Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Mathematical Sciences and Technology

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Nordex AIS in Wind Power Plants. Evaluation of Economic and Operational Effects

Bushra Butt

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How to design an optimal warranty of anti-icing system that will maximize the value for developers and minimize financials risks of Nordex Energy.

Bushra Butt

Norwegian University of Life Sciences

Department of Mathematical Sciences and Technology

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Abstract

There are many cold climate sites around the world that offer great wind energy potential with good wind resources and low population density (Wind Power Monthly, 2015). Yet the sites suffer from icing, which reduce the availability of, and the energy production from the turbine.

Optimizing wind farms in cold climate is currently an important topic in the wind industry. This December an event was hosted by Wind Power Monthly, where the focus was on the commercial and technical complexities impeding the operation of wind farms in cold and difficult climates. One of the main topics was *solutions on icing standardization measures to reduce uncertainties and energy losses whilst enhancing the project bankability potential*[1].

The reason I chose this topic is, icing on wind site has been a huge challenge for many sites and is going to be a topic of discussion in coming years in Norway. In addition, there are many wind site that has been given concession by Norwegian Water Resources and Energy Directorate that may face icing problems due to the location. In this paper, the focus has been to suggest a recommendation for a solution to the challenge of reducing financial risk and energy loss when developing wind farms in cold climates. To make this recommendation it has been important to provide an overview of which icing challenges are present in Nordic countries, and present a viable solution for these problems.

The paper concludes that it is beneficial to invest in anti-icing technology (AIS) to avoid production loss due to ice in cold climate sites. The main analyses have been carried out using net present value (NPV) with and without the AIS in a cold climate wind site. My results indicate that the AIS will positively affect a project financially if the loss due to icing is higher than 6 per cent. The results further indicate that in order to optimize the project value, there is need of a combination of power curve and availability warranties delivered with the AIS. This warranty design may help in reducing the annual energy production (AEP) uncertainties, potentially ease access to capital and reduce the cost of financing sites. The recommendation is based on interviews with potential customers of AIS. Individual warranty design for each site is recommended to minimize Nordex' risk associated with the given warranty.

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[1] The information about the event is available here: http://www.windpowermonthly.com/coldclimatesconference

Acknowledgment

I am grateful to my supervisor Prof. Ingemund Jordanger for his guidance, support and advice. My great thanks and appreciation to Nordex, especially Thomas Bak Mathiasen for providing me with data and knowledge about cold wind sites. I also want to thank NORWEA, my parents and friends for guiding me and supporting me on my last weeks before submission. Lastly, I extend my sincere thanks to all, who I have not mentioned here, whom without whose efforts this work would not be substantial and complete.

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1.0 Introduction

Numerous cold climate sites around the world offer great wind energy potential, with good wind resources and low population density (Wind Power Monthly, 2015). Cold-climate sites have now reached 100GW and an estimated growth of 19 GW by 2017 (Wind Power Monthly, 2015). Yet there are many sites suffering from icing, which can cause production loss; the mechanical lifetime of turbines to fall, noise emissions to increase and safety risks to rise through ice throw, among other challenges (Nordex, 2012).

At cold climate sites icing is often a source of sub-optimal production during colder periods, and as such an important factor in any evaluation of wind power projects in cold climates. It is a result of a number of factors as ambient humidity, wind and temperatures, especially in the range of +5 °C and - 10°C (Nordex, 2012).

Many sites are affected by accumulation of ice on rotor blades and it impacts the energy yield and shortens the life expectancy of the wind power generators. This is relevant for several sites in the Nordic countries, and is one of the reasons many wind turbine developers have developed anti- or de- icing technology. Since anti-icing technologies are currently in their infancy, developers report that is difficult to secure financial support for implementation of these systems[2]. In this paper the operational power production and technology are based on Nordex Energy AIS; section 2.1 provides a brief presentation of Nordex Energy. Nordex Energy desires to implement a valuable warranty in order to help developers get financial support to implement an AIS on their site[1].

The following research objective has been formulated in order to investigate this:

How to design an optimal warranty of anti-icing system that will maximize the value for developers and minimize financials risks of Nordex Energy.

The purpose of this paper is to clarify in which circumstances it is beneficial to invest in AIS technology and how warranty design delivered with the system will positively affect a project, and how the warranty delivered for this system may help reducing the risk associated with investments in cold climate sites. This will be done through interviewing the potential customers

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[2] Interview with Thomas Bak Mathiasen, Sales Manager in Nordex

that purchase the AIS and calculate when it is profitable for the developer of the wind sites to invest in the AIS.

1.1 Structure of the thesis

Chapter 2: This chapter presents the background of Nordex as well as the context regarding the relevance for the cold climate sites and the different types/kinds of icing and their effects.

Chapter 3: Presents the theory on the different ways and methods in measuring icing, and an overview of the technology in anti- icing systems.

Chapter 4: This chapter presents financial theory and economics analysis.

Chapter 5: Provides the background on the chosen methodology.

Chapter 6: Presents the decision analysis regarding the various uncertainty factors that affects a cold climate site.

Chapter 7: Provides an overview of the different warranties model and criteria of fulfillment of the warranty.

Chapter 8: This chapter gives an overview of production loss with and without the anti-icing system in Blaiken wind site.

Chapter 9: This chapter presents the net present value (NPV) with and without the AIS-system. The NPV analysis provides an indication of the system’s cost-benefit value based on production, energy prices, availability, methodology performance process and cost of the system.

Chapter 10: Presents the warranty, which is considered most valuable by the developers, based on the theory of warranty from chapter 7 and the interviews that are conducted with Nordex’s customers.

Chapter 11: This chapter gives an overview and discussion of the advantages and disadvantages in the warranty. In the final part of this chapter, it suggests a description of an optimal solution: generating maximum value for the developer and minimizing Nordex financial risk.

Chapter 12: This chapter provides a conclusion on the defined research question as well as it presents some suggestions for future research of the AIS in cold climate sites.

1.2 Delimitation

It is assumed that the reader of this paper is familiar with the wind industry and has basic the technology of wind turbines. This paper is solely focused on Nordex anti-icing system (AIS) and the parameters of the project that will affect energy production due to icing. Other parameters affecting a wind site are not considered where they are not perceived to directly influence the results of the analysis, as we assume that the investor have already evaluated the site. The main focus is to evaluate whether the investor should invest in AIS in a cold climate site. In this paper, the system of subsidy is based on the Norwegian –Swedish common certificates-market, as the data set is from Blaiken wind site. One of the main drivers of uncertainty is the volatility in energy demand, uncertainty related to meteorology forecasting, technology risk and political risk. The AIS is new in market and it is quite challenging to predict its benefits in securing additional production.

2.0 Background and context

2.1 Nordex Energy GmbH

Nordex energy was founded in 1985 in Give, Denmark and today the company is represented in 22 countries and has over 2,500 employees. The headquarters is situated in Hamburg, Germany while the main production site is in Rostock, Germany.

Based on common technical platform generations, the product portfolio currently consists of plant types of “Gamma” and “Delta” generations. The product range of the Gamma generation features efficient turbines for all wind classes and includes the N90/2500, N100/2500 and N117/2400. Generation Delta includes the N31/3000, N117/3000 and N100/3300 turbines. Nordex Generation Delta won the “special mention price” at German Design Awards 2015, in the category for “Excellent Product Design Industry, Materials and Health Care”. The product thus comprises powerful turbines for all wind classes. Intelligent options and numerous tower height options also extend the field of application of the equipment (Nordex, 2013).

Currently more than 6100 Nordex wind turbines are installed worldwide, comprising a total capacity of almost 10,700 megawatts, and covering in 38 countries. They offer technical identification of suitable sites from across the wind farm system, covering every aspect from initial planning to the technical implementation (Nordex, 2013).

2.2 Blaiken Test Site

The report is based on data from Blaiken, Västerbottens Län, Sweden. The data represents state-of-the-art standards in wind energy assessment methods. In this report the operational power production data is collected from thirty Nordex N100 wind turbines. The data has initially been analyzed and prepared by Kjeller Vindteknikk AS. Analyses of production loss due to icing were carried out based on the operational power data for the period October 10th 2013 to March 31st 2014. For this report, Nordex has supplied additional data with 10-minute resolution from each of the turbines. The data includes turbine power, availability flags, nacelle wind speed, power consumption and operational codes. Icing parameters based on the “Ice-Loss” model developed by Kjeller Vindteknikk has also been included in the different analyses. The calculation of ice load is based on Weather Research and Forecasting (WRF) model data. A description of some drivers of uncertainties and limitations in the analyses are also given.

The Weather Research & Forecasting Model (WRF)

The WRF Model is a mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs (WRF, 2006). The model serves a wide range of meteorological applications across scales (WRF, 2006). WRF can generate atmospheric simulations using real (observation, analysis) or idealized conditions (WRF, 2006). The model version used in the Blaiken report is v3.2.1. The model data includes time series of wind speed, wind direction, temperature, atmospheric humidity and cloud water at several vertical model levels. The geographical data is from National Oceanic and Atmospheric Administration (NOAA). The records include topography, surface data, albedo and vegetation.

2.3 Icing in North

The term “cold climate site” refers to a site that either shows conditions favorable for icing to occur, or which consistently experience temperatures that are lower than the operational limits of standard wind turbines (Laakso et al., 2010a). It is difficult to describe a typical cold climate site, as site conditions under the definition may vary to a great extent[3]. Each wind project requires a specifically chosen set of measurements to evaluate the condition of the wind site. For example, some sites may experience low temperatures, but no atmospheric icing. Another site can be mild in temperature, but show periods of heavy icing (Laakso et al., 2010a). Figure 1 shows a map of icing regions in Europe. The map does not take under consideration the local topography, which is indeed significant for the local icing climates.

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[3] Interview with Øyvind Byrkjedal from Kjeller Vindteknikk

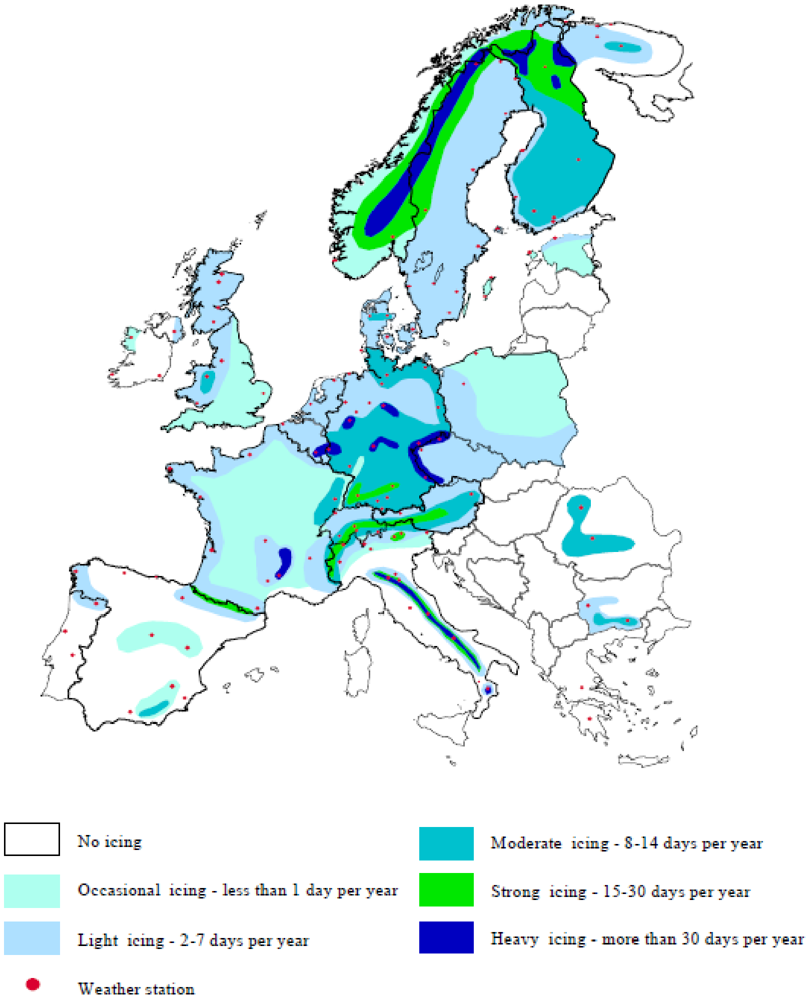
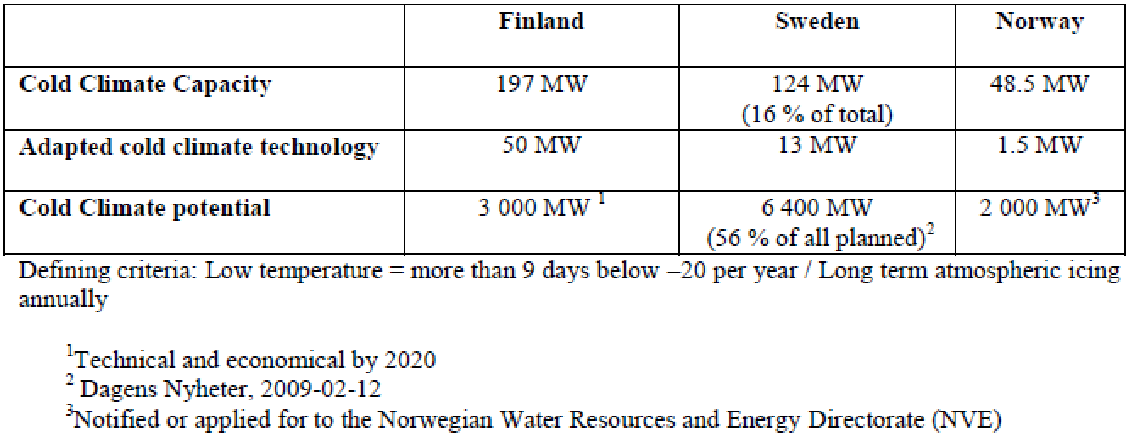


Figure 1 Icing map of Europe (Laakso et al., 2010; 11).

The installed cold climate capacity in Scandinavian countries is presented in table 1.

Table 1 Existing cold climate capacity in Scandinavia in 2010 (Laakso et al., 2010).



	Finland	Sweden	Norway
Cold Climate Capacity	197 MW	124 MW (16 % of total)	48.5 MW
Adapted cold climate technology	50 MW	13 MW	1.5 MW
Cold Climate potential	3 000 MW [1]	6 400 MW (56 % of all planned)[2]	2 000 MW[3]

Defining criteria: Low temperature = more than 9 days below –20 per year / Long term atmospheric icing annually

[1] Technical and economical by 2020
[2] Dagens Nyheter, 2009-02-12
[3] Notified or applied for to the Norwegian Water Resources and Energy Directorate (NVE)

Figure 2 Mapping the different regions

In Finland there have been reports of turbine down time due to ice and low temperature, as reported by National Wind Energy of Finland (Laakso et al., 2010b). According to the statistics the low air temperature has lowered turbine availability annually between 0.2 and 2.8% between 1997 and 2010. Depending on the year, 1 to 27 turbines have been forced to shut down due to low air temperature each year (Laakso et al., 2010b).

Icing has lowered turbine availability by approximately 1.3 % of normalized annual operational hours on average for those turbines that have been reported for icing between 1996 and 2010 (Laakso et al., 2010b). The decrease in availability due to icing has been between 0.3 % and 4.1 % / year per turbine (Laakso et al., 2010b).

However, in Norway there is no centralized system for collection of operational experience from wind farms. Therefore there are no available central data on downtime and production loss due to icing or low temperatures. There is one test turbine at Sandhaugen, close to the city of Tromsø, which has reported 20-25 icing days a year, but there are no detailed statics on failure or energy loss reported publicly (Laakso et al., 2010a).

There is an empirical relation among icing, location and seasonal icing profiles by effective hub height for each region, see figure 2. Region 3 shows the area between Sweden and Norway and the area has a mean annual loss of 7% to 13% at 700-800m hub height. Figure 4 shows how the mean annual losses are 1 % to 3% in 300-500 hub height. In Figure 5 the region 1 is presented and the mean annual losses are 0% to 0.5% in 100-300m-hub height. This is a result from 250 turbines in 10 different sites (Lars Tallhaug, 2015).

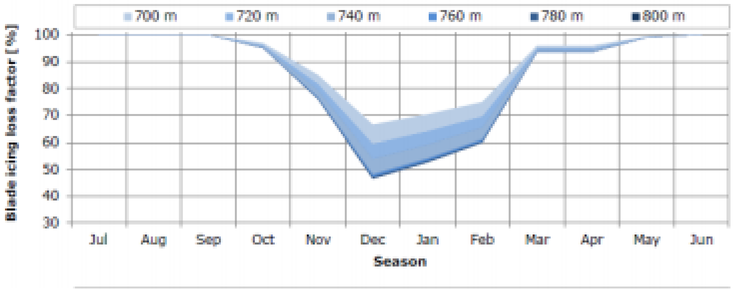


Figure 3 Region 3 – Empirical relation among icing, location and seasonal icing profile (Tallhaug, 2015).

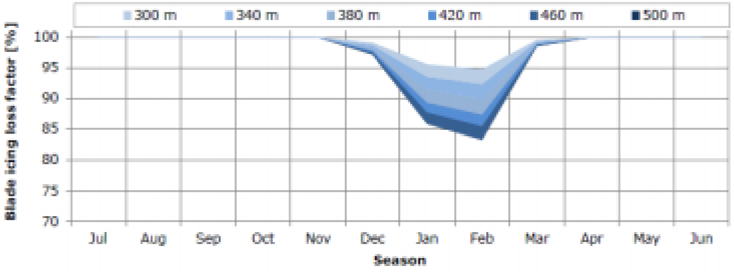


Figure 4 Region 2 – Empirical relation among icing, location and seasonal icing profile (Tallhaug, 2015).

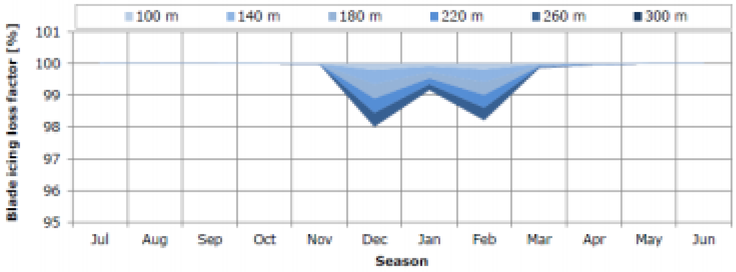


Figure 5 Region 1– Empirical relation among icing and location and seasonal icing profile (Tallhaug, 2015).

