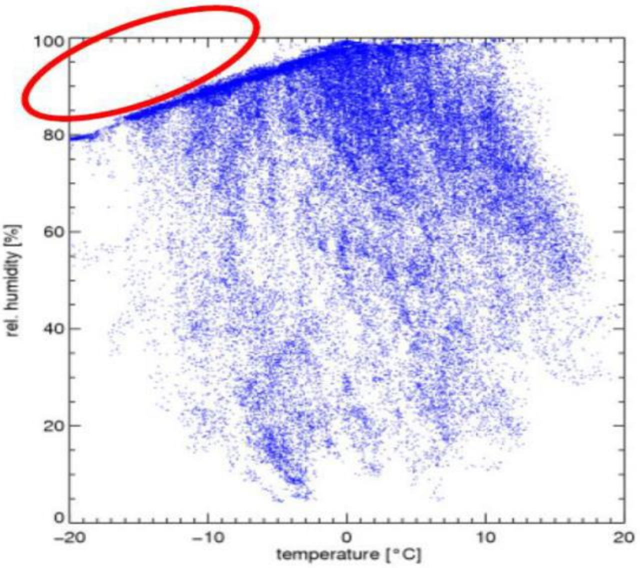


Figure 2.27 Temperature/ Relative humidity detection system, Source: Evaluation of ice detection system for wind turbines, René Cattin, Meteotest, 2016

Heated versus unheated anemometer

The deviation between heated and unheated anemometer is computed. This system is frequently installed on Senvion turbines. It only serves for instrumental icing. The cost is < 5’000 €.

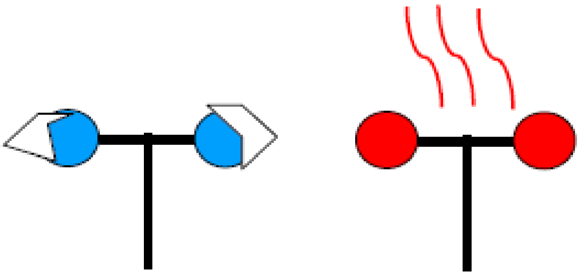


Figure 2.28 Heated versus unheated anemometer, Source: Detektion von Vereisung an Windkraftanlagen, Verbund, Dr. Thomas Burchhart, 2016

LabkotecLID-3300ID (FIN)

This Finnish system is represented by an ultrasonic vibrating wire, its amplitude decreases during icing. It is useful in case of meteorological icing, being adaptable for all turbine types, available on the market since 2002 with more than 3.000 units sold (price range between 5.000 – 10.000 €).

Figure 2.29 Labkotec ice detector, Labkotec Oy, Source: https://www.labkotec.fi/en/products/ ice-detection-system-for-wind-turbine/lid-3300ip-ice-detector-for-wind-turbines, 2018

Goodrich 0871LH1 (USA)

This ultrasonic vibrating finger records a decrease of frequence during icing. It is used for detecting meteorological icing. Being on the market since 1994, produced in USA, with over 700 units sold in the last 10 years. It can be installed on all turbine types, more often observed on Vestas and Alstom. Prices vary from 5.000 - 10.000 €.

Figure 2.30 Goodrich 0871LH1 ice detection system, Source: Evaluation of ice detection system for wind turbines, René Cattin, Meteotest, 2016

Combitech Ice Monitor (SWE)

It represents a vertical freely rotating cylinder and a load cell, to be used as well as for meteorological and instrumental icing. It can be installed on all turbine types. Being on the market since 2005, over 50 units were sold at a price between 5.000 - 10.000 €.

Figure 2.31 Combitech Ice Monitor, Source: Evaluation of ice detection system for wind turbines, Meteotest, 2016

HoloOptics T40 series (SWE)

This system generates a reduced infrared reflection when probe is covered with ice. It is used to detect meteorological icing, with over 40 units sold since 2009 at a price < 5.000 €. It can be used on all turbine types.

Figure 2.32 HoloOptics ice detecting system, Source: HoloOptics, http://holooptics.utrymmet.com/Products.htm, 2018

Leine Linde Systems IPMS (GER)

This German system measures the temperature and relative humidity, has an alarm and possivblity of ideo live streaming. It is on the market since 2010, with over 40 units sold at a price between 15.000 – 20.000 €, fitting to all turbine types.

Figure 2.33 Leine Linde ice detecting system, Source: Leine Linde Systems, https://www.ll-systems.com/en/company/product-news/ipmsr-ice-prevention-system/, 2018

NewAvionicsIceMeister 9734 (USA)

The device changes its opacity and index-of-fraction when the probe is iced. It is used for instrumental icing. This USA product is available on the market since 2014, at a price <5.000 €.

Figure 2.34 New Avionics Ice Master system, Source: New Avionics, http://newavionics.com, 2018

Sommer IDS-10 (AUT)

It is an Austrian system which changes the impedance on surface when probe is covered with ice. Being used for detecting meteorological icing, it is on the market since 2 years, prices varying from 5.000 to 10.000 €.

Figure 2.35 Sommer IDS-10 ice detection system, Source: Sommer Messtechnik, http://www.sommer.at/en/products/snow-ice/ids-ice-detection-system-20, 2018

Comparison nacelle systems

Table 2.2 Comparison nacelle system, Source: own research

	Since	Production	Icing type	Observations	Price
Temperature & relative humidity	Before 2000	Series	n/a	Strong overestimation, false alarms	<5.000 €
Heated vs unheated anemometer	Before 2000	Series	Instrumental	Robust, heated anemometer gets ice	<5.000 €
Leine Linde Systems	2010	Small series	Instrumental Rotor	n/a	15.000 – 20.000 €
Combitech Ice Monitor	2005	On demand	Meteorological Instrumental	Not robust, drift, noisy, weak heating	5.000 – 10.000 €
Goodrich 0871LH1	1994	Series	Meteorological	Robust, igloo, false alarms	5.000 – 10.000 €
HoloOptics T40	2009	Small series	Meteorological	Not robust, weak heating, false alarms	<5.000 €
Labkotec LID-3300IP	2002	Series	Meteorological	Robust, weak heating, false alarms,settings important	5.000 – 10.000 €
Sommer IDS-10	2016	Series	Meteorological	n/a	5.000 – 10.000 €
New Avionics Ice Meister	2014	Series	Instrumental	n/a	<5.000 €

During the comparison, it was observed that all systems have shortcomings, for example no nacelle system can measure rotor icing. Nevertheless, Labkotecand Goodrich demonstrated the highest technical maturity.

2.5.1.4.2 Rotor based systems

This system detects ice accumulation directly on the rotor blades. The sensors measure the vibrations of the blades directly in the blades as well as in the hub. The measurements are recorded by a central computer inside the hub and transmitted wirelessly to the access point inside the turbine's nacelle.

The turbine's own network then transmits the measured data to an analyzing computer in the tower base. If the system detects ice accumulation by analyzing the own frequency, it sends an alarm signal to the turbine's control system which will then stop the turbine.

This system can also be used as a condition monitoring system (CMS). It then detects also damages or lightning strokes on the blades. Thus, damages in the blades can be found early. Each turbine needs a separate own control system.

The condition monitoring system uses certain algorithms such as reference comparison.

These algorithms require a learning period to get to know this special blade type (up to 3 months). Other algorithms used to detect damages that compare the three blades with each other are directly ready for use after the commissioning.

The system automatically sends two alarm messages to the monitoring department and to other defined addressees, either by email or by text message (SMS).

The system stops the turbine immediately after it detects ice on the blades and sends a message.

Overview of existing blade based detection systems

Power Curve

It shows the deviation between produced power and power curve at low temperatures, detecting rotor icing anywhere on blade. At no additional costs, it is used for serial ice detection f.e. in Enercon turbines.

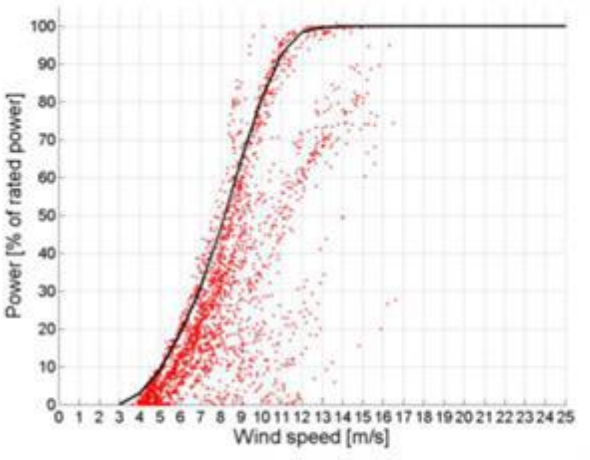


Figure 2.36 Illustration of power curve, Source: Evaluation of ice detection system for wind turbines, Meteotest, 2016

The disadvantage of the system ist, that it just can be used, as long as the rotorblades are in motion. So it has to be combined with another detection system, which is able to function f.e. during the standstill of a WTG.