2.4 Weather condition and different types of icing

There are different types of ice. Atmospheric icing is classified based on two different formation processes (S. Fikke et al., 2007). These are precipitation icing and in-cloud icing (S. Fikke et al., 2007). Precipitation icing is ice that form due to wet snow or freezing rain (Cattin, 2012). “In-cloud icing” occurs when super cooled liquid droplets (SLD) like clouds collide with a structure or object and freezes on the turbine blade. The physical properties and appearance of the ice accretion will vary on the variations in meteorological conditions during the ice growth. Parameters such as compression and shear strength for instance would be used to describe the nature of accreted ice. Other important factors would be for example humidity, temperature and the duration of the ice accretion (Ethiopian Standards Agency, 2001). The main preconditions for significant ice accretion are the dimensions of the object exposed and its orientation in relation to the direction of the icing wind (Cattin, 2012). Figure 6 gives an indication of the parameters controlling the major types of ice formation (Cattin, 2012). The density of accreted ice varies widely from low (soft rime) over medium (hard rime) to high (glaze).

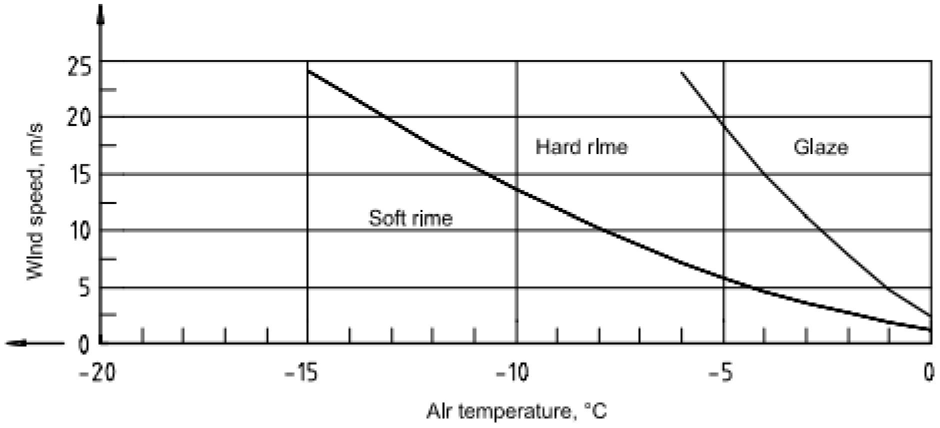


Figure 6. Type of ice as function of wind speed and air temperature (Ethiopian Standards Agency, 2001).

2.4.1 Glaze

Glaze is the type of icing that has the highest density, and is caused by freezing rain, freezing drizzle or in- cloud icing (Energy & Systems, 2012). It causes smooth evenly distributed ice accretion. The surface temperature of accreting ice is near freezing, and as a result, liquid water may due to wind and gravity flow around the object and freeze on the leeward side (L Tallhaug et al., 2009). The main factors in determining the accretion rate for glaze is rate of precipitation, wind speed and air temperature (Ethiopian Standards Agency, 2001).

2.4.2 Wet snow

Wet snow is able to stick to the surface of an object because of the occurrence of free water in the partly melted snow crystals. The accretion occurs when the air temperature is below the freezing point (Rindeskär, 2010). When the temperature decreases the build-up of wet snow will freeze (Ethiopian Standards Agency, 2001). The density and adhesive strength vary widely with the fraction of melted water, wind speed and other factors (Ethiopian Standards Agency, 2001).

2.4.3 Rime

Rime is the most common type of in-cloud icing and often vanes on the windward side of linear, non-rotatable objects. Icing on small linear objects is the cross section of the rime vane triangle with the WOP angle pointing windward nut as the width (diameter) of the object increase the ice vane changes its form (Ethiopian Standards Agency, 2001). Distributed ice can be formed by in-cloud icing when the object is a nearly horizontal "string" which is rotatable around its axis. The accreted ice on the windward side of the "string" will force it to rotate when the weight of ice is sufficient. The mechanism will continue as long as the ice accretion is going on. This may result a cylindrical ice accretion around the string. The most severe rime icing accrue on freely exposed mountains(coastal or inland), or where mountain valets force moist air through passes and consequently both lifts the air and increase the wind speed over the pass (Baring-Gould et al, 2009). The rime mainly varies with the dimensions of the objects exposed, wind speed, liquid water content in the air, drop size distribution and air temperature (Ethiopian Standards Agency, 2001).

2.4.4 Hoar frost

Hoar frost is caused by direct phase transition from water vapor into ice, and is common at low temperatures (Rindeskär, 2010). Hoar frost has low density, low strength and normally does not result in significant load in structures.

2.5 Effect of icing

Cold climate site affects the design of a wind turbine. Ice, rime and high air density at low temperatures will affect the aerodynamics. Thus the loads and power will further impact on the construction of the turbine (Seifert, 2003a). The control system can be affected if temperature and high masses of ice on the structure change the natural frequencies by high amplitude vibrations (Seifert, 2003a). Resonance and mass imbalance between the blades of wind turbine components may change the dynamics behavior of the whole turbine (Parent & Ilinca, 2011). Frozen and iced control instruments give faulty information to the supervisory system of the turbine. Extremely low temperatures will require special materials; for example, normal steel will become brittle at those temperatures (Seifert, 2003a).

There are health and safety restrictions in each cold climate operations and they have to be taken under consideration, for example large ice pieces falling down and ice fragments thrown over large distances may cause injury to humans and animals or damage objects. The turbine may also be affected by heavy unbalance due to unsymmetrical icing, because of changed natural frequencies of components exceeding the designed fatigue loads (Seifert, 2003a).

Low air density can increase the loads and maximum power output (Seifert, 2003b). If the turbine does not automatically react, the windings or transformers can burn, and gearboxes may be overloaded. Overloading may reduce lifetime of components and further damage the turbine, if it does not automatically react (Seifert, 2003a). Higher air density related to low temperatures and airfoil modification can lead up to 16 % overproduction in the wind turbine (Parent & Ilinca, 2011). In icing conditions the measurement errors of the wind speed can be up to 30%, maximum error of 40% for an ice-free anemometer and 60% for a standard anemometer during icing event (Parent & Ilinca, 2011). There are chances for lower production of energy due to increased vibration (higher load) and too low temperatures around the wind turbines. If the turbines are lightly iced, you will experience production loss even while the turbines are in operation. The reason for low production is that the ice changes the airflow across the air foil and creates turbulence, resulting in lower rotation, caused by a loss in aerodynamic lift and an increase in drag (Andersen, Börjesson, Vainionpaää; Silje Undem, 2011). The biggest production loss is caused by ice accretion on the tip of the rotor blade (Seifert, 2003a). The effect on power production will be approximately the same if the outermost 5% of the rotor blade is iced up as when about 75-95 % of the rotor blade is covered in ice (Andersen et al., 2011). Electrical failure may be caused by snow infiltration in the nacelle, and extreme temperatures may also lead to condensation in the electronics (Laakso et al., 2003a).

2.6 Production

Production may be severely affected by icing and figure 7 shows an example of simulated power curves of iced up wind turbines.

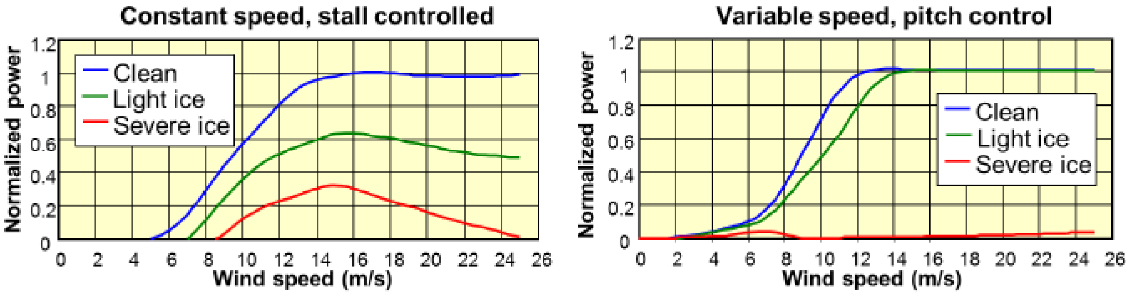


Figure 4. The impact on the power curves of stall (left) and pitch (right) regulated wind turbines in different icing conditions. Graph source VTT Finland (Wallenius T., 2007)

Standard deviation of wind speeds should be considered, as it may result in higher annual power production variability. This adds additional complexity to calculation of short term production uncertainty (P75, P90, etc). It is recommended that time-series of wind, ice accumulation and temperature are produced to estimate the uncertainty in the aerodynamic properties of blades covered in ice (Energy & Systems, 2012).

2.7 IEA Wind Ice Classification

This section presents an ice classification for wind energy sites from IEA Wind. The EIA Ice Classification is based on the classification which as elaborated in the EUMETNET/SWS II [4] projects (Tammelin et al., 2001). Classes LII4 and LII5 in the EUMETNET/SWS II classification are in a range where it is not feasible to develop wind energy projects. EIA propose a modified classification, as shown in Table 2. The classification is based on metrological and instrumental icing. Metrological icing is the period during which the meteorological conditions for ice accretion are in active ice formation (Tammelin et al., 2001). On the other hand instrumental icing is the period when the ice remains at a structure and an instrument or a wind turbine is disturbed by ice (Westerhellweg & Mönnich, 2010). There is a delay between the start

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[4] EUMETNET is a network of 18 National Meteorological Services: those of the EU plus Iceland, Norway and Switzerland; www.eumetnet.eu.or

of meteorological icing formation and the start of instrumental icing formation, called incubation time (Energy & Systems, 2012). The delay depends on the surface and the temperature of the structure. The delay between the end of meteorological ice formation and the end of instrumental ice formation is called the “recovery time”. This is the period when the ice remains, but it is not actively formed (Energy & Systems, 2012). How they affect the measurement is mentioned in section 6.2.1.1.

Meteorological icing can be modelled numerically with mesoscale weather prediction models. One of the most qualified methods of measuring meteorological icing is to measure it directly with an ice detector on site. Instrumental icing is defined as the period when the ice remains at a structure and/or an instrument or a wind turbine is disturbed by ice (Cattin, 2012).

Table 2. EIA Ice Classification with Corresponding Recommendations (Energy & Systems, 2012).

IEA Ice Class	Meteorological Icing	Instrumental Icing	Production Loss
	% 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

3.0 Technology in Icing on blades

Turbine technology is the key to any wind power project, in terms of efficiency, risk and supply/demand dynamics. Technical advice is needed to ensure that the choice of turbine has been adequately investigated, especially as the market is increasingly demanding different types of technology due to new projects in cold climates. Projects in cold climate site are new for many developers and currently there are not enough historical data to evaluate the turbines that are made for these conditions.

3.1 Modeling icing

The accretion of icing on objects is very complex. There are two different ways of modeling icing, the physical accretion process and the meteorological environment that rules the input to the models (S. M. Fikke, Kristjánsson, & Kringlebotn Nygaard, 2008).

The most relevant weather parameters are clouds, wind trajectories, stability, precipitation, topographical influence and turbulence (S. M. Fikke et al., 2008). There will always be data which is less representative, and in these cases the engineers have to use operating experience, inspection and "gut feeling".

The most common models used in predict icing is the Makkonen model:

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 w A V$$

Where *dM/dt* is the icing rate in a standard cylindrical icing collector (defined by ISO 12494 as a cylinder of 1 m length and 30 mm diameter), *w* is the liquid water content, and *A* is the collision area of the exposed object. *V* is the wind speed and α_1, α_2 and α_3 represents collision efficiency, sticking efficiency and accretion efficiency. The collision efficiency is a function of mass, velocity and drag force (Davis, Souza, Joseph, & Verdult, 2015). The Makkonen model uses an empirical function which is based on cylindrical object and small diameter (Davis et al., 2015). This model is also used on WRF model data.

It is possible to use modern high-resolution 3D atmosphere models

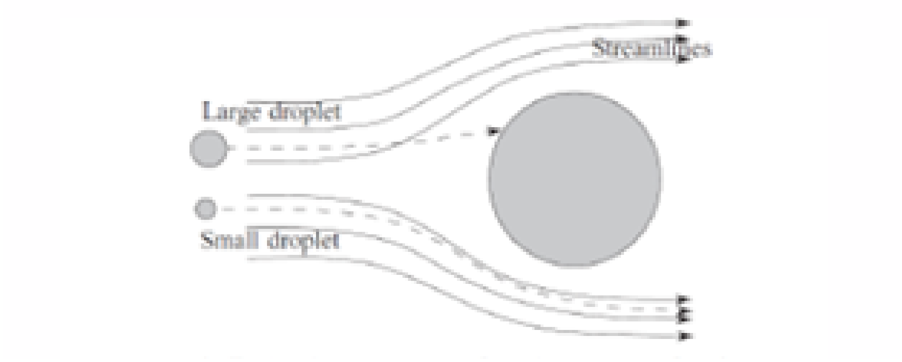

Figure 5 The relationship between chord length and rime icing on wind turbines (Davis et al., 2015)

3.2 Measuring icing

The ice accretion measuring can be performed by use of direct measurement, indirect measurement or numerical modeling.

Direct measurement may be conducted by changing physical properties like mass, reflective properties electrical or thermal conductivity, dielectric coefficient and inductance.

Indirect methods are based on detecting weather conditions that lead to icing: humidity, temperature and wind speed or by detecting the effects of icing.

Empirical or deterministic models are used to determine when icing occurs to evaluate the liquid water content (LWC) and median volume diameter (MVD).

The financial prospect is very important and a project’s cost efficiency depends on the available wind energy during the icing period and on the severity of icing. This analysis requires knowledge about meteorological conditions leading to ice accretion and the turbine’s geometry and operating conditions. The meteorological parameters used for icing prediction are mainly liquid water content (LWC), water droplet diameter (MVD), pressure, temperature and the horizontal distribution of the variables. This kind of measurement is expensive and difficult to conduct. Quantitative data is not always readily available and most of the estimation is empirical (Parent & Ilinca, 2011). It is also important that the measurement is done at the same height as the top blade tip.

Ice sensors

Ice mass measurement uses an ice collector that consists of a 30 mm diameter cylinder (Parent & Ilinca, 2011). This method of measurement is good, but there are always some uncertainties. Other sensors using different approaches, such as longitudinal wire waves, vibrating probes or optics exist, but are only used during the operational phase of the turbine. These technologies are expensive and demand high energy (Parent & Ilinca, 2011).

Double anemometry and vane

The use of equipment for measurement masts with one properly heated and one unheated anemometer to estimate wind resource measurements, is cheap and advisable (Parent & Ilinca, 2011). This gives a fairly good idea of the time that ice can affect the turbines. The disadvantages of this method are that it has poor measurement in the tip of the blades, where there is more icing. The other disadvantage is that low temperatures were found to cause negative errors which did not result from icing between heated and unheated anemometers (Parent & Ilinca, 2011). The method is optimal at relatively mild temperatures.

Relative humidity and dew point

Relative humidity is high during in-cloud icing, and the detection of high humidity over 95 % combined with temperature below 0 degree is used to detect icing. In practice air temperature is at frost point nearly all the time when in-cloud icing occurs, and a dew point detector that has been designed for subzero operation could provide valuable information for this situation (Laakso et al., 2005). The first measurement of relative humidity is more used then the dew point measurement. However, this method does not detect icing events during the same period as ice detectors. When the humidity is more than 95-98 % with temperatures of less than 0 degrees, the predictability of icing events using conditions of relative humidity is weak (Parent & Ilinca, 2011).

Visibility and cloud base

When the temperature is below 0 degrees with a minimum wind speed of 2 m/s, in- cloud icing may occur. To classify clouds, the qualitative quotes or visibility distance to estimate the LWC are used. These have a direct effect on the intensity of the in-cloud icing (Parent & Ilinca, 2011).

To measure this airport observation[5], a pyranometer, video monitoring or automatic sensors are used. Another alternative is to create an ice map. Airport observation provides cloud base heights and a cloudiness index based on the observation of the cloud density, on a scale from 1 to 8. When the index is higher than 6/8 and the cloud base height is lower than the wind turbine, icing is detected or the index can be used as a ratio for accretion intensity (Tallhaug, 2003). In Europe this map has been introduced, and may provide the predicted number of icing days with respect to the location. There has also been found that the severity of rime ice is strongly related to terrain roughness (Parent & Ilinca, 2011). This methods overestimates icing, if there has been input of wrong wind speed and temperature for the location. There have also been comments about the reliability of this method at 200 m above the ground (Parent & Ilinca, 2011). Therefore this formula can only provide a rough estimation of the predicted amount of rime accretion.

The pyronometer measures the solar radiation intensity and Dr. H Dobesch concluded that the solar radiation has an effect on the ice map[6] (Parent & Ilinca, 2011). Also, it is very difficult to get accurate data because the radiation network is very sparse and the use of analytical models is quite uncertain for the time span of one to several hours during the day. At higher latitudes the solar radiation intensity is too weak to enhance significant melting processes at low temperatures. Different wind turbines react different to icing, therefore icing maps cannot be interpreted as exact and must be used in combination with local topographical information and measurement statistics (Parent & Ilinca, 2011).

Models

In regional weather predictions, physical mesoscale models (MM5, MC2 and other) may be used to predict upcoming icing events or to describe the likelihood of such events for specific projects or time frames (Parent & Ilinca, 2011). For models that provide information about amount and the rate of icing, there has been used more sophisticated empirical and statistical models. These models consider parameters such as temperature (air, object, wet-bulb and dew point), wind

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[5] *"Automated airport weather stations are automated sensor suites which are designed to serve aviation and meteorological observing needs for safe and efficient aviation operations, weather forecasting and climatology."* (Wikipedia)

[6] Maps indicating light icing or icing in the studied area.

direction, wind speed, cloud height, cloud cover, the humidity profile, precipitation, regional topography, local topography, object size, shape and material composite and solar radiation (Parent & Ilinca, 2011).

Other methods

Visual detection using video filming of guy wires during icing events. Icefall due to wire vibration has to be accounted for in the analysis. Ice accumulation models are in reasonable agreement to the ice thickness observed on guy wires by an onsite web camera. Improvements may be had by using onsite temperature and wind speed measurements or water droplet density information from a combined analysis of on-site visibility records and cloud base observation from the airport (Harstveit et al., 2005). To detect freezing rain a rain detector with a temperature sensor may be used.

3.3 Anti-icing and de-icing technology

Anti-icing and de-icing are strategies for icing mitigation systems. These systems can be divided in passive and active methods. Passive methods such as ice repellant (ice-phobic) coatings on the blades is use to eliminate or prevent ice on the blade surface(Luo, Vidal, & Acho, 2014). Active methods make use of external systems and require a supply of thermal, chemical or pneumatic energy (Parent & Ilinca, 2011).

Anti-icing system prevents ice from accreting on the object. There are different passive methods used in anti-icing systems. Most manufacturers use epoxy or polyester matrix composites reinforced with glass and/or carbon fibers, because of their lower cost compare to the other alternatives (Parent & Ilinca, 2011). Black paint is also a passive method. It involves painting the blades black, which allows them to heat during daylight and is a solution used together with an ice-phobic coating. Chemicals are also an option to avoid the water to turn into ice on the blades by using chemicals to lower the water’s freezing point.

One of the methods for active anti-icing systems is thermal, where heating resistance and warm air can be used in anti-icing mode to prevent icing. Air layer is another method, which consists of an air flow originating inside the blade that is pushed though rows of small holes near the blade’s leading and trailing edges in order to generate a layer of clean and heated air directly around the blade surface. The last active method uses microwaves to heat the blade’s material to prevent ice formation.

De-icing removes the ice layer from the surface. There are different passive methods, and one of them is use of a flexible blade, which is flexible enough to crack the ice loose. Another method is active pitching and semi-active method, which use start/stop cycles to orient iced blades into the sun. For an active de-icing system heating through resistance is a good option. This method consists of electrical heating elements that are embedded inside the membrane or laminated on the surface. The idea is to create a water film between the ice and the surface, and the centrifugal force will throw the ice away. Warm air and radiator is also an active method, and it consists of blowing warm air into the rotor blade at standstill with special tubes. The heat is transferred through the blade shell in order to keep the blade free from ice. The ”flexible pneumatic boots” method inflates the blade with compressed air in order to break ice (Parent & Ilinca, 2011). The inflation cycles last for a few seconds to achieve optimal ice shed and prevent additional ice formation in the inflated surface. After the ice is cracked, it is removed through centrifugal and aerodynamic forces as the turbine turns. One of the last two active de-icing methods is electro impulsive/expulsive method. This method consists of rapid electromagnetically induced vibration pulses in cycles that flex a metal abrasion shield and crack the ice (Parent & Ilinca, 2011). The other one is microwave de-icing. The technology consists of carbon Nanoparticles in a coasting or film that absorb MW radiation and generate heat. The idea is to have microwave generators inside the blades (Johansson et al., 2015).

3.4 Nordex Energy – Anti-icing System

Nordex provides AIS to their developers. AIS operate while the turbine is running and consists of localized heating of the aerodynamically relevant blade surface. The system has reliable and lightweight electrical resistance heaters and optional manual control of heating, which means the system itself is autonomous. If data indicates the presence of conditions liable to cause icing, the heating elements are automatically activated. Energy-efficient heating prevents ice from accumulating on the rotor blades. Figure 8 shows thermal images from the anti-icing system in the Nordex rotor blade.

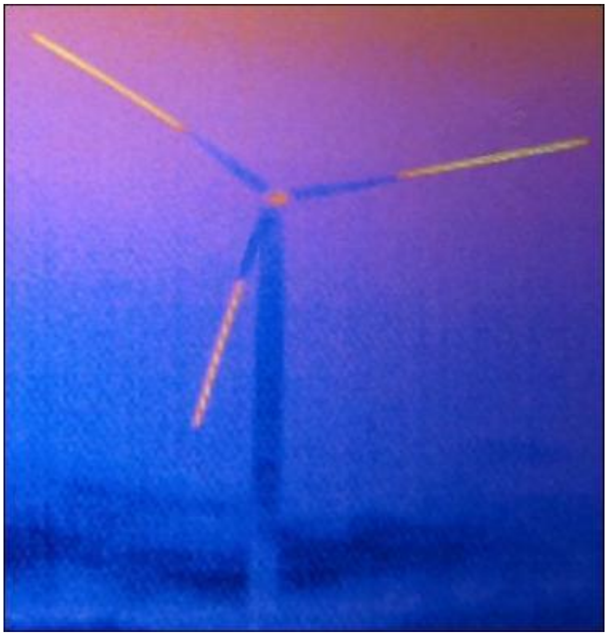

Figure 6 Illustration from a turbine with heating elements (Nordex, 2012)

In the rotor blades there are heating elements, sensors, electrical connection lines for power and signal transfer and a lightning protection system.

Figure 7 Picture in the left show rotor blade covered in ice and de-iced system during turbine operation in the right (Nordex, 2012).

With the anti-icing system in place the wind turbine would not need to be shut down even if ice were to form during operations. The system automatically removes any ice that has accumulated along the front edge of the blade and reduces the risk of potentially dangerous situations caused by falling ice. The advantages with this system are maximum yield even in protracted sub-zero temperatures. The system starts as a result of a number of factors such as ambient humidity, wind and temperatures, especially in the range of -5°C and-10°C (Nordex, 2012). The system has lower internal power consumption[7] and the internal power requirements for the anti-icing system are less than 0,3 per cent and are already factored into the test results (Nordex, 2012). Other advantages of the system are resilient solution integrated into the blade structure and the ability of removing ice during operation does not cause any drop in yield.

The system consists of one ice sensor, and heating elements on parts of the leading edge of each rotor blade. Figure 10 is an illustration of blades, one with AIS and the other without.

The first pilot installation was in 2010. Since then the system has been improved and there are four projects under construction. The Nordex solution is for the wind turbines N100 and N117.

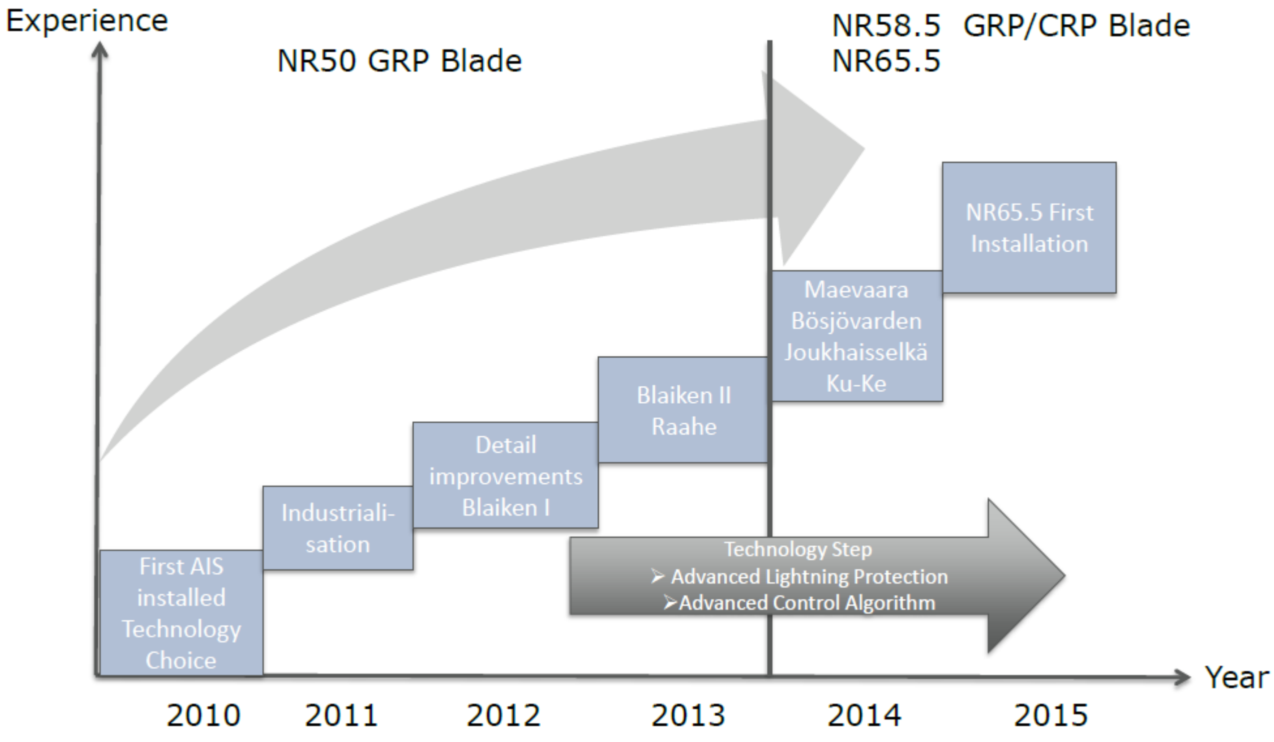

Figure 8 Innovation Curve of AIS

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[7] In manual mode the automatic heating control is deactivated. The following options can be selected for heating control: No heating (the heating control is deactivated), Level 1 (the contractor of the star connection is controlled for the period defined by a paramenter chosen Nordex) and Level 2 (the cntractor level of the delta connection is controlled for the period defined by a parameter chosen by Nordex.

3.4.1 System description of the anti-icing system

AIS consist of electrical resistive heating in the form of a heating element made from carbon fiber reinforced plastic (CRP), that is applied to the surface of the rotor blade. Ohmic resistance is utilized to create a heat source, which heats the elements and minimize the ice accretion on the rotor blade surface. The system has a star-delta connection[8] that makes it possible to operate the heating with either 100% or 33% output.

The following components are required for operating the AIS and are shown schematically in Figure 12.

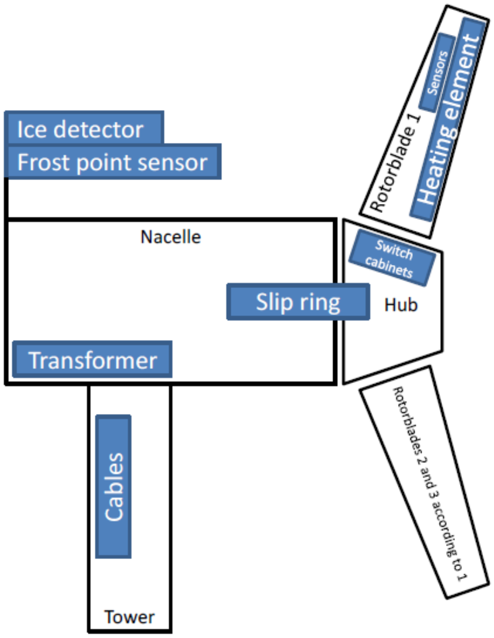

Figure 9 Diagram of the AIS components and their positions in the WT

Rotor blade

In the rotor blade there are CRP heating elements that enable electrical resistive heating. The sensors in the rotor blade have temperature sensors and overheating protection switches

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[8] Start-delta connection is a mathematical technique to simplify the analysis of an electrical network.

Switch cabinets in the hub

There are three terminal boxes for cables from the rotor blades and a control box that control and communicate for the AIS. The power box supplies the power and the center box is the terminal and distribution box.

Software

The system incorporates software with controlled algorithm of the heating and interfaces to the operational control with digital signals and Modbus[9] and a graphical user interface installed on the AIS controller. And through this user interface there are multiple available options for control, such as display of the AIS status, display of all recorded measurements, manual control of the rotor blade heating, etc.

Nacelle

The nacelle has a slip ring, transformer and two different sensors. The first is a Labkotec ice sensor and the other is a Vaisals frost point sensor. Both sensors pass the detected measurements via the Modbus to the AIS.

Tower

In the tower there are cables and connections.

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[9] Modus is a connection between the AIS control and the wind turbine. Through this bus the AIS is supplied with numerous operating parameters of the wind turbine, such as wind speeds, performance data, outside temperature etc.

4.0 Financial Theory

4.1 Economics aspects

This chapter presents the economic variables that are used to calculate NPV in Windmoney to make a basis for an investment project.

4.1.1 Wind Power Output

The power output of a wind turbine is based on the average wind speed, the average air density, a constant to yield power in kilowatt, maximum power coefficient and the length of the rotor blades. For calculating the energy, the formula is

$$P = kC_p \frac{1}{2} A v^3 \rho$$

Where P is power output, v is wind speed, A is the rotor area of the turbine, ρ is the density of the air, k is a constant (0,000133) to yield power in kilowatts and C_p is maximum power coefficient, ranging from 0,25 to 0,45 (Windpower Engineering, 2010).

This calculation can help the wind turbine owner to estimate the power output they can expect and get an elevation of the site.

Wind turbines do not extract 100% of the available resources available in the movement of wind due to limitation of efficiency and generator size. There is a law called, Betz´law that says that it is only possible to convert less than 16/27% of the kinetic energy in the wind to mechanical energy using a wind turbine.

4.1.2 Annual Energy Production (AEP)

The AEP is the kinetic energy and is a calculation of the projected energy outcome if the turbine based on a given annual wind power output multiplied with time.

4.1.3 Energy Yield Calculation – Low temperature Effects

In cold climate site an assessment of annual energy output (AEP) will be affected due to cold temperature. There will be lower turbine production/availability due to temperature below the operational limits. The lower measurement availability due to low temperature should be included in the AEP calculation. A statistical analysis can be based on long term diurnal and seasonal temperature and wind speed profile (Energy & Systems, 2012).

The effect of low temperatures on energy production are estimated using

$$E_t = E_O(1 - \int_{-\infty}^{T} f(t)dt$$

Where E_T is energy output in low temperatures, E_O Energy output, T lower temperature limit of the turbine and *F(t)* is the probability density function for air temperature.

4.1.4 Capital Expenditure (CAPEX)

Capital Expenditure is the total cost of developing and constructing a plant, excluding any grid-connection charges.

4.1.5 Annual Operating Expense (OPEX)

Operating expenditure is the total annual operating expenditure, starting from the first year of operation, given per unit of installed capacity term.

$$OPEX(t) = FC + (VC * Q_t)$$

Where FC describes the fixed costs and VS describes the variable costs. Q_t is production in year, *t*.

4.1.6 Capacity factor

Capacity factor is the actual annual energy output divided by the theoretical maximum output. This is the ratio of net megawatt hours of electricity generated in a given year to the electricity that could have been generated at continuous full power operation.

4.1.7 Depreciation

Tax depreciation methods differ from country to country and in this paper will aim to reflect the methodologies applied at the local level. In this paper it is assumed that capital expenditures are deprecated using straight-line approach.

$$D_{L,t} = \frac{CAPEX}{n}$$

D_t is the deprecation in year, *t* and *n* is quantum of years with deprecation.

4.1.8 Taxes

This paper is about cold climate sites in Northern Europe and there are differences in tax systems across the countries considered. In this paper the Swedish standard taxes have been used to make the financial model.

4.1.9 Subsidies

Subsidies in Northern Europe are different between countries. To simplify, the model in this paper is based on the subsidies regime in place at the time for Blaiken wind site. The Norwegian -Swedish certificate market creates a common subsidy system. It is a marked-based subsidy system for renewable electricity production. Read more in 6.3.5.

4.1.10 Net Cash Flow

Net cash flow is the undiscounted capital that remains after all expenses are deducted.

$$NCF_t = GR_t - CAPEX - OPEX_t - Taxes_t$$

$Taxes_t \ is \ the \ paid \ tax \ that \ year.$

4.1.11 Discounted cash flow

Discounted Cash Flow (DFC) is a method used to estimate the attractiveness of an investment opportunity. All the cash flows are estimated and discounted by using cost of capital to give their present value.

$$DCF_t = \frac{NCF_t}{(1-r)^t}$$

The discount rate, *r* is the time-value of money and a market risk. The time-value of money is the fact that a EUR today is worth more than a EUR tomorrow, this means that an investor is getting rewarded for giving up a present cash flow for a later one (INC, 2014). The market risk reflects that some investments are more risky than others.

4.2 Economic Analysis

4.2.1 Cash Flow analysis

Wind energy projects will have varying lead times. It can take up to 10 years from the point when the developer applies for concession until the turbine is producing electricity. This corresponds to about eight years from the first exploration of cost until the first major capital cost prevails. Production takes place over a long period, normally 20 years. The first four years the cash flow is normally negative for å wind site project. There are different cash flow analyses that are carried out by suppliers and developers of wind sites in evaluation of each site.

In this paper, the analysis is prepared by looking at the IRR that is base for three levels as explained in Table 5.2.1. The base for level 1 is operational project IRR, EBITDA. It is the ratio used to compare projects if no information is available about legal, tax- or financing structure of a project. Base level 2 is IRR with main focus IRR from an investor's perspective, FCF. The last base, level 3, is IRR FCF for shareholders.

Table 5.2.1 IRR on three levels

	Revenues
	OPEX (O&M, Land, Management, Insurance, Studies etc.)
=	**EBITDA (Earning Before Interest, Tax, Depreciation & Amortization)**
./.	Deprecation
=	**EBIT (Earning Before Interest, Tax**
./.	Interest
=	**EBT (Earning Before Tax)**
./.	Tax
=	**Profit & Loss (P&L according to Balance Sheet)**
+	Deprecation
+	Interest
+/-	Outflow/Inflow in Cash Accounts
=	**CFADS (Cash Flow Available for Debt Service)**
./.	Principle and Interest
=	FCF Project (Free Cash Flow)
./.	Tax Shareholder
./.	Other Costs Shareholder
=	**FCF Shareholder**

4.2.2 Net Present Value

The present value is a type of discounted Cash Flow (DCF) model. One of the advantages with this model is that it allows for easy comparisons of potential investment (Boundless, 2015). This method will be one of the tools to use here in order to evaluate whether the project is profitable or not with an AIS. The goal is to maximize the stakeholder's financial assets, and help the stakeholder make an informed investment decision, in projects that are worth more than they costs. The present value is a formula in finance that calculates the present day value of an amount received at a future date (Finance Formulas). The first step of NPV calculation is to estimate the revenue and cash flow that will be generated during the project's lifetime (Economics & Political Weekly, 1971). Furthermore, the model requires a calculation of the required rate of return for the current project. This will reflect the risk associated with the project and, including opportunity costs. High-risk projects call for a higher rate of return, while lower risk projects demand relatively low returns. Rate of return, r, is used to discount the future cash flow related to the project. The sum of all cash flows will be the project's present value. The difference between investment cost and present value is described as NPV. If the difference between the present value and the total investment cost is positive, there is a basis of investment. If the difference is negative, the project will not be profitable. The formula for NVP is

$$NPV = -I + \sum_{t=1}^{n} \frac{C_1}{(1+r)^n}$$

The investment is profitable if NPV > 0.