Bosch Rexroth BladeControl (GER)

This German technolgy uses Piezo-Electric Accelerators, which identifies the change in natural oscillation frequencies when blade is iced. It detects rotor icing anywhere on blade. The system fts to all turbine types and is on the market since 2005, with over 1.500 units being sold at prices between 10.000 – 15.000 €.

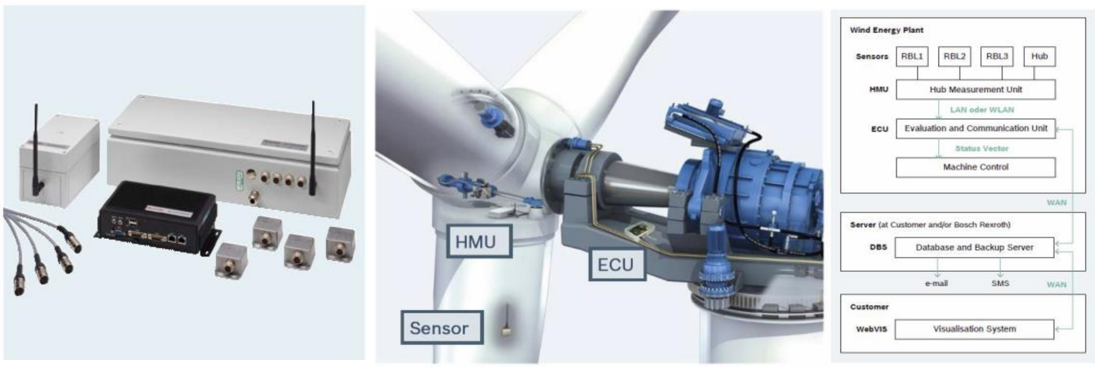


Figure 2.37 Bosch Rextroth BladeControl system, Source: Rextroth, https://www.boschrexroth.com/en/us/service/service-by-market/renewable-energies/service-products/condition-monitoring-system/index, 2018

Wölfel SHM.Blade/ IDD.Blade (GER)

The system is based on accelerators (Structural Noise Sensors) that detect change in natural oscillation frequencies when blade is iced. This German system detects rotor icing anywhere on blade. It is on the market for Nordex turbines since 2012 and for other turbine types since 2016. There were sold more than 100 units at prices between 15.000 – 20.000 €.

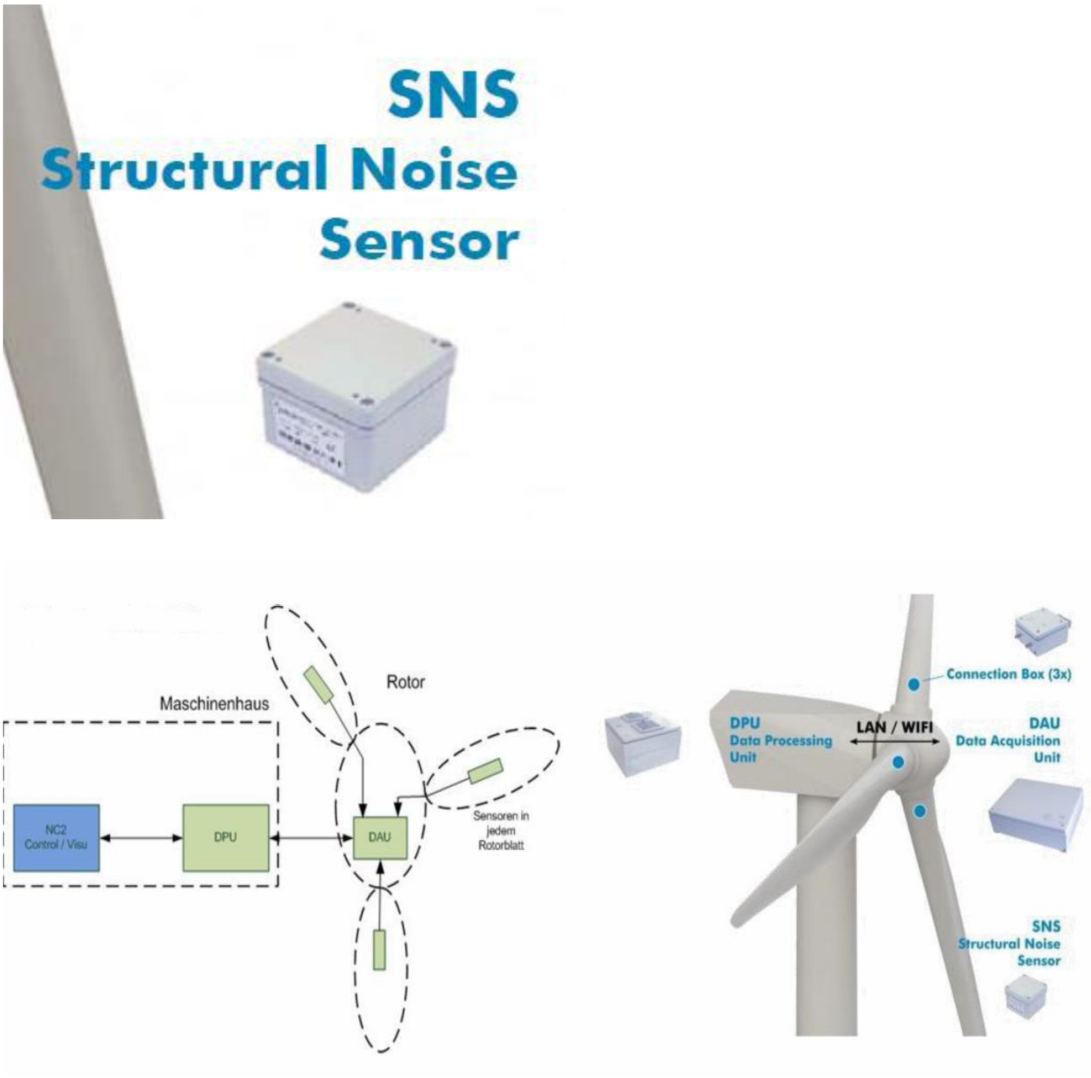
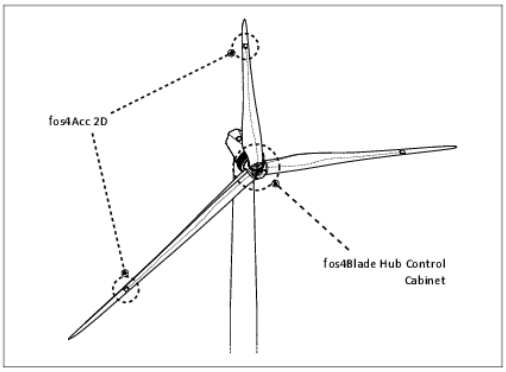


Figure 2.38 Wölfel SHM.Blade - IDD.Blade system, Source: Wölfel, https://www.woelfel.de/en/industries/wind-energy/offshore-cms/shmblade.html, 2018

Fos4x IceDetection (GER)

It uses fibre-optic accelerators which record the changes in frequency when blade is iced. This German system detects the rotor icing anywhere on blade. Being on the market since 2013, it fits all turbine types, with prices between 10.000 – 15.000 € and aprox. 50 – 70 units sold.



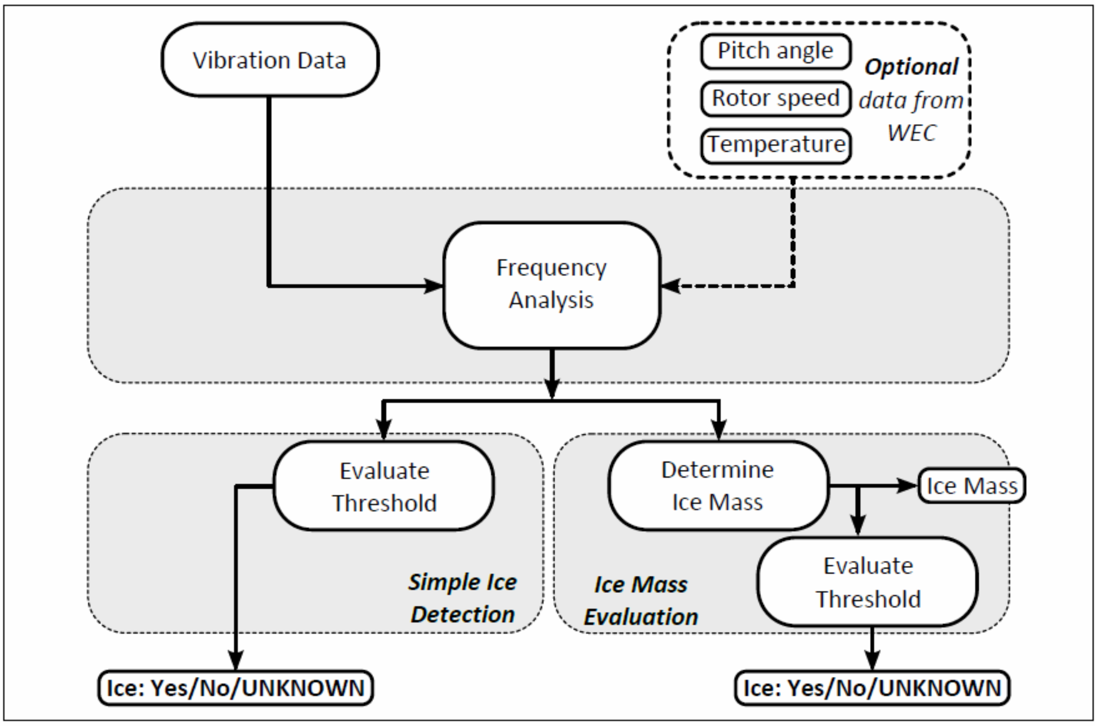


Figure 2.39 Fos4x IceDetection system, Source: Fos4x, 2018

Eologix (AUT)

This Austrian system reflects the change of impedance/ capacitance on sensor surface when probe is iced. It detects rotor icing at specific spots on blade. It fits to all turbine types, since 2015 there were sold over 20 units at prices between 10.000 – 15.000 €.

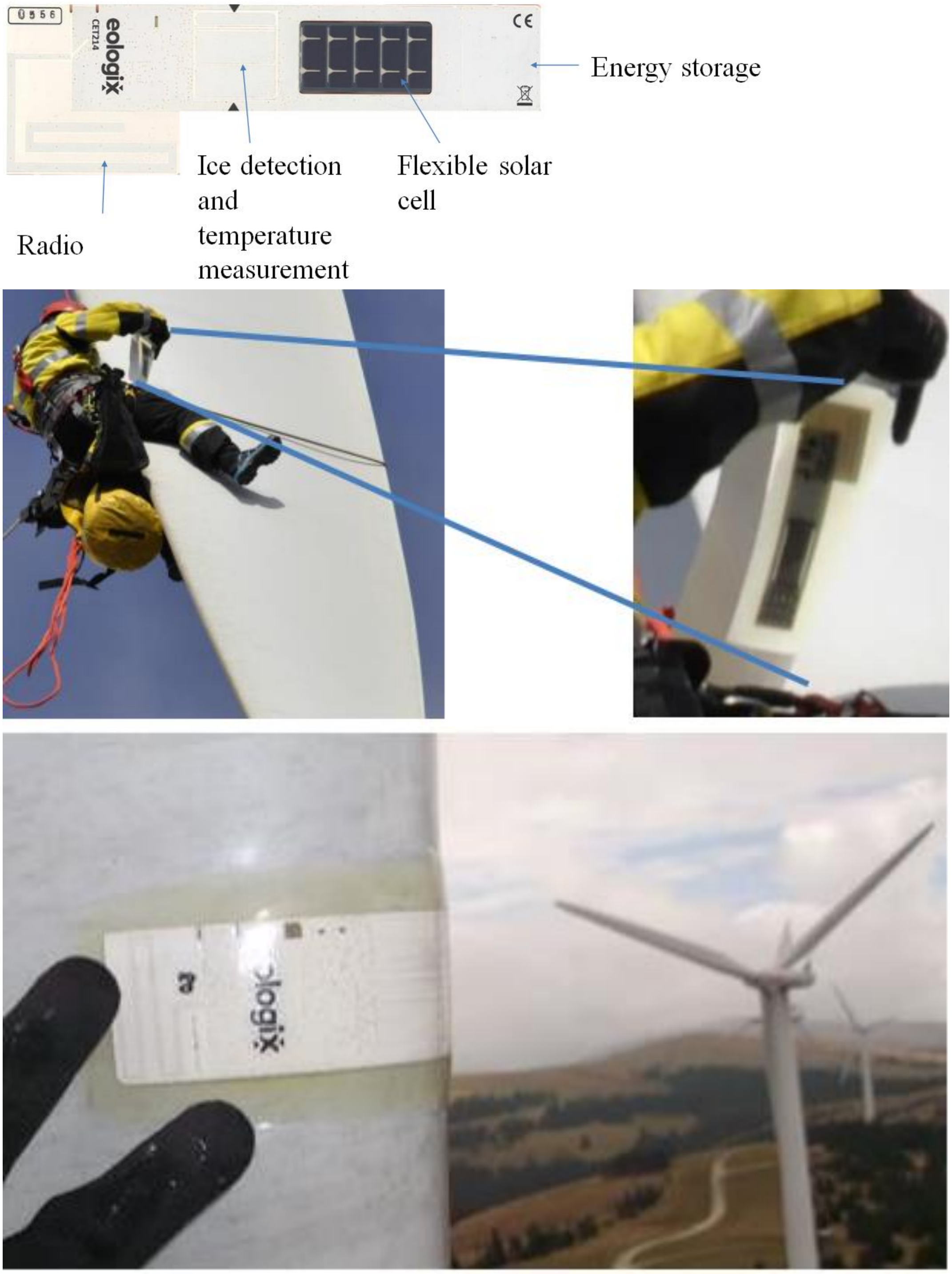


Figure 2.40 Eologix system, Source: Eologix, 2018

Comparison blade systems

Table 2.3 Comparison blade system, Source: own research

	Since	Production	Icing type	Observations	Price
Power curve	n/a	Series	Rotor	n/a	n/a
Fos4 Ice Detection	2013	Small series	Meteorological Rotor	Field test 2014/15	10.000 – 15.000 €
Bosch Rexroth BladeControl	2005	Series	Meteorological Rotor	Own evaluations	10.000 – 15.000 €
Wölfel SHM Blade/ IDD.Balde	2012	Series	Meteorological Rotor	Field tests Nordex SWE & GER 2014/15	15.000 – 20.000 €
Eologix	2015	Small series	Rotor	Field test 2015/16	10.000 – 15.000 €

It was observed that all blade ice detection systems can measure rotor icing and are not much more expensive than nacelle systems. There were not conducted independent evaluations, therefore there are no field tests available. Bosch Rexroth holds the longest experience.

2.5.2 Passive

2.5.2.1 Coating – anti-icing

Passive techniques prevent ice accumulation, while no additional source of energy is required. The advantage of these techniques is they reduce the operational cost and there is no need for any control system or special lightning protection, while keeping the blades ice-free. Most of these techniques use coatings that have anti-icing properties that modify the physico-chemical properties of blade surfaces. Passive systems involve coatings for the blades that can diminish the effects of ice, without using a source of energy.

De-ice the blade by reducing the adhesion between the ice and the coating. When the water droplet touches the coating surface, it will drip off under the hydrophobic effect of coating. In this way, no water will remain on the coating surface.

There are several methods to decrease the strength of ice adhesion on a surface. Usually, there is installed an icephobic coating on the surface. These coatings have a low surface energy.

Table 2.4 Comparison between de-icing methods, Source: own assessment

	Electrothermal de-icing	Flow of hot air	Vibration (ultrasonic)	Surface treatment
Technical maturity	High	High	Low	Medium
De-icing effect	High	Medium	Low	Low
De-icing efficiency	High	Low	Medium	Medium
Cost (pre-installation)	Low	Low	Medium	Medium
Cost (post-installation)	High	Medium	Medium	Medium

2.6 Operation

Basically, the operator is responsible for the safe operation of his property and the protection of the surroundings around the WTG. The options described in this document do not release the operator from this duty of care.

The operator must take suitable measures to ensure a safe operation of the WTG and to keep the surroundings safe. It is necessary to prevent ice from falling onto roads, buildings, persons or animals.

As soon as the sensor detects ice, the turbine is stopped and cannot be restarted automatically. The turbine remains in that state until the alarm is quit with the reset button in the tower base. After ice has been detected, the alarm may only be resetted after a visual check on site has determined ice-free rotor blades.