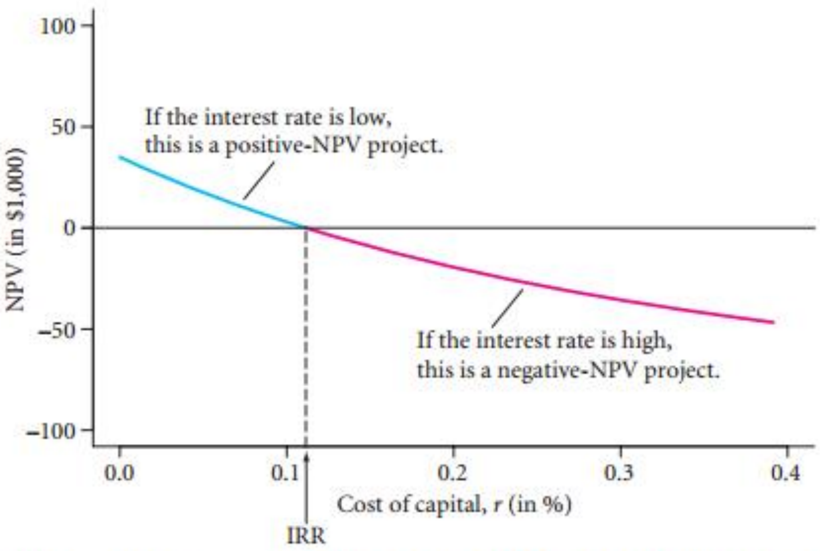
Where I is the investment cost in time t=0, C^1 is the cash flow at period t, r is the rate of return and n is the number of periods.

4.2.2 The Internal Rate of Return (IRR)

The internal rate of return, IRR is calculated from a project's cash flows by setting the NPV =0 (Investopedia, 2015). It is normal practice for a wind turbine supplier to use this method of valuation to assess the profitability of an investment (Wind Power Engineering, 2012). IRR is given as

$$0 = C_0 + \frac{C_1}{1+IRR} + \frac{C_2}{(1+IRR)^2} + \frac{C_3}{(1+IRR)^3} + \dots \frac{C_t}{(1+IRR)^t}$$

Where C is the cash flow for all time periods, t.. The IRR does not depend on the prevailing cost of capital. This formula is useful when a project has more than one inflow and outflow (which is generally the case for all complex decisions). There is an acceptance rule which says to accept the project if the IRR is greater than the opportunity cost of the project (Conditions, 2005). There can be several IRR solutions or no IRR solution, and it is recommended to make a plot with NPV and IRR as illustrated in Figure 12.



This figure draws the NPV for a project that costs $100,000 and pays $5,000, $10,000, and $120,000 in consecutive years. The IRR is the *x*-coordinate where the NPV function intersects the horizontal axis at 0.

Figure 10 NPV as a function of the interest rate (Welch, 2009)

The advantage of IRR is that it is a simple way to communicate the value of a project to someone who doesn’t know all the estimation details (Conditions, 2005). Estimating a required return can be a difficult task, and you may not need to do it if the IRR is high enough. IRR is unreliable in situations where there is a non-conventional cash flow; IRR is a single calculated value and cannot model multiple discount rates, and it is therefore not suitable for mutually exclusive projects (Favaro, n.d.).

4.2.3 Cost of electricity

The levelized cost of electricity (LCOE) is the net present value of the unit-cost of electricity over the lifetime of a generating asset. In this case the net present value is set to zero and the internal rate of return equals the applied discount rate (Energypedia, 2014). In this calculation the annual project costs, such as operation and maintenance and dept service[10] are included. The inflation rate is set to zero. This type of calculation is normally done to give an estimation of the expense of technology. This calculation makes it easy to compare the price between energy production technologies.

The cost of electricity is a EUR/MWh value that represents the total lifecycle costs of producing one MWh of power using a specific technology.

$$LCOE = \frac{Sum\ of\ cost\ over\ lifetime}{sum\ of\ electricity\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where $LCOE$ is the levelized cost of energy (EUR/MWh). I_t is the investment expenditures in year t. M_t is the operational and maintenance expenditures in year t. F_t is fuel expenditures in year t. E_t is the electricity generation in year t. The discount rate is r and n is the expected lifetime of the system or power station. In this paper we have not taken fuel expenditures into consideration since this paper is only looking at AIS system.

4.3 Project expanses

There is a multitude of economic risks associated with utilizing wind power. Operating in cold climates adds cost and performance variability that must be assessed when a wind turbine site or project is considered. It is crucial to determine the potential loss of availability and production to know if a project is economically feasible and what mitigation measures might be cost effective (Energy & Systems, 2012). IEA Wind recommended Practice 2013 mentions how there are no specific guidelines for assessing the economic impacts and risk associated with projects in cold climates (Energy & Systems, 2012). The understanding will increase as more projects are developed and realized. It is important to pay attention to recommended practices when designing a project (Energy & Systems, 2012). This section provides an overview of the economic risk associated with operating turbines on cold climate sites.

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[10] The cash that is required for a particular time period to cover the repayment of interest and principal on a debt.

4.3.1 Economics aspects of AIS

There is very little publicly available information on the economic aspects of AIS. Instead, this chapter is based on conclusions from the results of the study. There are no specific guidelines, for either the supplier or developers, in assessing the economic impacts and risks associated with warranties provided for AIS. However, the knowledge will increase as more turbine suppliers provide this service to their developers.

4.3.2 Cost of the Anti-Icing System

The system has an own price that is calculated by the company. The price calculation is project specific, and will thus be made on a project-by-project basis. In this paper it is assumed two prices for AIS, based on own experience.

4.3.3 Maintenance and Service

Maintenance of turbines in cold climates is harder than in “normal” conditions. There is an extra service cost for AIS that is not included in the normal service price.

4.3.4 Financial losses

Financial losses result from an assumed increased risk associated with operations in cold climates and consequent losses in energy production, and the costs of more demanding maintenance. There is also economic uncertainty associated with energy prices. A further explanation is provided in section 6.2.1.

4.3.5 Mapping of Ice

Mapping and modeling of icing is time consuming and thus expensive. The measurement of wind, climate and icing is expensive. Icing of instruments often requires an increased demand of maintenance. In this paper the cost of mapping is not included. It is assumed the developer will already have made this calculation.

4.3.6 Electricity Certificate Price

On January 1st 2012, a joint subsidies system in Norway and Sweden was established. The combined goal was of establishing 26,4 TWh new renewable electricity production by 2020 (Regjeringen, 2014). The “electricity certificates market” is a marked-based subsidy system for renewable electricity production. The electricity produced from a renewable energy sources is entitled to certificates for 15 years. Electricity suppliers and certain end users are required to purchase certificates corresponding to a certain proportion (quota) of their electricity sales or consumption.

4.3.7 Spot price

Norway is a part of Nord Pool Spot, which is the central market for Nordic and Baltic countries. The balance between supply and demand determines the spot price. The electricity price in Norway is an auction-based exchange for the trading of prompt physically delivered electricity (Noordpoolspot, 2015). Nord Pool Spot publish a spot price for each hour of the coming day to balance supply and demand. The members post their volume in MWh/h that they are willing to buy or sell at specific price level to the auction for the next day.

4.3.8 Warranty

Banks and credit institutions play an important role in the wind farm execution and demand a risk minimization of the whole project. The performance of a wind farm is mostly dependent on the wind turbine’s power curve and technical availability. The company takes a risk when they provide verification of the performance warranties. Different types of warranties are explained in chapter 7.

5.0 Methodology

In this chapter I discuss the methodology that was used for obtaining data. The AIS is in the commercial phase, and there is still not enough historical data from wind sites with AIS to evaluate the warranty model that will optimize the customers' value and minimize Nordex's risk. To make the estimation, it is important to know how the investors', developers' and suppliers' estimate their own financial risk, related to the project.

This thesis is based on the use of mixed methods that consist of qualitative and quantitative studies. The reason behind choosing a qualitative method is due to the fact that there has not been any further research on the advantages the AIS provides to the customers of Nordex. In addition, there are not many document reviews describing this perspective. The quantitative method was chosen naturally due to the statistical material that needed to be calculated.

5.1 Qualitative Analysis– Interviews

The majority of the data collection consists of interviews of Nordex customers, financial investors and developers. This is done in order to provide a better understanding of Nordex's customers' perspective. Furthermore, I have been looking into what value different warranties generate for Nordex's customers.

The interviews were conducted through skype calls, meetings and telephone calls during the semester. I designed in-depth interview guides that were semi-structured. This was done in order to have some structure but at the same time have the liberty to let the interview subjects speak freely about the general topic or come up with new topics. Interviews with financial investors and consultants were tape-recorded.

The interviews with Nordex's employees and the developers of the wind sites were conducted through e-mails and telephone calls. These conversations were not tape-recorded. Instead they were documented by taking notes. The interview questions are constructed based on the background of the individual interviewee. My conducted interviews were not time limited as they allowed me to converse and question until I had gathered the necessary information.

5.2 Quantitative Analysis - Data Analysis

Quantitative analysis is a method for understanding behavior using mathematical and statistical modeling, measurement and research (Investopedia, 2015). The analysis can be done for a number of reasons, and in this paper is it chosen to predict NPV with and without the AIS.

The collected data regarding the production numbers at the Blaiken wind site was provided by Nordex. The data presents the energy production and loss due to ice of each turbine that is observed during one specific winter season.

I have also gained access to a report from Kjeller Vindteknikk that evaluated the site and loss of production due to ice. More information of the data from Blaiken Wind site is explained in section 2.2.

In this paper the Nordex sales calculation tool[11] has been used to determine the turbine price. To determine an optimal prediction for the investment cost and revenue the sales tool, Windmoney, has been used to calculate the NPV of the system with different turbine prices and percentage of loss due to ice. This simulation tool is constructed to show the projects financial portfolio. In this calculation different turbine prices and losses due to ice where chosen to find the point where the AIS will have positive financial impact on the project.

5.3 Literature study

The literature in this paper generally considers icing in cold climates and information on existing anti- and de-icing technology available in the market. Theory about financial risk and different financial warranties is also explained in this paper. The information is based on a literature study by the Nordex technology department and a number of research articles about icing. Information about financial risk is obtained from NTNU's and NMBU's database. Most of the articles were recommended by my advisor at NMBU and by Nordex. Some of the information is collected from NORWEA[12], Norwegian Water Resources and Energy Directorate (NVE), wind seminar presentations and IEA Wind[13] recommended Practice.

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[11] The calculations in these programs are based on Nordex estimations and is used in sales

[12] NORWEA is the Norwegian Wind Energy Association.

5.4 Simulation Tools

Sales calculations and WindMoney from Nordex have been used to predict the AIS price and NPV. The main uncertainty in these sale tools is that it is developed by Nordex, and the parameters input is based on their experience. Therefore, the financial results are based on Nordex assumptions and perspectives. The uncertainties in the parameters that are calculated in Windmoney are explained in section 9.4.

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[13] The international Energy Agency Implementing Agreement for Co-operation in the research, development and deployment of wind energy systems. IEA Wind is a vehicle for member countries to exchange information on the planning and execution of national, large-scale wind system projects and to undertake co-operative research and development projects called Tasks or Annexes.

6.0 Decision analysis under uncertainty

The wind industry is characterized by a significant degree of uncertainty. The challenges of long-term forecasts of weather and global climate changes have contributed to an increase in the uncertainty.

The AIS is still new in the marked and there will be uncertainty in interpretation and understanding of different facts, data and the ability to make decisions.

6.1 Decision analysis

The aim of a management model for decision making is to present an effective, targeted and sufficiently simple procedure (Jordanger, n.d.) Mentioned below are some criteria that should be taken into account for the investment.

- *The entire project life cycle must be taken into account in the management of the project, not only in the analyses. I.e. planning phase, implementation phase and operational phase.*
- *Accrued expenses (with uncertainty) over all project phases must be included in the management foundation.*
- *Accrued benefit / revenue (with uncertainty) in the operating phase must be included in the management foundation.*
- *Accrued economic factors are discounted to decision time.*
- *Accrued qualitative benefit is discounted in decision time; corresponding quantitative present value.*
- *Qualitative disadvantages and qualitative advantage weighted together with quantitative conditions in final decisions.*
- *Balancing between quantitative and qualitative factors in the decision.*

Source: (Jordanger, n.d.).

6.2 Uncertainty in Wind Energy

6.2.1 Uncertainty in Meteorology

An analysis of the data collected on the different sites during the wind resources measurement with AIS should be performed in order to find possible deviation of the flow model and thus calculate correction factors to affect the results. The uncertainty is around the data from meteorological icing, instrumental icing, incubation time and recovery time (Battisti, 2015). It is difficult to make a universal model of meteorology uncertainty, as data varies greatly between geographic areas, and is further affected by other conditions which are difficult to assume (Laakso et al., 2010b).

The duration of the technical perturbation of the instrument due to icing with time as unit is defined as instrument icing (Battisti, 2015). It is normal to use an anemometer as the instrument. But there is uncertainty around an anemometer, because it may be affected by icing as well and not work optimal. For example, heated sensors can have ice build-up during heavy ice snowfall, and this may disturb the measurements. By using AIS, the incubation time may be extended.

The description of the icing characteristics of a site are based on Wind Energy in cold climates (Energy & Systems, 2012), where the incubation time is set to zero. It is assumed that the meteorological and instrumental icing start at the same time. The described duration of meteorological and instrumental icing in this report refers to unheated anemometers.

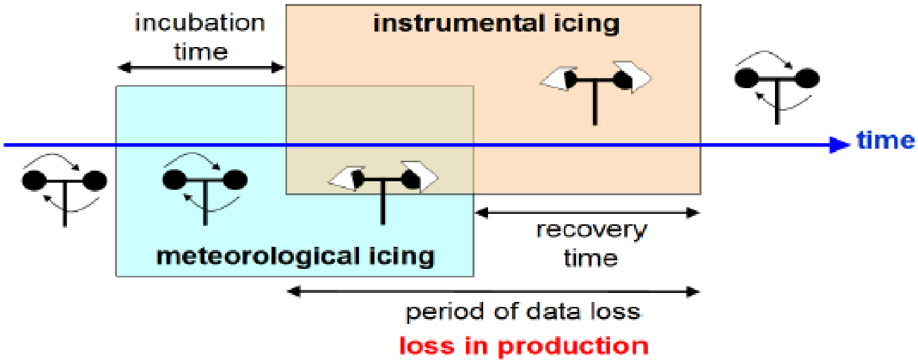

Figure 11 Definition of meteorological icing and instrumental icing from IEA Wind Report (Energy & Systems, 2012)

Figure 13 shows a timeline for the icing process and the important parameters of the process; icing rate, ice accumulation per time [g/hour], maximum ice mass accreted on a structure [kg/m] and the type of ice.

In cold climate there is an uncertainty in how long ice may remain on a structure after meteorological icing has taken place. It is defined by performance index. And the formula is:

$$Performace\ Index = \frac{Instrumental\ Icing}{Meteorological\ Icing}$$

6.2.2 Wind Speed

The main variable in the production formula is wind speed. In this paper the wind speed is assumed to be the average wind speed for a class 2 turbine, which is 7.5 m/s[14]. The uncertainty related to wind speed in this paper is based on Nordex' calculation from WindMoney[15]. Wind speed carries unsystematic uncertainty, and thus affects projects individually. The unsystematic uncertainty denotes the consequence of conditions that accompany random fluctuation and are turned both ways (Jordanger, n.d.).

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[14] Interview with Thomas Bak Mahiasen, Sales Manager at Nordex Sales

[15] Calculation tool for workers in Nordex Sales.

6.2.3 Technology

AIS is a fairly recent technology applied to wind turbines and these systems are now being implemented on operational wind farms. The first installation (except for on test turbines) was in 2012 (Nordex, 2012). Currently, there is a lack of track-record information and data on the performance of these systems.

The highest technology related uncertainty is in the ice detection sensors themselves. If the system works perfectly, the system will be heated up before ice accumulation and there will be no ice buildup on the blades at all. The heating system will start based on the measured temperature in the blade, which is fed to the control unit from the sensors situated along the blades. Unfortunately the ice detection has insecurity in their sensors, and the sensor may not detect the ice or will start when there is no ice on the blade[16]. It is possible to control the ice detection manually and choose two different heating systems.

6.2.4 Production loss due to ice

The predicted production loss due to ice is based on the correlation between different meteorological parameters and the observed production losses from individual turbines based on the Weather Research and Forecast model (WRF) data, also explained in section 2.2. The results are taken from Blaiken wind farm. Kjeller Vindteknikk AS prepares the report and WRF data. There are 5 defined classes of ice loads based on the modeled weight of ice on a standard cylinder. Definitions of the five different classes are given in section 8.1.3. The values for the AIS classes are given as the average correlation coefficient ± the standard deviation. One of the uncertainties in the analysis is whether one reference turbines is representative of the loss without AIS. The other uncertainty is linked to the use of an anemometer in the calculation of production.

There are a lot of contextual uncertainty due to production loss, project environment, nature and the project's basic conditions. These have in common that they entirely or for a large part are outside the project's control and are difficult to predict.

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[16] Interview with Øyvind Byrkjedal, Kjeller Vindteknikk

6.2.5 Forecasting of icing

The forecast simulation was carried out with the WRF model to predict icing at Blaiken. The WRF model is described in section 2.2. The model was initiated four times daily with input from the Global Forecast system (GFS) from the US National Weather Service, and applied with a horizontal resolution of 6 km x 6 km. The calculation for each forecast simulation is given in section 3.1. By carrying out validation of a forecasting system Kjeller Vindteknikk have in their report showed that the icing events can be forecasted (Län, 2014). The probability of detection of icing is found to be 74%, with a low false alarm ratio of 5 % for the reference turbine. An energy gain is expected if icing forecasts were implemented in the AIS as a supplement to the ice detection system (Län, 2014).

6.2.6 Estimation of power production

The power curve for each turbine in Blaiken wind farm has been estimated. For each turbine, Kjeller Vindteknikk have estimated a power curve valid for the summer and the winter season respectively. In summer, the power curve data is from May to June. In the winter season, data from November to March have been used.

Air density is an important part of the production and to adjust the power curve a time series of air density calculated from WRF has been utilized to perform a correction. The correction is done according to IEC 61400 -12-1 by Kjeller Vindteknikk.

6.2.7 Spot Price

In the wind industry the price of electricity is one of the most uncertain factors in investment projects. Figure 14 shows great variations in the spot price since 2012. The price has ranged from 9.55 EUR/MWh in July 2015 to 49,06 EUR/MWh in January 2012. It is difficult to estimate a future price, because it depends on the demand of electricity and supply of energy from other sources. This type of uncertainty is known as systematic uncertainty. It acts in the same direction in several projects and is not diversified even in large portfolios (Jordanger, n.d.).