The operator of the windfarm or a park guard has to confirm the alarm and to restart the turbine after it has been stooped due to ice detection. The blades can only be inspected under the following conditions:

- Clear view of the blades must be ensured. An inspection is not possible if it is foggy, dim or dark.
- The sight check must be done with field classes near the turbine.
- The front and back sides as well as all edges of all three blades must be checked.
- It is mandatory to wear a helmet during the inspection as there is still danger of falling ice.

If the conditions on site do not allow a safe and clear statement that the turbine is free of ice (fog, twilight or similar), the turbine must remain out of operation. The safety of persons, animals and property around the turbine is more important than the operation of the turbine.

After the alarm has been quit, the turbine will not start automatically. It must be started manually with the button “Start”. After that, the event must be recorded in the turbine’s ice detection journal, indicating date and time of the restart, the acting person/company, the works that were carried out and the state of the turbine after leaving. It is possible that the turbine is stopped again only a short time after it was restarted. Unfortunately this cannot be avoided during certain weather periods.

The following procedure describes how rotor blade de-icing works.

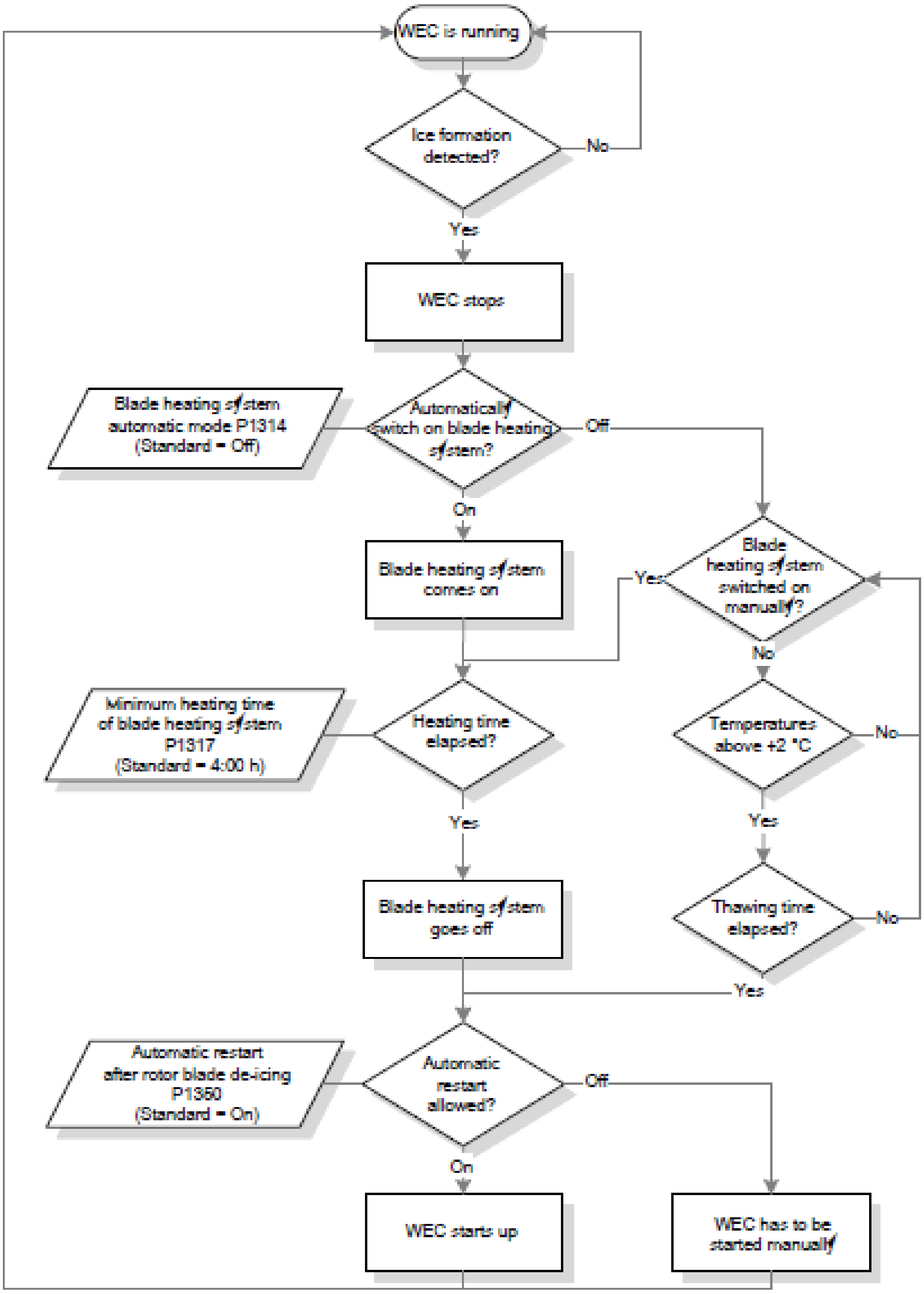


Figure 2.41 Blade de-icing procedure for WTG at standstill, Source: Enercon

As soon as the ice detection system detects ice formation using the power curve method and the WTG stops, the blade heating system is automatically activated. Once the heating time preset in the WTG has elapsed, the blade heating system is switched off and the WTG has to be started manually.

If ice is still detected on the rotor blade after start-up the WTG stops again and restarts the de-icing process.

Blade heating for WTG in operation

If the safety assessment of the site's conditions has determined that it is safe to access the surrounding area, de-icing may be allowed for the WTG in operation.

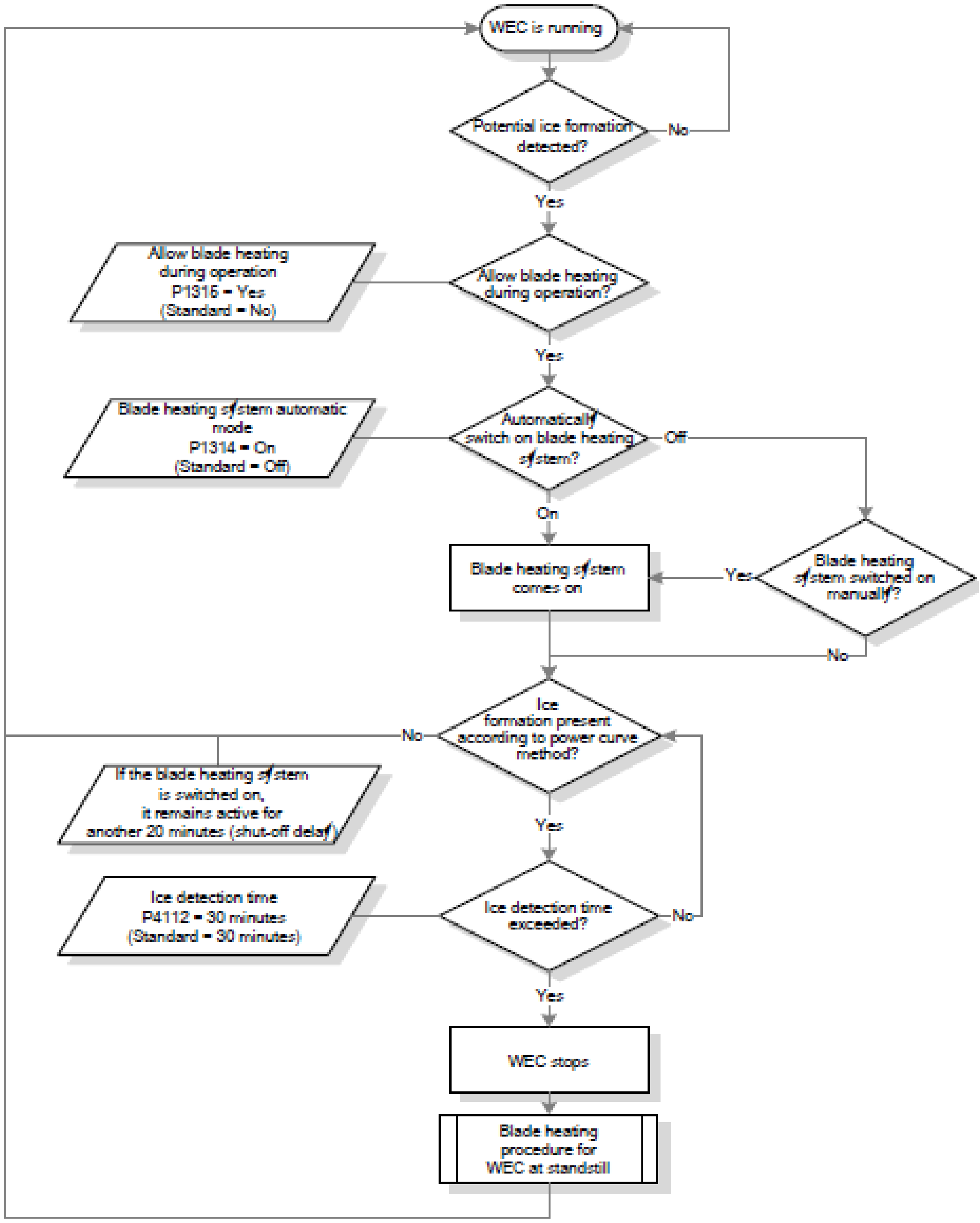


Figure 2.42 Blade de-icing procedure for WTG in operation, Source: Enercon

If the blade heating system is activated in a running WTG at an early stage, ice-build-up can be significantly reduced but not excluded. The ice melted by the blade heating system may fall off or be thrown off the WTG.

If, in extreme weather conditions (e.g. freezing rain), ice build-up continues to increase despite activation of the blade heating system, the WTG will be stopped again.

2.7 Measures

2.7.1 Ice warning panels and warning lights

In order to prevent a fundamental danger to persons, they are optically warned from distance (out of the risk area) of possible icefall. This ensures that all persons do not enter the project area in case of possible ice formation.

Ice warning signs and warning lights are set up in front of all marked paths to the project area. When the system detects ice for a single wind turbine, all the warning light systems in the wind farm are automatically activated via a GSM module of a corresponding mobile network operator or via cable. The warning lights are deactivated when the ice detection systems of all wind turbines in the wind farm no longer detect ice. The warning lights are automatically activated when the ice accumulation is reported by the system in the wind farm. This will warn people if there is a possibility of icefall.

Figure 2.43 Ice detection systems, Source: Energiepark Bruck/Leitha

2.7.2 Creating alternative routes

If it is the fact that routes are passing through the risk zones, there is also the possibility to create alternative routes that can be safely used. These are created as close as possible to the existing road network.

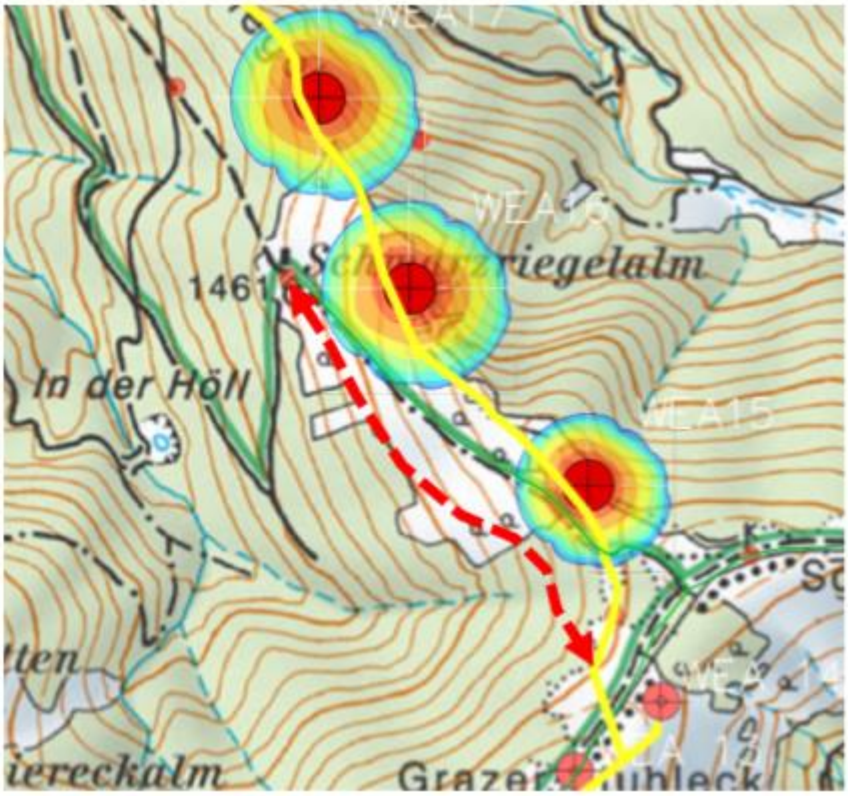


Figure 2.44 A potential workaround model, Source: EWS-Verein, Ice Throw Study, Windpark Pretul

2.7.3 Measures for operating personnel

The operating personnel should be trained on possible hazards due to ice fall during the winter months. The operating personnel is warned by the switched on hazard warning lights against the risk of icefall and can react to the danger. First of all, appropriate protective clothing (helmet) must be worn in case of icing events in the danger zone and the operating personnel may only approach the facilities after checking the icefall probability (strength and type of icing, current temperature conditions, current prevailing wind conditions).

In addition, the operating personnel is encouraged to approach the wind turbines with switched on hazard warning lights only with a vehicle and to stop directly in front of the entrance door.

Figure 2.45 Mobile roof built by GDF Suez ar Caribou wind parc to access wind turbines requiring maintenance when there is a risk of ice throw, Source: Ice Throwing in Practice, René Cattin, 2011

3 Methodical approach

In order to assess the market demands of the operators of wind parks under icing conditions, how these are met by the solutions offered by technology suppliers and the directions for further development, the author has used several research paths.

First, the specific literature, articles, studies and researches on wind energy technology under cold climate conditions were reviewed by the author.

Also, the author has studied the legislative frame-work, including the Agreement following the United Nations climate change conference in Paris, COP 21.

The author has examined various expert reports related to Environment Impact Assessment authorization processes in Austria.

The technical specifications from wind turbine suppliers and the technical description of de-icing and anti-icing systems were analyzed during the preparation of the Master Thesis.

For a better market approach, the author has conducted interviews with technology suppliers for ice detection systems as well as operators of wind farms.

Having a practical experience over 10 years in the wind energy field and based on the on-site observations and documentations available, the author has described in more detail in chapter 4 and 5 a relevant case-study.

4 Description of the research problem

Since icing causes economical losses and brings safety risks during the operation of the WTGs under cold climate conditions, the main objective of this chapter is to define which measures should be taken during the planning and operation phase of a wind energy project in order to minimize the damages.

Also, given the gap between the information available on the market on the technology suppliers and the operators, the author exemplifies the use of already existing technologies for operators.

The case project will show on the one side the evolution of different technologies and strategies for the operation, risk management and economy of a given area in the Eastern Alps in Austria. On the other side it will be an outlook for the future, which potentials the author sees in the combination of different technologies and in the modification of actual strategies.

Figure 4.1 Project area Pretul II, Fischbacher Alps, Austria

The project area is located on a sea level between 1400 and 1600 m. The environment is dominated by intensive grazing management, combined with highly frequented hiking trails in the summer period (May to October). In the winter period the area is used by less people who are ski touring or snowshoeing.

Due to the excellent wind energy yield parameters, in the last 13 years over 50 WTGs were installed in the area. When the first installed WTG (mid of 2000 years) there was no proofed de-icing system available.