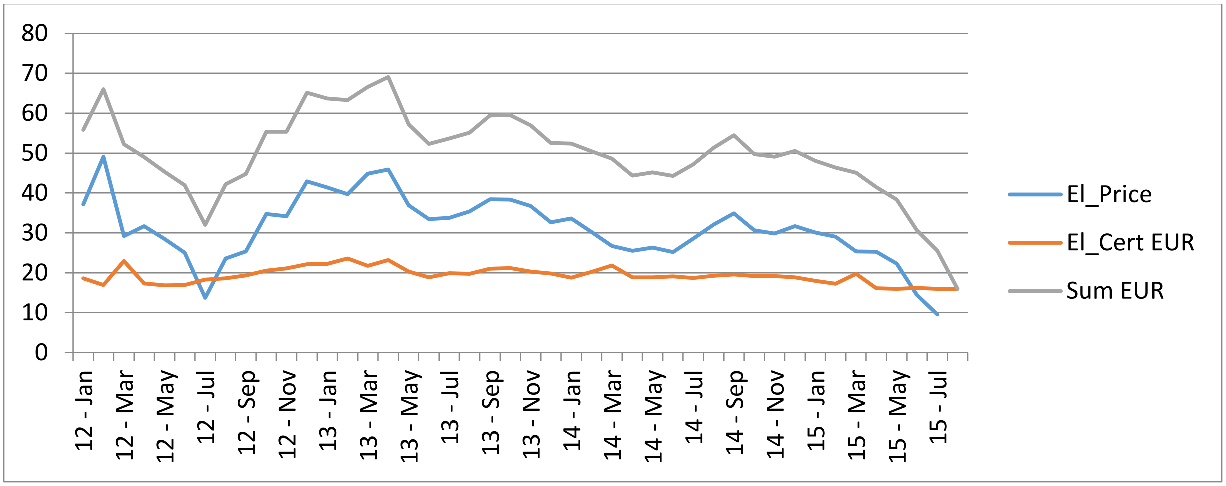

Figure 12 Monthly average price of electricity and certificates in EUR in Norway (January 2012 – July 2015). Source: Swedish Energy Agency (SEA) and Nordpoolspot

6.2.8 Electricity certificate Price

The electricity certificates prices have historically been more stable than spot prices. There are different tax regimes between Sweden and Norway, and therefore the output of the investment will be different. The largest uncertainties with the electricity certificate scheme are political risk for changes to the scheme. The government is currently getting advice from the experts: if Norway should continue with electricity certificate or not (Vindkraftnytt, 2015). The future of the certificate after 2020 is very unclear. The other risk is, if there will be under or oversupply of certificates after 2020 (Lind & Rosenberg, 2014).

6.2.9 Other uncertainties

Other financial uncertainties can be taxes and legislation risk, as well as regulation at national and international level for cold climates sites. The technology related uncertainties are geographical location, wind conditions, wake losses, grid connection and the different component in the turbines. This uncertainty is also known as event uncertainty. It expresses the probability with which the incident will happen and the size of consequences due to it.

Adding to regulatory uncertainty, the economic reality of a slow recovery in Europe has also impacted on investment plans and decisions, new orders and the financial health of existing assets.

6.3 Quantification of uncertainty - uncertainty in Investment Analysis

"*Investment decision making is one of the most crucial managerial decisions. The importance of these decisions results from the fact, that the consequences of such decisions have long-term impact on the company and are capital intensive accompanied with the high risk of the possible losses. Not efficient investment can lead to the financial problems and loss in competitive advantage at the market. Fundamental tools of the investment decision-making are economic criteria of the investment project valuation*." (Hermeling & Mennel, 2008)

There are different ways of doing an investment analysis and evaluate risk. In this paper three types of analyses have been made. These analyses are done in order to evaluate and quantify the risk the developer is taking when investing in wind power. To qualify the value of the investment to the developer, it is important to choose a tool to evaluate/analyze the risk that is coming with the project. The specific type of analyses has been chosen after a recommendation from the advisor in NMBU for this thesis.

6.3.1 Sensitivity analysis

Sensitivity analysis is used to study the uncertainty in the project. It is an easy method to see the potential changes and their impacts (David Pannell, 2015). This method basically uses the investment valuation on the basis of the NPV to calculate the effect of the changes on the included variables. One way to do this is to evaluate the "Low", "Best-bet" and "high" scenarios. By plotting all scenarios on the same graph we are able to create a spider diagram. A spider diagram is used to indicate which variables have the biggest influence and the nature of that influence, if it is negative, positive, linear or non-linear.

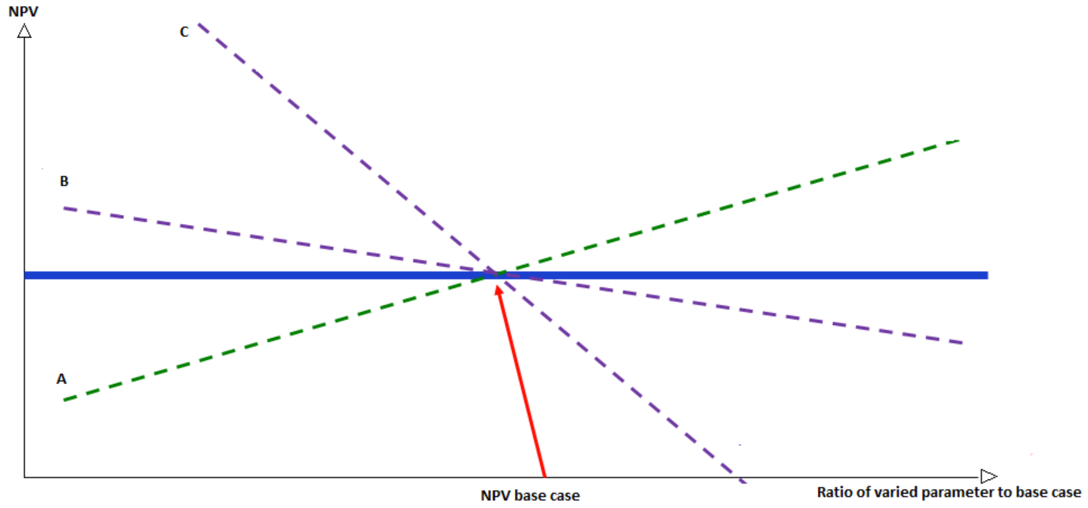

Figure 13 Typical spider diagram where the NPV is the output value and A, B and C is the economical factors in the analysis

There are different sensitivity variables in a wind farm. In this paper the focus is on evaluating the value of AIS, and only the parameters that are affecting the AIS are taken in consideration. In this paper the focus is on investment cost of the system, service price, energy losses with and without the system and energy prices.

It is possible to use different tools to make this analysis.

6.3.2 Scenario Analyses

The parameters that are included in the scenario analysis in this paper are investment cost of the system, service price, energy loss due to ice and energy prices.

The investments projects of any wind park have the scenarios to predict different electricity prices combined with other factors to see how the project portfolio is affected. This allows the project developer to get an overview of key factors related to the investment decision. There is also a possibility that one of these conditions or parameters may change during the project if it has a long time horizon. Therefore, it is important to have different scenarios so the developer is ready to handle the changes.

6.3.3 Break-even analyses

A break-even analysis is to performed in order assert at which point it is not profitable to invest in an AIS. The aim of this analysis is to find different levels of important factors that make the investment of AIS profitable. These measurements are easy to interpret. In this paper the main focus is going to be on production of energy with and without the system.

7.0 Wind turbines warranty model

In the wind energy industry today it is normal to give an availability warranty in order to allow risk sharing between the developer and the supplier. In this chapter the different warranties due to AIS would be mentioned. These warranties are in high demand, and have the potential to optimize the developer's value. To reserve the supplier's risk, it is important to make sure that all the factors that the supplier cannot control, and should therefore not be held responsible for, are not included in the warranty.

7.1 Project finance for wind power projects

In this section the most used warranties in the wind industry are introduced.

7.1.1 Availability Warranty

This warranty ensures the reliability of the turbines and that the turbines will be ready to produce electricity whenever the wind is blowing.

The agreement the contractor warrants is one where the average technical availability of the wind park will not be less than a specified percentage agreed upon by the contractor and the customer. The average technical availability provided by a contractor is around 95%. That means the supplier of wind turbines will pay for the production loss if there are any mechanical failures that reduce the availability under 95%. (Matos et al., 2014).

7.1.2 Power curve warranty

A power curve shows the relationship between wind speed at the wind turbine location and the associated expected power being produced (Wind farms construction, 2015). The power curve warranty is delivered by the contractor and is measured under the standard conditions from the latest revision of the IEC standard[17] (Wind farms construction, 2015). The warranty ensures the efficiency of the turbine according to specification. A turbine may meet the mechanical-availability and output warranties and yet not be producing as much electricity as it could under the same wind conditions due to inefficiencies resulting from poor design, manufacture, or installation. One or two turbines are selected to be tested to determine their actual power curve to

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[17] The standard IEC 61400-12-1 'Wind turbine generator systems, Part 12-1: Power performance measurements of electricity producing wind turbines', hereunder referred to as 'the IEC standard'.

determine compliance with the power curve warranty. If the actual power curve of the tested turbines is less than the warranty power curve, the turbine manufacturer is liable for liquidated damages calculated with reference to the cost of replacement power (or cost to cover) of an amount equal to the forgone production due to failure to meet the warranty (Einowski, 2009).

7.1.3 Parent guarantee

Many turbine manufacturers are subsidiaries of larger enterprises and the financial strength often resides in the parent or another affiliate (Einowski, 2009). In some cases the performance warranties often require backing (in the form of a guarantee of payment) from the manufacturer's parent or affiliate in order to give them substance over the long term (Einowski, 2009).

7.2 Criteria of fulfilment of the warranty

According to A. Albers, it is hardly possible for contractors to avoid losses due to extraordinary power reductions completely, i.e. the warranty should provide the contractor some allowance of such production losses (Windows et al., 2014). Normally it is suggested to sum up the production losses due to extraordinary power reductions for the same reference periods for which also the turbine availability according to an availability warranty is assessed. It is further proposed to calculate the relative production loss due to extraordinary power reductions in such a reference period as follows (Windows et al., 2014).

$$E_{\text{ref.loss}} = \frac{E_{Loss}}{E_{true} + E_{Loss}}$$

Where $E_{ref.Loss}$ is the relative production loss due to extraordinary power reductions in a reference period, E_{loss} is the production loss due to extraordinary power reductions in a reference period, and E_{true} is the true energy production in a reference period.

The turbine availability in a reference period as defined in the availability warranty should be reduced by the relative production loss due to extraordinary power reductions:

$$A_{\text{reduced}} = A - E_{\text{rel.Loss}}$$

Where R_{educed} is the reduced availability, and A denotes the availability according to the definition of the availability warranty.

The power consistency warranty and availability warranty is suggested being fulfilled if

$$A_{\text{reduced}} \geq A_{\text{warranted}}$$

Where $A_{\text{warranted}}$ is warranted availability.

This regulation provides the contractor with the possibility to compensate production losses due to extraordinary power reductions by availability above the warranty level.

8.0 Case study based on AIS investment in Blaiken

Measurements have been carried out for thirty (30) Nordex N100 wind turbines with anti-icing system (AIS) that are in operation at Blaiken wind farm in Västerbottens Län in northern Sweden. There has been one reference turbine, (T13) where the heating system was switched off during the winter. Five (5) of the turbines have not been included in the analysis, because they were used for parameter testing of the AIS, and due to availability issues.

Data with 10 minutes' resolution from each of the turbines have been supplied from Nordex. The data includes turbine power, availability flags, nacelle wind speed, power consumption and operational codes. Kjeller Vindteknikk has also used their own icing parameters based on the IceLoss model in the study.

The analyses were carried out based on the operational power data for the period October 10th 2013 to March 31st 2014. The analyses clearly showed that there were large production losses on the reference turbine in the period 15th December 2013 until 3rd March 2014.

8.1 Metrological data

Calculations of ice load are based on the WRF model; data that is explained in section 3.1. Periods of active meteorological icing is identified from the model data when the icing rate *(dM/dt)* exceeds 10 g/hours. The number of active icing is defined as "icing hours" in the report. Kjeller Vindteknikk has defined the period with instrumental icing as the periods when the ice mass, M, exceeds 10 g/m.

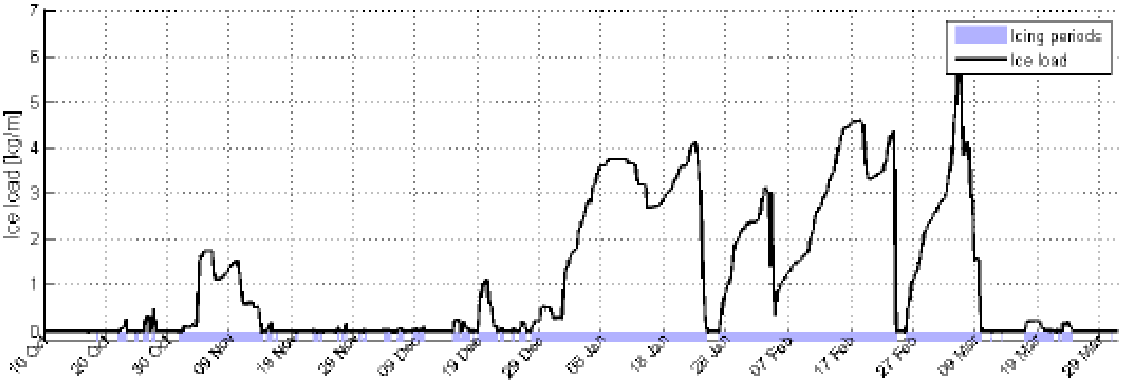

Figure 14 Ice load and icing periods calculated from the WRF model for period 10.10.2013 – 31.03.2014. The figure is from Kjeller Vindteknikk report

In this graph in Figure 16 there are the icing periods that is influencing the power production. The ice is present during almost all of January and February. The first icing events happened in October, but it is too small amounts of ice to influence the power from the turbines to any significant extent. Strong icing is apparent in the beginning of November. There are few periods with icing that are found during the middle of November and December. The ice formation in this period is not expected to influence on the energy production at the site.

8.2 Production Loss

Each of the turbines has a calculated power curve that represent the nacelle anemometer and power data for the turbine for the winter season. There is also a defined threshold power curve. The period is flagged as icing when the power from the turbine is below the threshold power curve, given that the operational codes indicate normal operation and the temperature is lower than +3°C (Län, 2014). The production losses are calculated as the aggregated difference between the actual production and expected production during the periods flagged with icing. For the AIS to reduce the icing losses it was required that the blades were heated during buildup of ice on the blades, the AIS had to be available at the time of ice buildup and icing must be identified from the icing sensor.

The production losses due to icing has found to be 25% lower than the reference turbine, while it averaged 7,9 % for the AIS turbines (see Figure 17). The losses on the individual turbines vary in the range of 3.1-19.8 %.

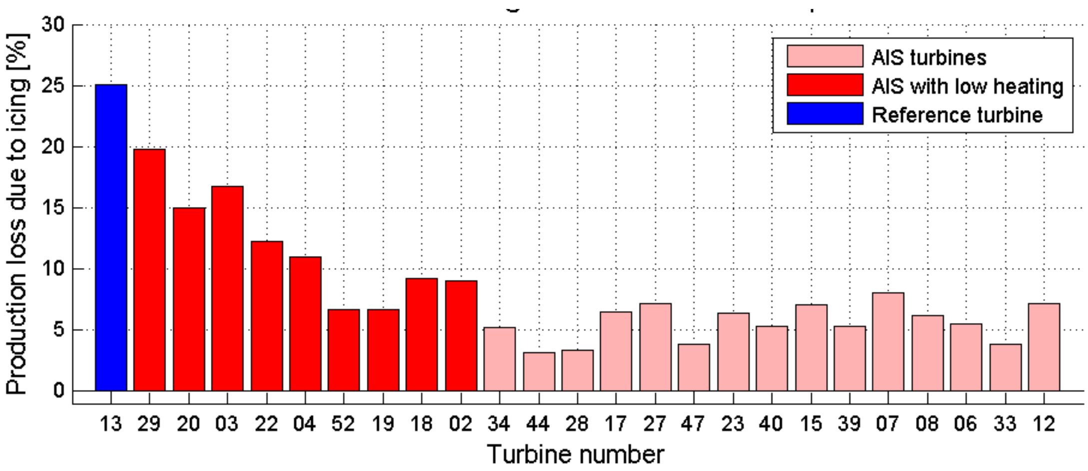

Figure 15 Production loss icing evaluation of N100 with AIS at Blaiken (Sweden) from 10.Oct. 2013- 01.Apr. 2014. Data is collected from Kjeller Vindteknikk report (Län, 2014)

8.2.1 Correlation between production losses and icing parameters

The correlation between different meteorological parameters and observed production losses for the reference turbine and AIS turbines are shown in Table 5. The calculation is from the report (Län, 2014) and is calculated from daily values of production losses from the individual turbines and daily averages of the meteorological parameters based on WRF data.

Table 3 Correlation coefficient between different icing parameters and production losses. The value for the AIS is given as the average correlation coefficient ± the standard deviation

	Reference Turbine [T13]	**AIS Turbines**	
		Average Correlation Coefficient	± Standard Deviation
Ice Loads	0,78	0,26	0,11
Icing Intensity	0,34	0,16	0,08
Temperature	-0,38	-0,1	0,08
Relative humidity	0,56	0,28	0,06
Liquid Water Content	0,46	0,34	0,08

8.3 Total Power Production

The total production for each turbine is shown in Figure 8.3. The result from the report shows that the average energy produced from the AIS turbines during the analysis period was 4971 MWh, while 3462 MWh was produced by the reference turbine. The AIS turbines produced, on average, 1509 MWh more energy than the reference turbine. Most of the difference in produced energy in the site is due to ice loss.

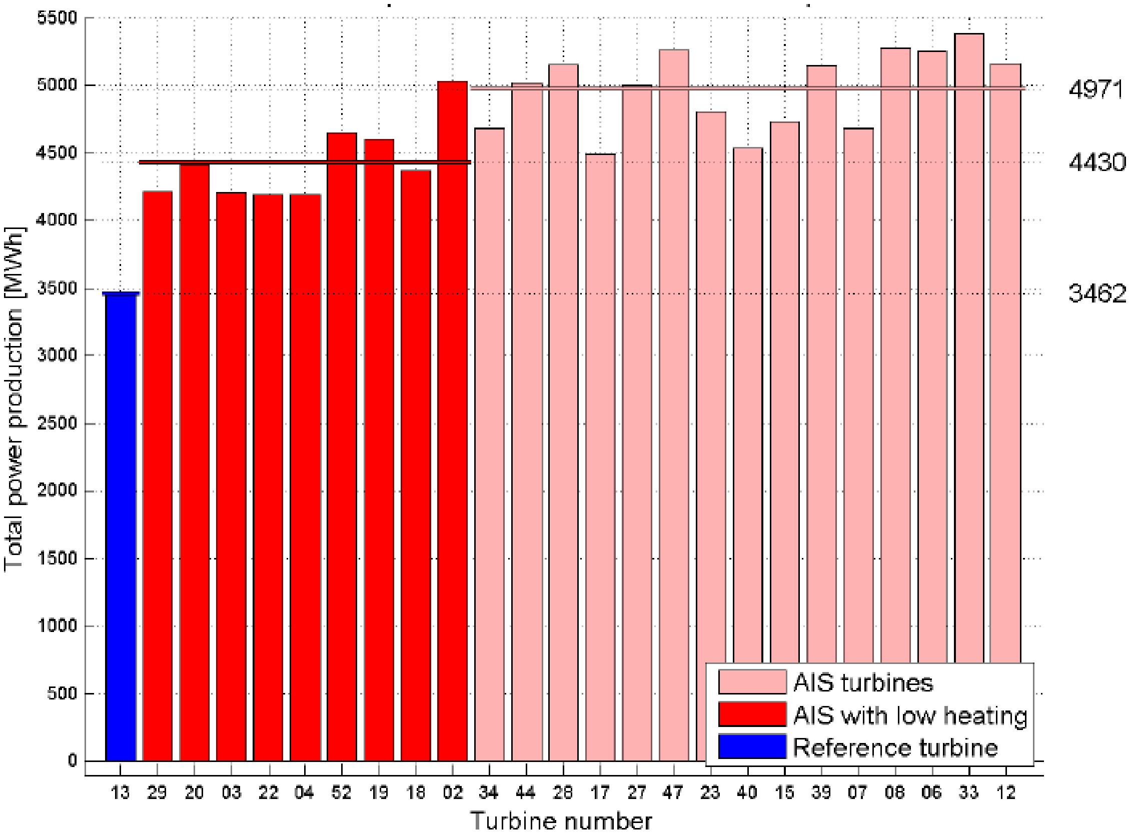

Figure 16 Total energy production for each turbine during period 10.10.2013 to 01.04.2014 (Län, 2014)

The blue horizontal line is the energy production from the reference turbine. The red horizontal line in Figure 18 shows the average energy production for the AIS turbines with low heating, the light red horizontal line shows the average of the AIS turbines with high heating.

8.4 Energy Consumption of the Anti-Icing System

The energy consumption in heating the blades is shown in Figure 19. The average amount of energy consumed by AIS turbines was 105 MWh; while the gain in electricity production was 1509 MWh compared with the reference turbine. The energy gained by installing the AIS system is Is significantly larger than the energy consumed by the heating system.

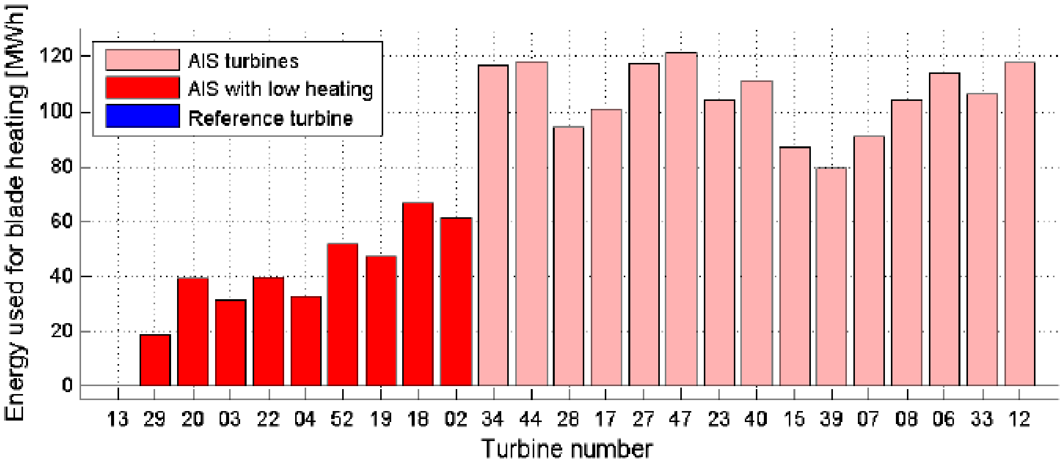

Figure 17 The energy used for blade heating given in MWh. The turbines are sorted according to the percentage of heating hours (Län, 2014),

9.0 Financial analysis

9.1 Nordic Power Price

The energy price is one of the main parameters used in calculating the NPV. The assumption regarding the energy price used in making the NPV analyses for AIS in this paper are based on historical data, future investment and predicted demand and supply of energy. There is also going to be a sensitivity analysis to show how different energy prices affects the NPV.

The hourly trade of electricity on the spot market will lead to prices that can strongly fluctuate depending on the supply and demand situation (Keles, 2013). The electricity wholesale price is one of the main parameters that form the basis for any investment in the wind energy industry. The price of electricity is a sensitive variable in NPV. To get a realistic description of the uncertainty in NPV one should therefore include variation in electricity price. The energy sector has to consider uncertainty during their decision making process. The results show that the model based on stochastic dynamic programming (SDP) has the best annual return and the highest IRR amongst the methodologies, which is revolved around the electricity price uncertainty (Keles, 2013). A deterministic cycle determined for electricity prices is the annual seasonality, which results from the differences in demand for electricity during each season of the year (Keles, 2013).

Table 4 Basic statistics of electricity price (data source: Nordpool Spot)

Electricity Price				
[Euro/MWH]	**2012**	**2013**	**2014**	**Sum**
$\text{Mean}_{\text{El\_Price}}$	31,27	38,12	29,60	33,00
$\text{Std}_{\text{El\_Price}}$	9,35	4,26	3,20	7,10
$\text{Skewness}_{\text{Elprice}}$	0,15	0,62	0,08	-0,03
$\text{SPE}_{\text{Elprice}}$	30 %	11 %	11 %	22 %

The price means of a single year may vary significantly from the regression line. As shown in Table 5, the inner-year distribution of the price varies strongly. The “normalized” standard deviation, which is called “Standard Percentage Error” (SPE) reaches values of up to 30%. SPEs and standard errors vary greatly across years, showing how the volatility is not constant over the years, and thus the electricity price series is heteroscedastic.

Table 5 Total price of Electricity and electricity certificate prices (data source: Nordpool Spot)

[Euro/MWH]	2012	2013	2014	Sum
$\text{Mean}_{\text{Elprice+Elcert}}$	50,42	59,11	48,97	50,64
$\text{Std}_{\text{Elprice+Elcert}}$	9,90	5,54	3,21	9,45
$\text{Skewness}_{\text{Elprice+Elcert}}$	-0,04	0,47	-0,10	-0,35
$\text{SPE}_{\text{Elprice+Elcert}}$	20 %	9 %	7 %	19 %
Correlation between El_Price and Elcert	0,15	0,83	-0,13	0,44

If we include the electricity certificate price in the price, the Table 6 shows more stability in standard deviation between years.

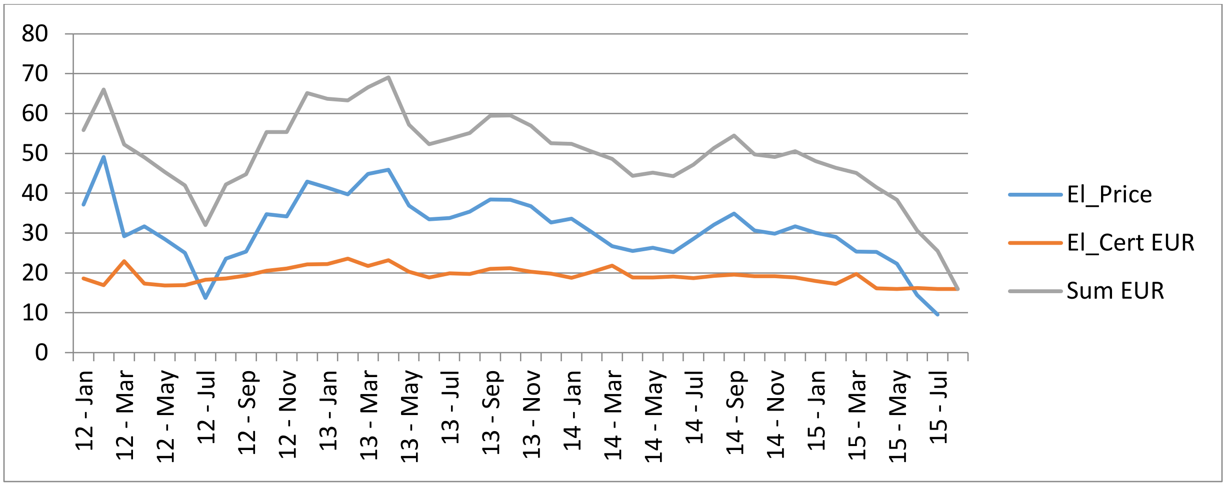

Figure 18 Electricity and Green Certificate price (data source: Nordpool Spot and Statnett)

The electricity prices are at their lowest during the summer of 2015. Senior analyst Olav Johan Botnen in Markedkraft, stated that many groups that work with energy prices believe that electricity prices will rise sharply after 2020 (E24, 2015). Markedkraft believe that the prices will have low increase in the future based on their experiences. Future contracts at Nasdaq OMX

Commodities show that the spot price is expected to be around 26 euro/MWh in 2016 and that it will increase to 28 euro/MWh in 2020 (E24, 2015). *We believe that the stock exchange price of electricity should only be increased slightly after 2020, to the 30-35 Euros per megawatt hour*, said Botnen to E24 newspaper. The stock price will arguably always be lower than the real market price, because of factors such as electricity certificates, tariffs and government taxes. The main reason for the expectations of low electricity prices in the future is an expectation of decreasing demand for electricity, compared to its supply – and thus a changed equilibrium price. There are major developments of new renewable energy projects, additionally, a new reactor in Finland is scheduled to go online with commercial production already in early 2019 (World Nuclear Association, 2015). The coal prices and quota price of CO2 is expected to see a relatively weak price increase in coming years (E24, 2015). These weak increases may make coal energy less expensive in the future (E24, 2015).

Even if energy prices are assumed to be low in the near future there are indicators pointing to increased energy prices after 5 years (E24, 2015). Four reactors in Sweden are scheduled for decommissioning from 2018 and onwards (World Nuclear News, 2015). In recent years, an energy-intensive pulp and paper industry in Scandinavia has been phased out, resulting in a loss of demand of 15 TWh (E24, 2015). The planned grid connection to the United Kingdom and Germany (which will be finishing in 2021) will also lead to an increase in electricity demand. The two main reasons for a predicted sharp increase in electricity prices after 2020, however, are: a tightening of climate policies, which is thought to cause the price of CO2 quotas to increase by 2020 (E24, 2015). The second main reason is the supply for energy, which will decrease after 2020 due to the closure of nuclear power in Germany and Sweden.

Table 6 shows the average electricity spot prices and standard deviations for all years since the electricity certificates arrived in the market. It is easy to calculate statistical values from Table 7, but it is not so simple to estimate future values in order to predict future electricity- and certificate prices. One way to evaluate is to assume that the price volatility will increase proportionally with time. Then price volatility over time may be shown as

$$\sigma_t = \sigma\sqrt{t}$$

Where σ is the standard deviation and t is the year.

Table 6 Volatility in electricity price and green certificate (data source: NordPool Spot and Statnett)

Volatility in Electricity price			
[Euro/MWH]	**2012**	**2013**	**2014**
Std_elprice	0,33	0,09	0,09
Volatility yearly (Elprice) [252 trading days]	5,23	1,49	1,44
Std_elcert	0,13	0,07	0,06
Volatility yearly (Elcert) [252 trading days]	2,12	1,04	0,92

Table 7 Electricity Price and Green certificate price volatility.

Volatility [Euro/MWh]					
Year	**El_price**	**El_cert**	**Year**	**El_price**	**El_cert**
1	0,09	0,06	**11**	0,30	0,19
2	0,13	0,08	**12**	0,31	0,20
3	0,16	0,06	**13**	0,33	0,21
4	0,18	0,12	**14**	0,34	0,22
5	0,20	0,13	**15**	0,35	0,22
6	0,22	0,14	**16**	0,36	0,23
7	0,24	0,15	**17**	0,37	0,24
8	0,26	0,16	**18**	0,38	0,25
9	0,27	0,17	**19**	0,40	0,25
10	0,29	0,18	**20**	0,41	0,26

In this paper the average electricity price over the period considered is assumed to be 33 Euro/MWh, and the price of electricity certificates is assumed to be 20 Euro/MWh. The assumptions are based on the average price for the prior three years.

In order to simulate the annual future electricity price a probability distribution must be determined (as shown in Figure 21). Normal distribution is a natural choice because its assumed in the paper, in the first place, that its considered equally probable that prices will increase or drop.

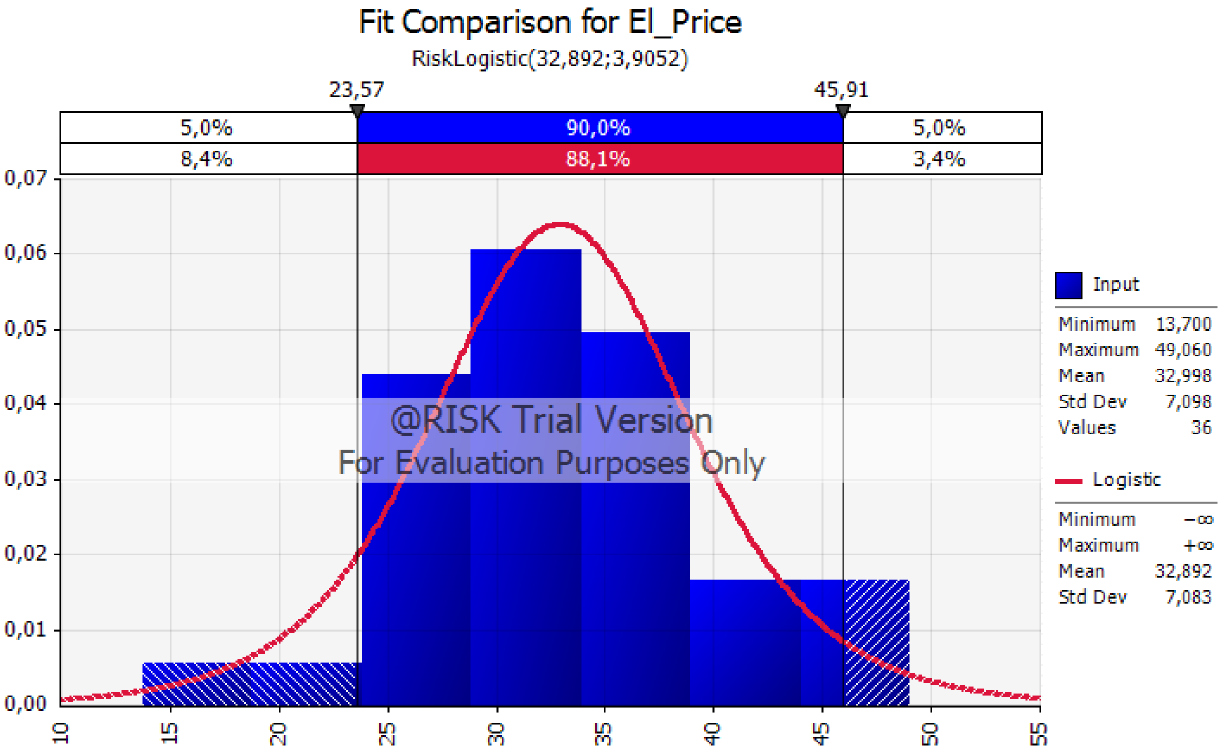

Figure 19 Normal distribution of electricity price.

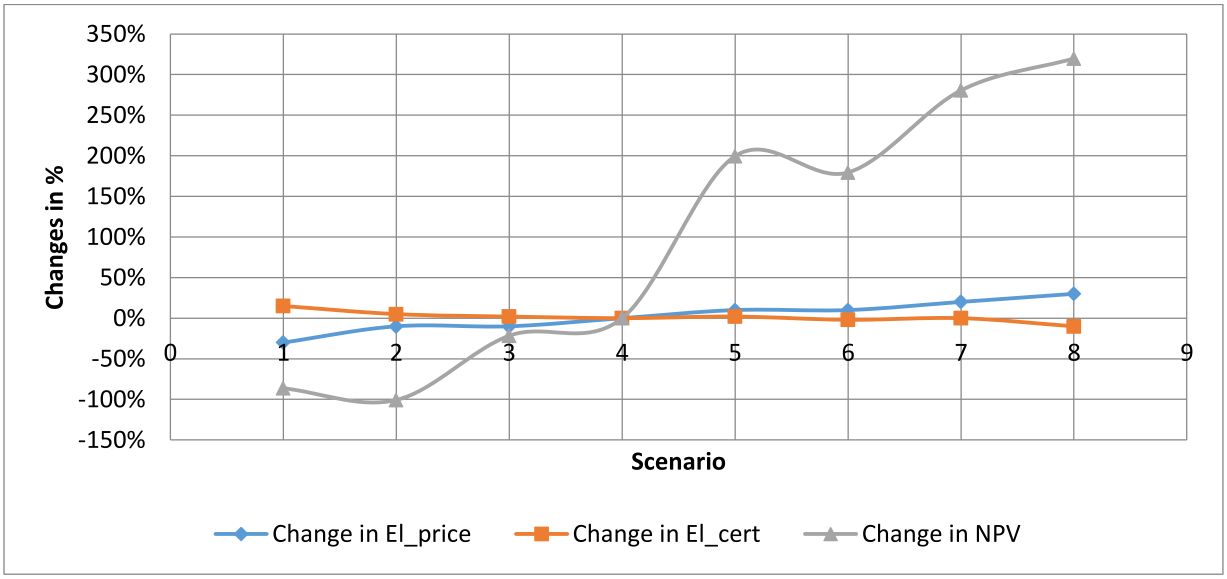

Figure 20 Eight (8) scenarios of how NPV is affected by changes in Electricity and Green Certificate Price in %. This model is based on 10 Nordex turbines with AIS. Scenario four (4) has the reference price of electricity and green certificate. This model is based on Swedish market.

As Figure 21 shows, the NPV is very sensitive to price changes. Scenario 2 shows how, if the electricity price decrease by 10%, and the price electricity certificates increase by 5 %, the total NPV will decrease with 100% compared to a reference NPV with no price changes. This price sensitivity is a risk the developer is taking when they make investments in the wind industry. If the production decreases due to ice, the total NPV will have even lower value. Small changes may render the NPV of an investment negative.