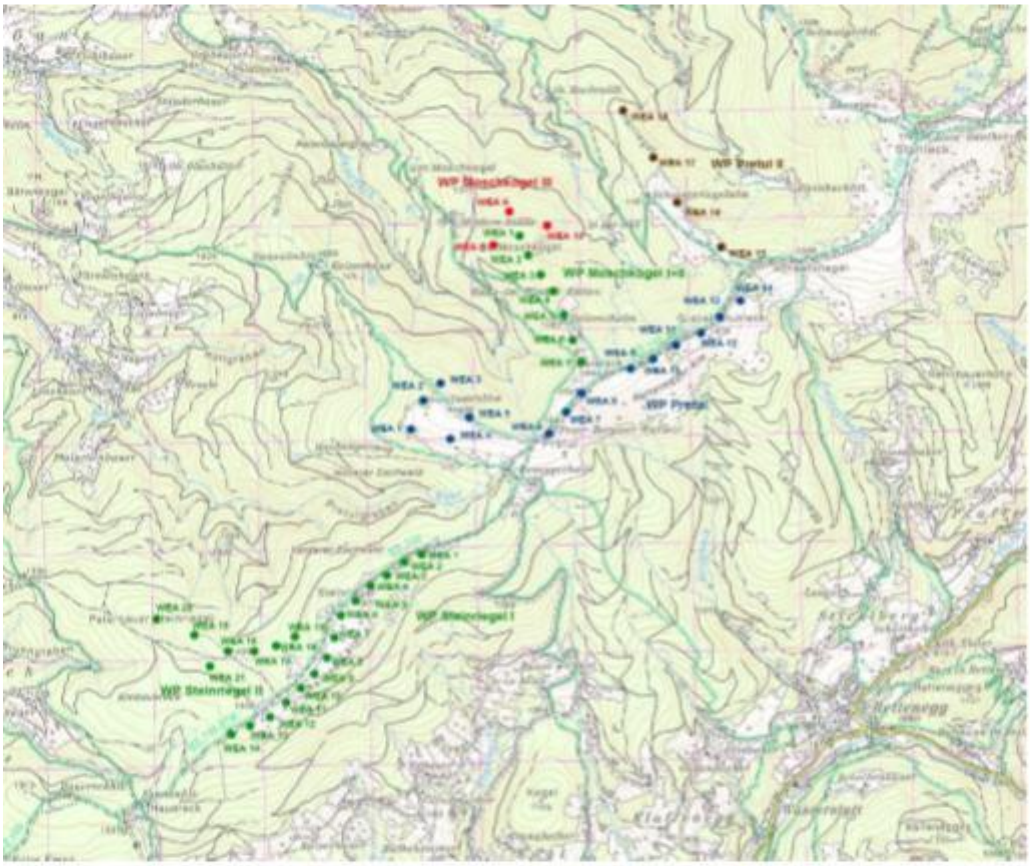


Figure 4.2 Overview of the full project area, Fischbacher Alps, Austria

To reduce the risk of ice falls and damages on persons and assets, the WTGs were stopped either by rotor ice detection systems or by the first available nacelle detection systems (Labko systems). The control system stopped the operation of the WTG (or a WTG group) until the operator detected, by a visual control on site, “no ice on the rotor blades” and switched on manually the WTG. The WTG would be stopped then in the moment when the system detected ice again. Under the specific climate conditions on that sea level, it could take weeks until the WTG was started again. Based on interviews with the former operators of that WTG, they talked about losses due icing of up to 20% of the Annual Energy Production.

In the following table, there is presented the status of the ice detection, de-icing and measurements from 2006.

Table 4.1: Detection strategy, case project status 2006

Detection	Visually		Nacelle			Rotor	
	Local	Remote	Temp. Relative humidity	Heated vs unheated anemometer	Labko	Power Curve	Eologix
2006	x				x	x	

Table 4.2: De-icing equipment, case project status 2006

De-icing process	Start			Stop		Technology	
	Pro-active	Detect ice	Manual	Automatic	Half automatic	Hot air inj.	Resistive heater
2010			x		x		

Table 4.3: Safety measurements, case project status 2006

Measurements	Ice warning		Alternative route		Surveillance	
	Lamp	Blades	Available	Barrier	Camera	Security team
2006	x	x	x			x

After the first proofed de-icing technologies (hot air injection) was available, some of the rotor blades upgraded to that new technology of de-icing the rotor blades. The hot air injection system was accelerating the ice melting process and the WTG could have been started earlier. Nevertheless, the de-icing process had to be started manually by the operating staff after accessing the WTG site. According the structure and the thickness of the ice on the rotor blades the melting process took several hours, till the operating staff detected visually “no ice on the rotor blades” and started manually the WTG. With all related problems in this process, mainly the difficult access to the WTG site during winter period, combined with the utilisation of heavy snow plough equipment, it was a huge progress in the management of de-icing.

In 2015/2016 a new wind project with 14 WTG was constructed and for research reasons the operator mounted on 3 different WTG on each rotor blade between 3 and

12 sensors from Eologix (rotor blade-based system described in chapter 2.4.1.4.2 Rotor based systems). The aim was to understand exactly the differences between the existing systems and certified Labko Tec system and the new upcoming technologies. In general, the authorities as well as the operators of WTG's had their doubts about the reliability and the effectivity of the new technologies. The operator of the new wind park project together with a specialized consulting company investigated the following questions:

1. Check the reliability of the Eologix sensors installed for testing purposes (or basically their ice-free notification) and the validation of an automatic restart after the sensor notifies ice-free and analyze the possibility of controlling or optimizing the heating duration based on the data from the Eologix sensors.
2. Comparison of the data from Eologix sensors with those from Labko sensor for the wind speed range of 0 to 4 m / s.
3. Comparison on the economic efficiency of the different operating modes: which additional yield can be achieved by an automatic restart after ice-free reporting by the Eologix sensors for both the proactive and the manually heated system.
4. Evaluation of the influence of microclimate on icing at three WTG sites (West - Central - East).
5. Determination of the effects of different operating modes and microclimatic conditions on the risk of life and death in the Pretul wind farm

In the following table is shown the status of the ice-detection and de-icing strategy during the research period 2006 – 2016.

Table 4.4: Detection strategy, case project status 2016

De-tection	Visually		Nacelle			Rotor	
	Local	Remote	Temp. Relative humidity	Heated vs unheated anemometer	Labko	Power Curve	Eologix
2006	x		x		x	x	
2016	x	x	x	x	x	x	x

Table 4.5: De-icing equipment, case project status 2016

De-icing process	Start			Stop		Technology	
	Pro-active	Detect ice	Manual	Automatic	Half automatic	Hot air inj.	Resistive heater
2006			x		x		
2016			x		x	x	

Table 4.6: Safety measurements, case project status 2016

Measurements	Ice warning		Alternative route		Surveillance	
	Lamp	Blades	Available	Barrier	Camera	Security team
2006	x	x	x			x
2016	x	x	x		x	x

As a summary of the study it can be concluded, that the Eologix Ice Detection System is a product that has great strategic potential. Due to the fact that the icing is measured directly on the rotor blade, the signals can not only be used for shutting down the wind turbines in case of safety - relevant icing, but also for an intelligent control of the heating time as well as for the automatic restarting of the wind turbines after the senzor detected ice-free rotor blades

Another interesting aspect of the study was, that in comparison with the Labko sensors, the Eologix system generated considerably fewer ice detection messages during the same period. At the WKA 01 (consideration independent from wind speed), 16 icing messages were reported by the EologixSystem, which are significantly below the 33 Labko messages. For WKA 12, there were only 4 Eologix ice detections over a period of 44 Labko messages. In addition to the influence of microclimate, the relevance of the number of individual sensors installed is noteworthy in this context. Ultimately, however, the difference in the number of detected icing events can be explained as with a high number of sensors increases the probability that icing which is unevenly distributed on the rotor blade is detected.

Regardless of the theoretical potential, it can be noted that the results of the evaluation from past winter half-year indicate that the Eologix ice detection system is not yet fully developed and ready for use at this time. This concerns on the one hand the failures of individual sensors, which prevented a restart signal after an icing event, but also the temporary failures of the entire system, which would have led to a shutdown of the wind turbines via the fail-safe control and thus to greater yield losses.

In the year 2017 the owner of the Windpark Pretul I decided to start the planning and the authorization of an extension for additional 4 WTG in striking distance to the existing 14 WTG. The author is involved in the process and from the first day it was demanded, that all the experience with the operation of WTG under cold climate conditions should be taken in consideration.

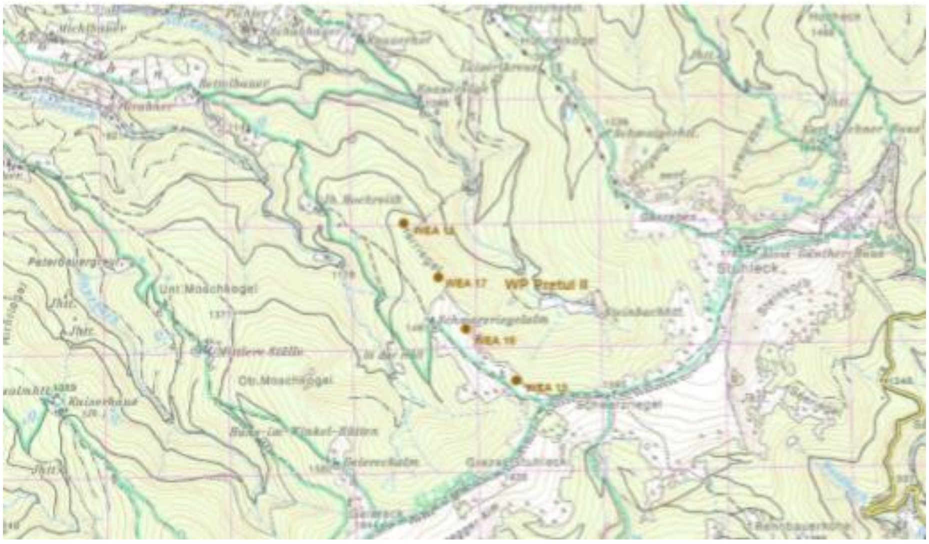


Figure 4.3 Overview of the Pretul II project area, Fischbacher Alps, Austria

As a first step a new wind measurement campaign in the direct project area was started. Next to the fact that the new turbine positions are between 100 and 200 m lower than the ones from the existing wind park, the influence of micro-climate should be respected. In such complex terrain the measurement campaign should at least run over 12 months. The campaign consisted of a new wind mast installation and additionally some weeks of measurement campaigns with Lidar wind measurement equipment.

With the outcome of all the meteorological data’s a specialized consultancy company was able to calculate the theoretical ice fall ellipse and a corresponding risk assessment for the working staff and not working staff during the operation of the WTG under cold climate conditions.

These calculations and reports have been done under the following assumptions:

4 WTG: ENERCON, Type: E-115, max. electrical power: 3,2 MW, HH (hub height): 92 to 122 m

The calculated ice throw ellipsis based on the given wind rose looked the following:

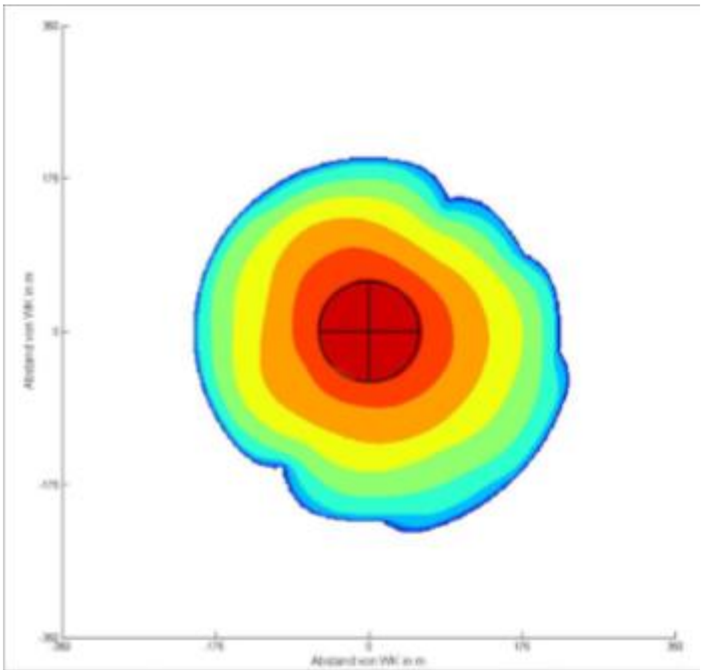


Figure 4.4 Ice hit probability, Source: Ice Throw Risk Assessment EWS-Verein, Pretul 2018

The colour of the ellipse from red to blue shows the probability for hits of ice (see chapter 2.4 Planning, subchapter 2.4.2 Analysys).

The ellipse is now integrated in the map, with the actual WTG positions (WTG risk area).

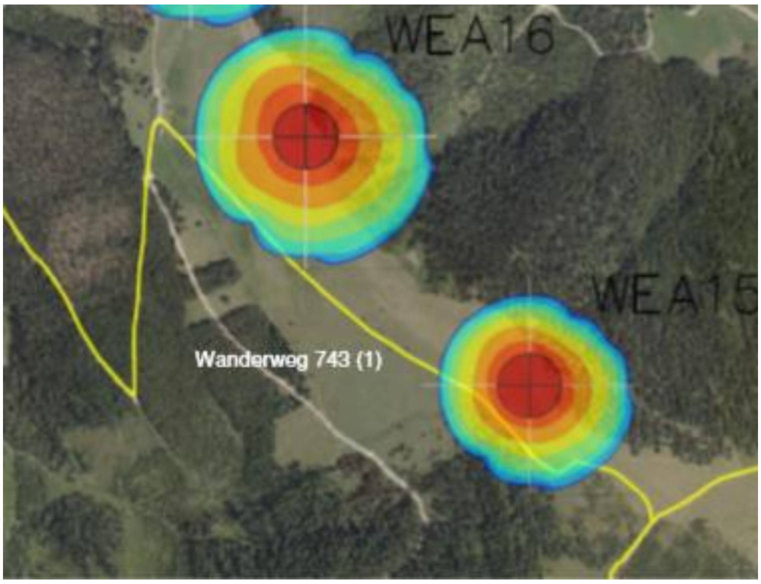


Figure 4.5 Integration of the ice hit probability, Source: Ice Throw Risk Assessment EWS-Verein, Pretul 2018

Based on that overview, the planning for the necessary safety measures started and was integrated in a “visitor steering concept”:

- Right positioning of the warning lamps and blades (respecting the necessary distance to the WTG risk area and at logical waypoints)
- Planning of alternative routes to avoid that persons, which are already in the entire area, have to pass the WTG risk area
- Planning of necessary barriers
- Offering of a visitor’s information concept, for all seasons with analogue brochures as hand out in the municipality halls, tourist info centres and the surrounding “Gasthütten”. Next to big information blades at the entrance of the mountain area
- Offering digital services by messaging the alarm of the installed sensors to the owner of the “Gasthütten”, so that they can inform their guests immediately; activating additional via messaging services signal lamps at the entrance of the mountain area
- Special training for the operating staff regarding safety equipment in general cold climate conditions

In detail the planning of the alternative routes and barriers looks the following

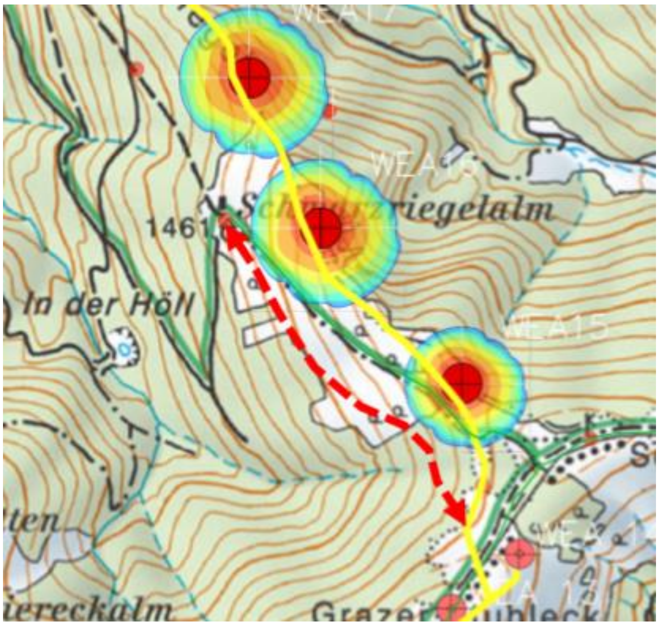


Figure 4.6 Alternative route, Source: Ice Throw Risk Assessment EWS-Verein, Pretul 2018

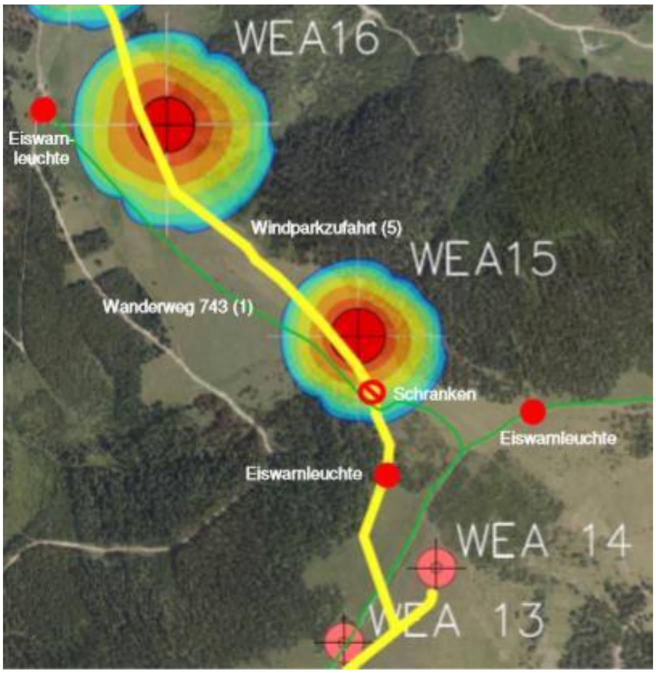


Figure 4.7 Detail ice warning lamp and barriers, Source: Ice Throw Risk Assessment EWS-Verein, Pretul 2018

Next to the safety issue, the investor would like to optimize the operation of the WTG's during cold climate conditions, based on the experience of the last years of operation.