9.2 Financial view of an investment in AIS

This analysis is done to see how much value the AIS will give financially to the developer. The price of the AIS system is assumed to be 7% of the total turbine price[18]. Calculations of NPV for different turbine prices, with different losses due to ice, have been made in order to see how it will affect the NPV with and without AIS. By taking the price sensitivity under consideration, the price of the electricity for this investment is assumed to be 33 EURO/MW with 20 EURO/MWh for electricity certificates. The calculation is based on 30 N100/2500 Class 2 turbines and a wind speed of 7,5 m/s.

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[18] The total turbine price is without the AIS based on the sales calculation sheet given by Nordex. The price is of a turbine without any extra equipments. In real life the prices will be a little different, as the developers will usually want to specify project specific functions on the turbine.

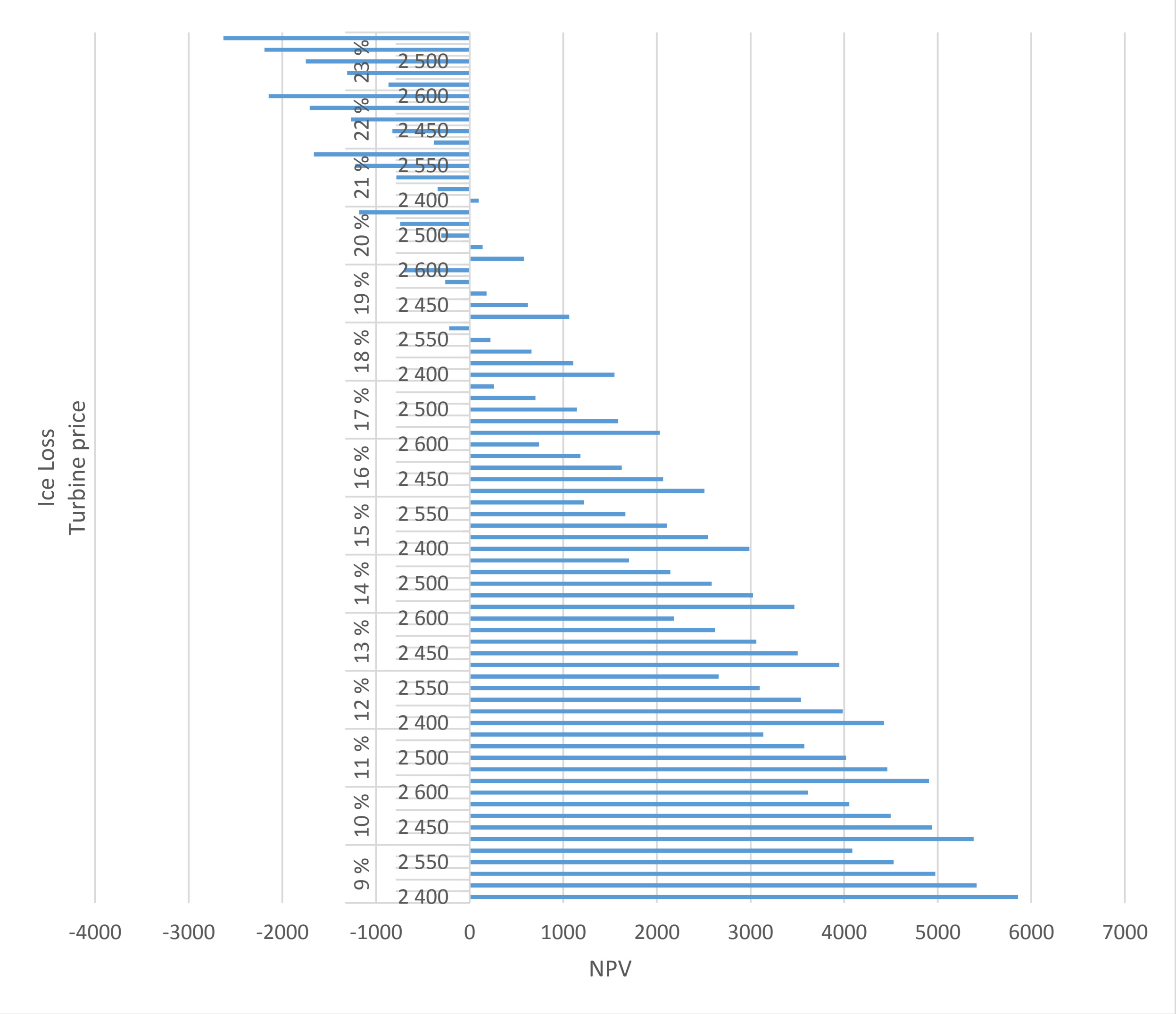


Figure 23 Different Ice loss scenarios with different 10xN100/2500 Nordex turbines prices without AIS and the total NPV for each scenario.

Figure 23 shows the ice loss varying from 9% to 23%. The N100/2500 Nordex turbine will give negative NPV after 19% loss due to ice. The realistic price for a site will be somewhere between these prices. To make sure that the investment is positive for the developer they must make sure that the production loss is never higher than 19% in their worst case scenario.

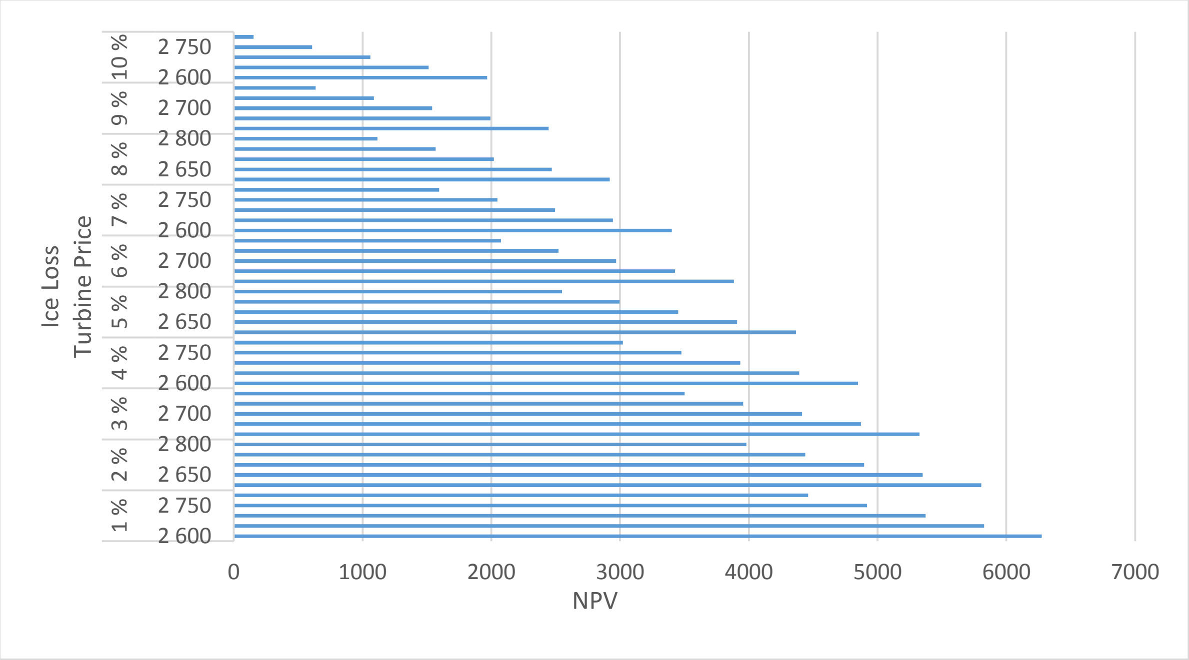


Figure 24 Different Ice loss scenarios with different 10xN100/2500 Nordex turbines prices with AIS.

Figure 24 explains a N100/2500 Nordex turbine with AIS installed. The AIS will ensure reductions in the ice loss, and ensure an increase in total production on the site. If the site is assumed to be extremely affected by ice and the ice loss with the system is observed at 9% in a worst case scenario, the investment will still give positive NPV. Even if the cost of the system is 7 % of the turbine price[17]. If the developer look at the total asset, the investment of AIS will have a positive effect on their site and increase the total value of their portfolio.

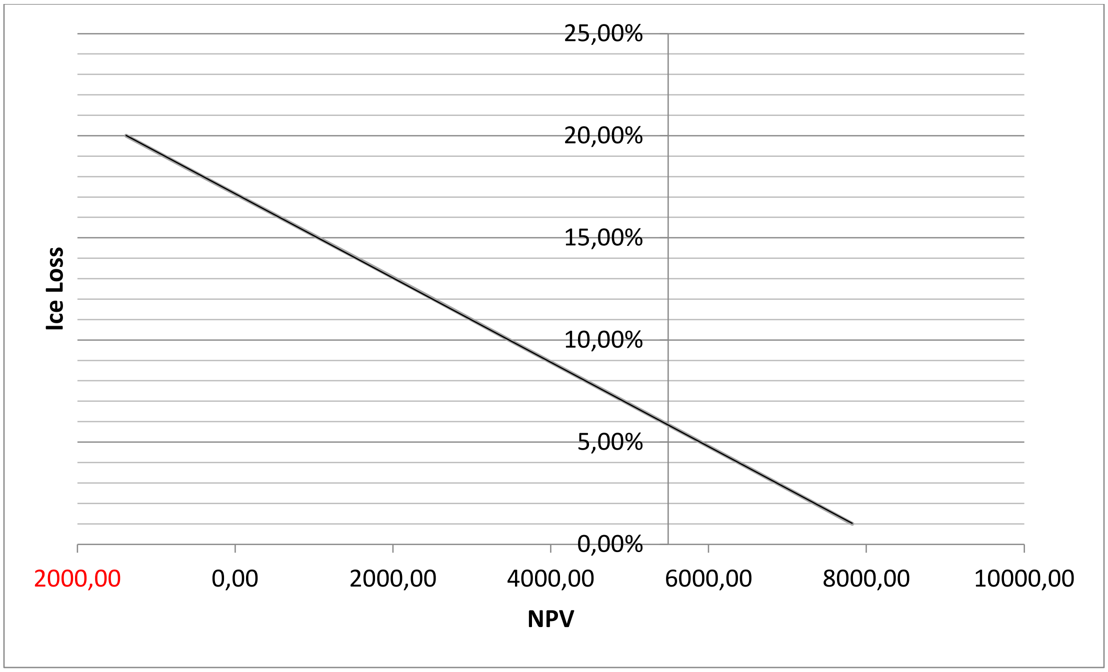


Figure 25 Illustration of when it is profitable to invest in a N100/2500 Nordex Turbine with AIS. The straight line in x-axis shows when the investment of turbine without AIS the same as the turbine with AIS.

By looking at the turbine price with AIS, it is profitable for the developer to invest in AIS if there on average will be more than 6% loss annually on the wind site due to icing. In this calculation it is assumed that the cost of the system is 7 % of the turbine price; so if the cost for the system increases, the intercept in the graph will also change. The illustration of the intercept is shown in figure 25.

Figure 25 and the associated data show how, as long as the AIS reduces the loss due to ice with 6 percentage points, an investment in AIS will yield a positive return.

Table 8 Data from 30 x N100/2500 Nordex turbines without AIS.

Ice Loss [No AIS]	LCOE (ct/kWh) (Equity return: 10%) [SEK] [No AIS]	IRR Operational (EBITDA) [No AIS]	IRR Project Company (FCF atax) [No AIS]	NPV Project Company (FCF atax) [kEURO] [No AIS]
6 %	5,88 kr	11,46 %	13,99 %	5412,82
8 %	6,00 kr	11,02 %	12,98 %	4444,02

10 %	6,12 kr	10,57 %	11,95 %	3473,97
25 %	7,23 kr	6,99 %	2,79 %	- 3835, 34

Table 9 Data from 30 x N100/2500 Nordex turbines with AIS that cost 7% of the turbine price.

Ice Loss [AIS]	**LCOE (ct/kWh) (Equity return: 10%) [SEK] [AIS]**	**IRR Operational (EBITDA) [AIS]**	**IRR Project Company (FCF atax) [AIS]**	**NPV Project Company (FCF atax) [kEURO] [AIS]**
2 %	5,91 kr	11,26 %	13,05 %	5008,57
4 %	6,02 kr	10,85 %	12,13 %	4048,78
6 %	6,14 kr	10,4 %	11,18 %	3083,15
8 %	6,26	10 %	10,22 %	2116,85

Table 10 Data from 30 x N100/2500 Nordex turbines with AIS that cost 10% of the turbine price.

Ice Loss [AIS]	**LCOE (ct/kWh) (Equity return: 10%) [SEK] [AIS]**	**IRR Operational (EBITDA) [AIS]**	**IRR Project Company (FCF atax) [AIS]**	**NPV Project Company (FCF atax) [kEURO] [AIS]**
2 %	5,97 kr	11,03 %	12,55 %	4551,75
4 %	6,08 kr	10,62 %	11,63 %	3588,16
6 %	6,20 kr	10,20 %	10,69 %	2623,07
8 %	6,32 kr	9,78 %	9,72 %	1657,47

Table 10, 11 and 12 show LCOE, IRR and NPV with different percentages of loss due to ice. There are three different scenarios, the first is with no AIS installed, the second is with AIS that cost 7 % of the turbine price and the last is with AIS that cost 10% of the turbine price[17] As the table shows the LCOE is higher if AIS is implemented in the turbine and the loss due to ice is higher than 6%. The prices are in SEK, since the electricity certificate price is in Swedish currency.

9.3 The Economics and Technological view of Blaiken

In this section the financial aspects of Blaiken and how the economic models are going to be with and without the system will be described. In this calculation the average output data from Kjeller Vindteknikk previously shown in table 13 has been used. From the data, we observe that the average loss due to ice without the system was 25%, and 8% with the system installed. As mentioned before, it is only one reference turbine and the loss without the AIS will contain some degree of uncertainty. The electricity- and electricity certificates prices are assumed to be EUR 32,14 and EUR 20,87 respectively. The real result will be different, as the availability is assumed to be similar in this calculation, whereas in real life the system with AIS will have higher availability.

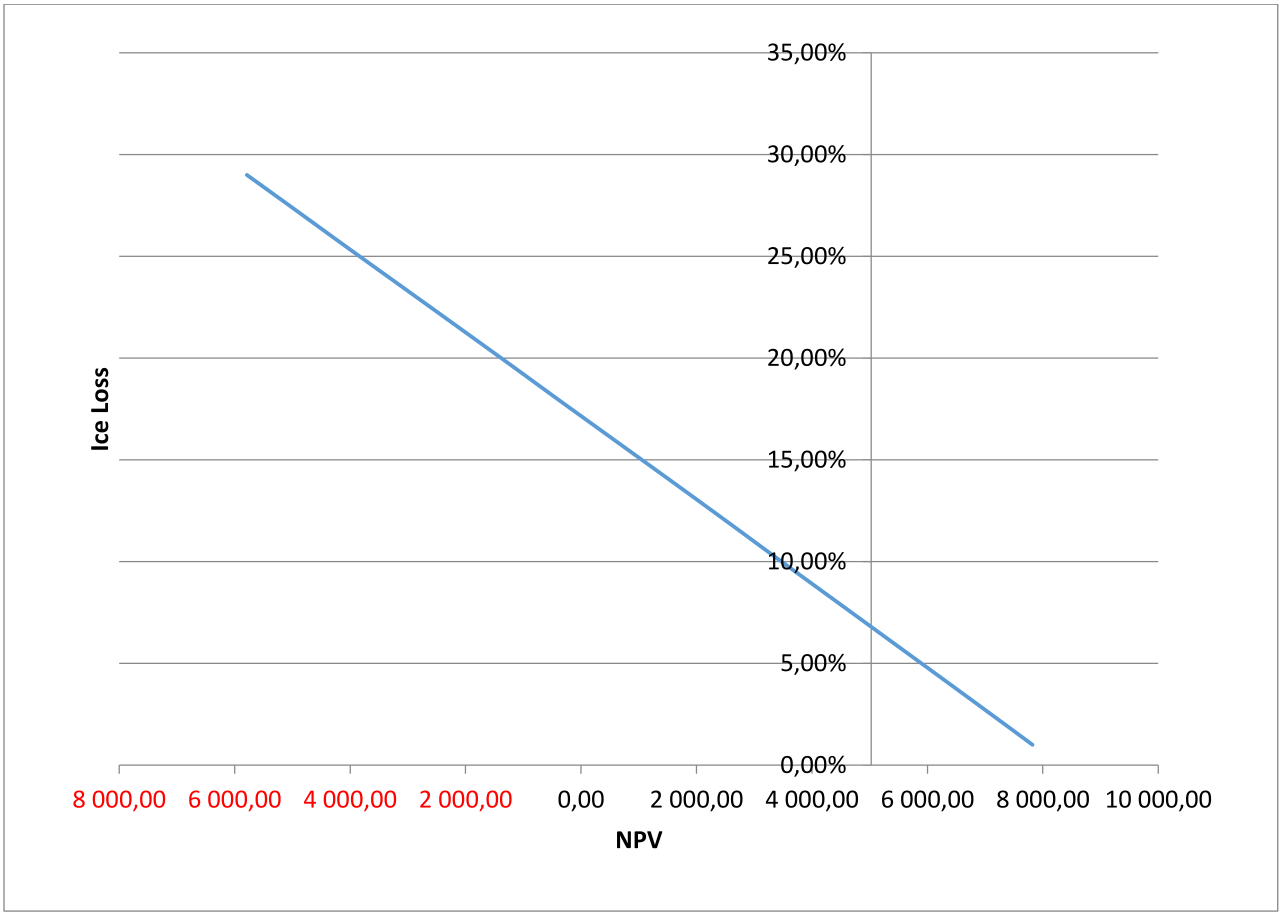


Figure 26 Illustration of when it is profitable to invest in N1000/2500 Nordex Turbine with AIS that cost 10% of turbine price.

If the AIS price is 10% of the turbine price, the investment will be positive after 7% loss due to ice. Beyond this point an investment in AIS would be profitable, if the loss due to ice with AIS is less than 2%.

Table 13 Average and STD loss due to ice from Blaiken wind site.

	Reference Turbine [T13]	AIS Turbine
	Production due to icing per Turbine[%]	Production loss due to icing per Turbine[MWh]
Average	25,00 %	7,9 %
STD	-	4,3 %

Figure 26 shows that the break-even point is between 17% and 18% loss due to ice without the AIS. After 18% loss due to ice, all NPV will be negative. By looking at the production loss from Blaiken, the turbine without AIS [T13] with 25% loss due to ice would give negative value of NPV. Table 10 shows that when the reference turbine had 25% loss due to ice, the average ice loss with AIS was 7,9%. Based on the experiences from Blaiken, we may conclude that the turbine with AIS would give higher NPV than the turbine without.