The selected WTG type ENERCON E 115 is still working with a hot air injection system for the rotor blades and the integrated power curve system, to detect ice on the rotor blades, when the wind speed is over 4 m/s. For the operation of the whole system under a wind speed of 4 m/s ENERCON is offering the latest version of Labkotec sensors and additional already an integrated version of Eologix rotor blade sensor systems.

Based on the experience of the last years and especially based on the above mentioned comparison report the utilisation of the rotor blade-based detection system is a must, but the author recommends having the Labkotec system installed as:

- Driver Parameter for the signal for the ice warning components (signal lamps, messaging services)
- Back Up system, if the Eologix system can not be restarted cause of technical reasons

Like discussed in the chapters above, shall the pro-active operation of the blade heating system and the fully automatic switch-off be used to optimize the technical availability of the WTG.

In the first month of the operation of Windpark Pretul the operators faced a lot of technical issues, in the connection with the operation of the WTGs under Cold Climate Conditions; just a in deep check of all the installed technical equipment, incl. soft- and hardware components showed finally the desired success. All involved participants had and must respect such extra ordinary locations and standard solutions from "flat-land" projects are not always helpful or successful.

To support the technical operators and the operating staff the installation of HD (High Definition) cameras on the nacelle shall be installed. The coverage area of the camera can be changed by remote control, so a control of the rotor blades, but also of the surrounding area can be monitored

5 Presentation of the results

After the analysis of the background information and the case-study, it was observed that all systems have shortcoming.

Several technologies with different specifications are available, but sometimes there is no clear status on their efficiency. Given the complexity of the cold climate and its effect on wind turbines, an analysis has to be undertaken for each wind farm in order to identify the suitable protection system. (Source: Ice protection systems for wind turbines in cold climate: characteristics, comparisons and analysis, 2016 Elsevier Ltd).

There are direct and indicrect effects of icing on wind energy in cold climate, such as increased loads, vibration and a shorter component life. Also, there can be a higher noise level, which represents an increased risk for health and implies environmental measures. These lead to shuting down the WTGs.

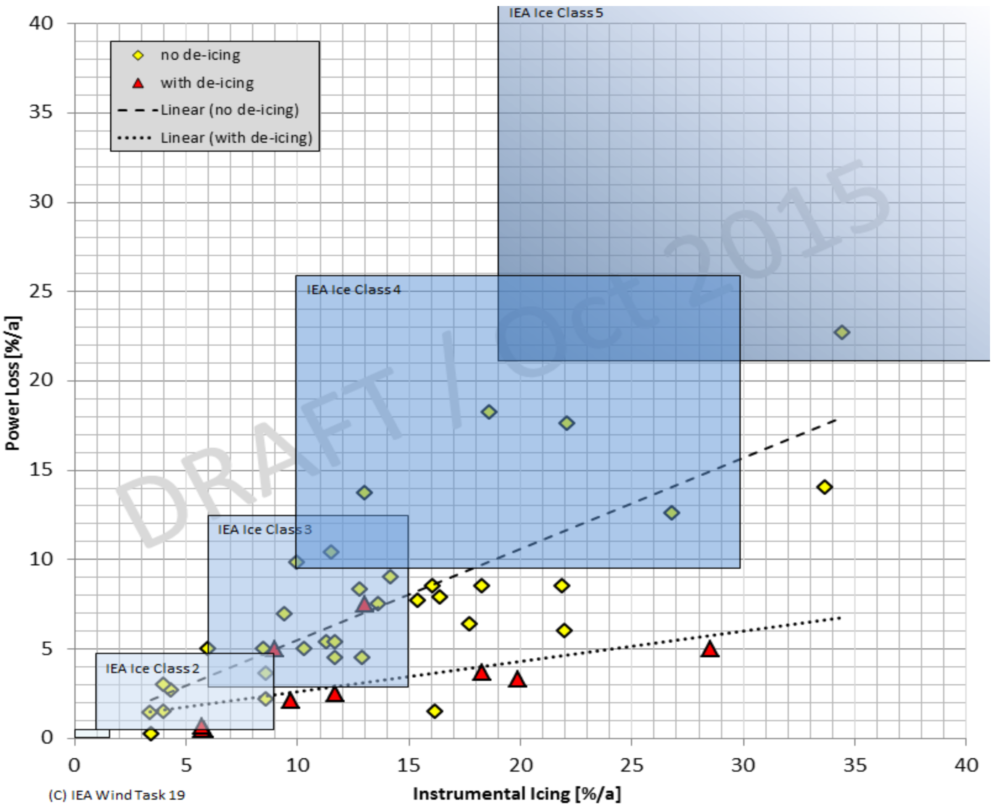


Figure 5.1 Power loss in case under instrumental icing conditions, Source: IEA Wind Task 19, 2018

Under icing conditions, it has been proven that the aerodynamig of the WTG blades decreases, and so is the power generated.

So the author recommends every developer and operator of a wind farm under cold climate conditions to analyze in detail the potential risks, based on that to select together with the responsible authority the necessary strategy, including selection of de-icing technology, ice detection system, necessary measures for the protection of people and assets.

The author described in chapter 4 how to develop such strategies from the wind measurement campaign, risk analysis and necessary measures. The author divided the potential measures, in those which can be implemented already during the planning phase and those, which are related to the operation of the WTG.

Prior to any wind farm investment or the optimization of the AEP of an existing wind farm, mapping of all potential risks are keys to success. Icing may significantly influence energy production. Still, there is a lack of international standards that can quantify the power losses due to icing. In cold climate (CC) conditions, it is important to perform a thorough site assessment, including the impact of icing.

There are available several solutions that can be used by the WTG producers in order to decrease the power losses and to increase safety on site, even for the projects located in cold climate conditions. Still, each project has to be assessed individually, prior to deciding which is the best technological approach. The market is under development, but the available solutions, such as blade ice protection (anti-icing and de-icing) can be already implemented.

It is the set of measures which allows the right balance between optimization of the AEP and the necessary risk mitigation.

6 Conclusions

The implementation of ice detection and de-icing technologies is the solution for a significant reduction of risk negatively affect persons and assets. Secondly, it’s key in increasing the AEP.

When planning and operating wind farms under icing conditions, the risk of ice throw must therefore be assessed in each case and a corresponding park layout and risk concept has to be worked out. Based on the meteorological data of the measurement campaign a so-called ice fall study followed by a risk assessment

Based on that assessments a “comparative” matrix shall be prepared for the entire wind energy project, as well as for each individual WTG. This matrix gives the operator of the WTG and the responsible authorities the base for implementing the necessary measures.

The author recommends not just to rely on the recommendations of the technology supplier, but to compile several ice protection measurements in order to decrease the general risk on assets and persons. There are some examples highlighted by the author in the case study.

Every location has its own particularities and should be individually evaluated.

The author is convinced that in the next years the integration of ice detection systems and de-icing technologies will be standard for WTG projects, even not only in typical CC conditions. In the last years various new promising technologies were developed and the first ones already successful integrated. Nevertheless, as the author described in the paper, progress is still needed. In the future, the rotor blade-based detection systems will be able to manage pro-active heating and automatic switch on and off modes.

Referring to the technology for de-icing the rotor blades, resistive heating systems, directly under the surface of rotor blades, are more efficient than hot air injection systems. But the disadvantage in a more complex production of the rotor blade and the risk of direct lightning strokes in the heating system and full or partly damages is still not answered. So, the author assumes the penetration of that technology in the next years also having in mind the possibility to use it for retro fit applications as well.

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8 List of Abbreviations

A – air flow

AEP – annual energy production

ALARP – as low as reasonably practicable

AUT – Austria

CC - cold climate

CENELEC – European Committee for Electrotechnical Standardization

CMS – condition monitoring system

E – energy

EIA – environmental impact assessment

Ekin – kinetic energy

EU - European Union

GER – Germany

GHG – green house gas emissions

GWh - gigawatt hours

HSE – Occupational Safety and Health Administration

I – current

IC – icing climate

IEA – International Energy Agency

kW – kilowatt

LTC – low temperature climate

M – mass

M – torque

MEM – minimum endogenous mortality

Mio – million

MWh – megawatt hours

MWh/a - megawatt hours per year

P – power

PDMS - polydimethylsiloxane

Pmech – mechanical power

PTFE – polytetrafluorethylene

Pwind – power of wind

TWh – terawatt hours

U – voltage

US – United States

V – velocity

WT – wind turbine

WTG - wind turbine generator

WTG – wind turbine generator

Ω – rotor angular velocity

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