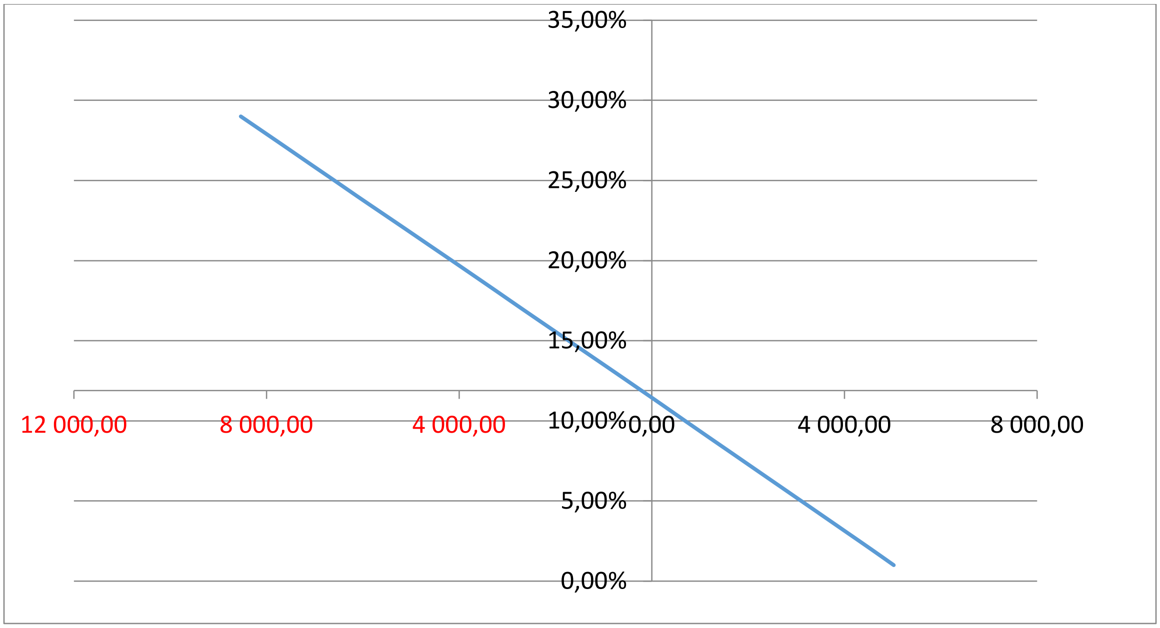


Figure 27 Illustration of N1000/2500 Nordex Turbine with AIS that cost 10% of turbine price.

Figure 27 shows how the investment has positive NPV if the loss is less than 12% for the turbine with AIS. The production loss from Blaiken is shown in table 10. An investment in AIS would in this example yield a positive value for the developer.

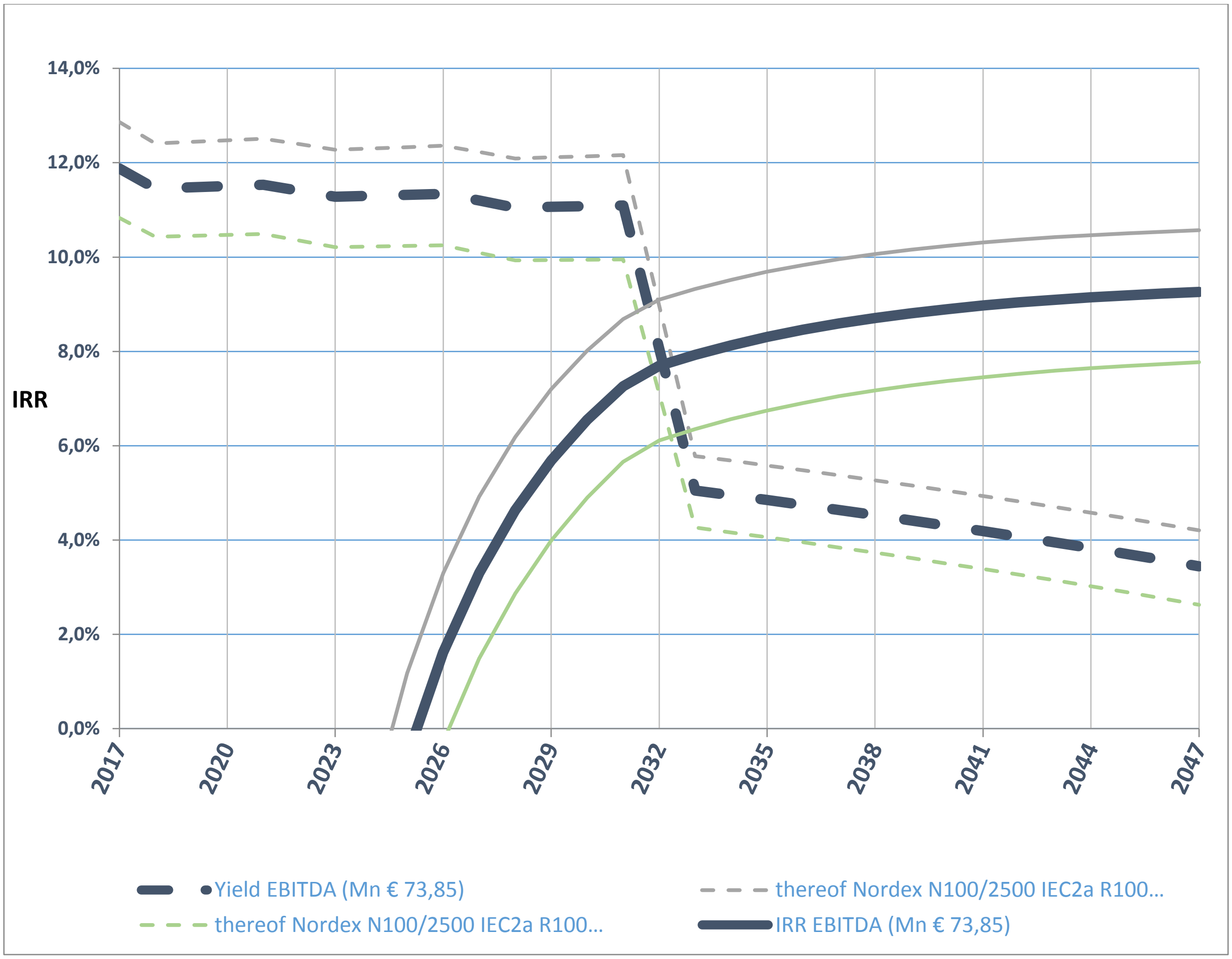


Figure 28 IRR distribution graph for Blaiken. The top line is N100/2500 Nordex turbine with AIS and the green line is N100/2500 Nordex turbine without AIS. The line in the middle is the Yield EBITDA and IRR EBITDA.

In figure 28, the graph is based on the production data from Blaiken. It is assumed that the loss due to ice is 25% without the system and 8% with AIS. The AIS price is 10% of the turbine price. As the graph shows, the ROI on the total investment will be higher with the system installed. It will always have higher IRR. The LCOE without AIS with 25% loss due to ice is 7,23 SEK and 6,32 SEK with AIS, when the price of the system is 10 % of the turbine price[17]. The return on equity is 10% in both cases. If the price of the AIS system is 7% of the turbine price, then the LCOE is 6,26 SEK.

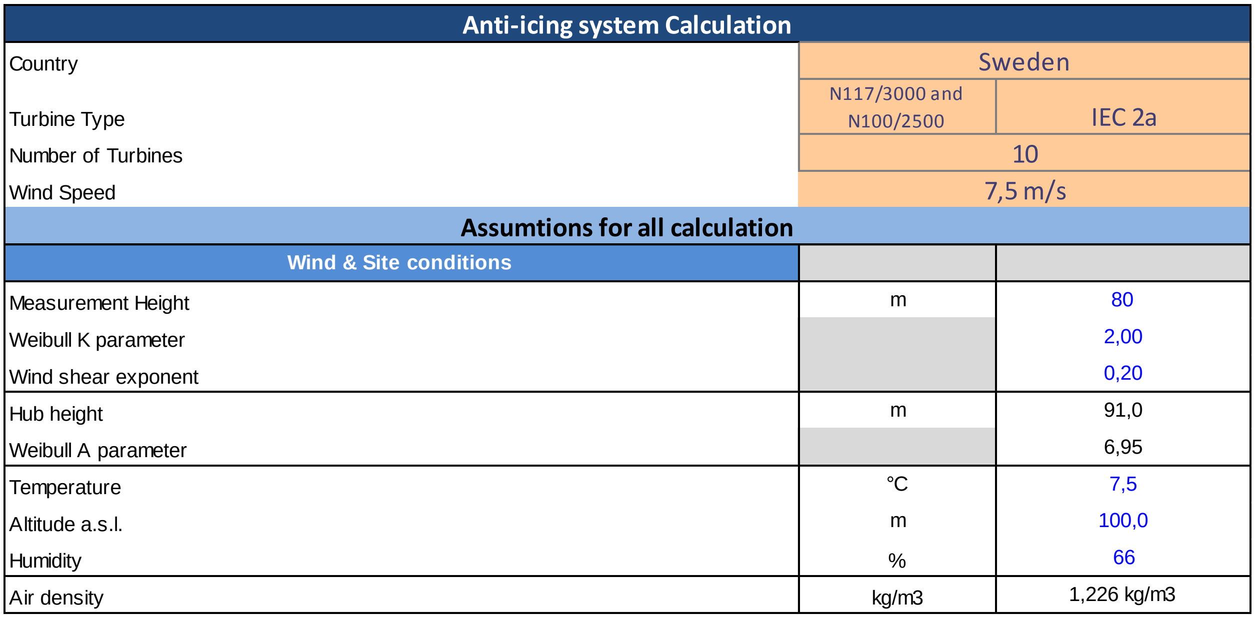
9.4 Uncertainty and Assumptions

Table 13 provides an overview of the most important factors, and an estimate of uncertainty due to the calculation tool that was used to do the analysis for this paper. In the first column it is assumed to be 7 % loss due to ice without AIS, and in the second column it is assumed a 2% loss due to ice with AIS installed. This level of loss is chosen because this is the breakeven point for the investment in the AIS.

Table 11 Overview of uncertainty in parameters in the analysis without AIS in the left and with AIS in the right.

	Standards:	Nordex N100/2500 IEC2a R100				Nordex N100/2500 IEC2a R100			
Source of uncertainty		**Wind speed**		**Energy output**		**Wind speed**		**Energy output**	
		%	m/s	%	GWh/annum	%	m/s	%	GWh/annum
Anemometer accuracy	2,0%	2,0%	0,16			2,0%	0,16		
Period representative of long-term	1,6%	1,6%	0,13			1,6%	0,13		
Correlation accuracy	1,2%	1,2%	0,09			1,2%	0,09		
Reference station consistency	2,0%	2,0%	0,16			2,0%	0,16		
Extrapolation to hub height	**3,0%**	**3,0%**	**0,24**			**3,0%**	**0,24**		
Overall wind speed uncertainty		4,58 %	0,36	5,9%	5,16	4,58 %	35,94 %	5,9%	4,90
Substation metering	0,3%			0,3%	0,26			0,3%	0,25
Wake and topographic calculation	5,0%			5,0%	4,35			5,0%	4,13
Wind rose representative of LT	0,5%			0,5%	0,44			0,5%	0,41
Energy loss factor assumptions	0,025			0,03	2,18			0	2,064373
Future wind variability									
1 years		6,00 %	0,47	7,77 %	6,76	6,00 %	0,47	7,77 %	6,41
20		**1,34 %**	**0,11m/s**	**0,02m/s**	**1,51**	**1,34 %**	**0,11m/s**	**0,02m/s**	**1,43**
Overall energy uncertainty									
1 years		**11,27 %**		**11,27 %**	**9,81**	**0,11**		**0,11**	**9,31**
20				0,08	7,27			0,08	6,90
Sensitivity of net production to wind speed				**574,43**				**545,12**	

Table 12 Assumption to make this calculation



Anti-icing system Calculation		
Country	Sweden	
Turbine Type	N117/3000 and N100/2500	IEC 2a
Number of Turbines	10	
Wind Speed	7,5 m/s	
Assumtions for all calculation		
Wind & Site conditions		
Measurement Height	m	80
Weibull K parameter		2,00
Wind shear exponent		0,20
Hub height	m	91,0
Weibull A parameter		6,95
Temperature	°C	7,5
Altitude a.s.l.	m	100,0
Humidity	%	66
Air density	kg/m3	1,226 kg/m3

Table 14 shows the assumptions that have been made in the analysis. The selection of the turbine and wind speed have an effect on the price. This paper is aiming at quantifying the value of the AIS, and that is why the selection of the turbine and wind speed will have no effect on the results.

10.0 Warranty

Chapter 7 presented the different possible warranties to provide to the developer. After conducting a number of interviews, it was clear that most of the developers were interested in a technical guarantee with regards to the AIS. After considering the different warranties in chapter 7; the warranty considered most valuable by the developers (based on interview answers) were a combination of power curve and availability warranty.

The power curve and availability test is carried out to determine whether the actual power output meets or exceeds the warranted level. If the test shows less than the warranted power output over the test period, the wind turbine generator (WTG) contractor will be liable for liquidated damages (LD). There are various issues surrounding power curve tests which need to be considered such as (London, Metzger, Steadman, & Mulqueen, 2012);

- The period of the Owner to notify the WTG Contractor that is wished to carry out a power curve test.
- The number of retests allowed and over what period
- The events giving rise to adjustments in the warranted power curve
- How many WTGs are included in the testing sample to be representative of the whole wind farm
- The duration of the tests
- The basis for calculation of LDs.

10.1 Suggested AIS Warranty

10.1.1 Power Curve

The Winter PC warranty will be based on substantially the same terms as the regular power curve warranty as proposed in the specific project.

10.1.2 Measurement and Metrology

Measurement and verification should be conducted in accordance with IEC norms and standards. This will require a MET mast, meeting the requirements stated in the IEC standards, to be installed at the site by the developer. There must be equipment that are adapted for winter conditions, as ultra sonic anemometer suited for icing conditions and.

The warranty is provided for a temperature filter from -5°C to -10°C and all measurement points outside this range will be excluded.

10.1.3 Life of Warranty

The winter power curve would be warranted for the period it takes to repay the cost of the AIS. The payment will depend on the production that is gained by having AIS and will thus be site-specific. If the production loss is large, the repayment will be faster than on a site with low production loss.

10.1.4 Payment of Liquidated Damages

The upper limit of the liquidated damages[19] for insufficient power curve performance should be 25% of the AIS price in total, and must be determined on the basis of the standard calculation in Appendix A. The parameter will depend on the site and evaluated by a sales engineer.

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[19] The American Law Reports annotation on liquidated damages states, *"Damages for breach by either party may be liquidated in the agreement but only at an amount that is reasonable in light of the anticipated or actual harm caused by the breach. … A termfixing unreasonably large liquidated damages is unenforceable on grounds of public policy as a penalty"* (12 A.L.R. 4th 891, 899).
Source: http://legal-dictionary.thefreedictionary.com/Liquidated+Damages

11.0 Discussion

11.1 Technology

Different types of icing have been mentioned in the theory discussion, but the most usual one is in-cloud icing and freezing rain. The “WRF”-model is used to model the ice and to calculate the ISO-standard for ice intensity. The parameters from the WRF-model are important, as they are used in the Makkonen equation from section 3.1. The size of the cloud is also important, and higher wind speeds will make the drops collide more frequently with the blade. If the temperature drop is significant, the drops will collide with the blade and form ice. These assumptions are absent in the models; but impact significantly on the icing processes and must be taken into consideration. It is possible to make the assumption: from experience with operating wind farms in different environments, we know that by the seashore there will be large cloud droplets, while inland smaller droplets will form. The physical model is not perfect, yet the adequate calculations have been made. Ice buildup on blades has been modeled thoroughly. To decrease the developer’s risk it is important to evaluate this kind of information. This information can also help the developer in getting a better understating of the conditions on the site.

Sweden is most vulnerable to icing and have the record for the most loss in production due to icing problems. The sites in Norway are often built in lower altitude areas that are closer to the coast. On turbines on these sites formation of ice happens for shorter time periods, moreover these icings melt more quickly from the blades. No major icing issue in wind sites in Norway has been recorded (Laakso et al., 2010a). Nonetheless, concessions have been given to Norwegian projects on sites on altitudes of more than 1000 meters, which are experiencing tougher icing conditions; even more challenging than in Swedish terrains. For instance, this is the case for sites in Nordland district and the nearby coast. During most of winter there will be, as experienced and expected, onshore wind and damp air. Wind farms located below 500 meters above sea level will have icing for shorter periods than ones located above the 500-meter threshold[20]. The sites that are located 1,000 meters and above and have lower than 0 degrees Celsius will have icing problem for longer periods. These areas will often have clouds and thus higher probability of

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[20] Interview with Øyvind Byrkjedal from Kjeller Vindteknikk

icing on blades during the winter. However, there are some local variations: For example, the "Ålvik Mountain" site has experienced icing during all of the winter[20]. In mainland Norway, Hedmark and Oppland have similar environment conditions as in seen in Sweden, and therefore face similar challenges. The overall cold climate potential in Sweden is 6400 MW, which is 56% of all planned investment and 2000 MW in Norway[20]. These results show clearly that an investment of de/anti-icing system is important for these countries.

De-icing and AIS are both designed to eliminate production loses due to icing problems. For a wind site that experience ice on blades the entire year, it is recommended to have a AIS that lasts for 20 years, which will contribute to optimal production[21]. The disadvantage of anti-icing is that it requires more energy than de-icing, since AIS requires initiation prior to the formation of the ice. On the other hand, de-icing is not started before the ice actually starts to form, and ice accumulates on the blade. It is less effect on short periods on the blades to melt the ice by using de-icing system. The selection of the exact system depends on the sites as well. The number of icing issues and the frequency of icing occurrences are recommended variables to be taken into consideration when deciding between anti- or de-icing system. When the wind park has less frequent ice formation the de-icing option should be considered. Primarily because compared to AIS, de-icing requires less energy and is used only when needed.

Even a single heating system may have various types of technology. Nordex and Siemens use carbon fiber in their de-and anti-icing system and the fiber is close to the surface of the blade, while Enercon and Vestas rely on warm air circulating technology[22]. The heating mat is closer to the surface of the blade and will be better than hot air. The disadvantage of carbon fiber is that it gets cut in the carbon chain[23], which can affect the whole chain. Yet, it depends on how the system is structured. If the carbon chain is divided or organized into different categories, it may reduce the risk of getting a cut in the chain. With hot air these problems are avoided. It is easier to replace a hot air system as opposed to carbon fiber when considering reparations and replacements. However, another advantage of AIS is that one can reduce the changes of ice,

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[21] Interview with Andreas Thon Aasheim, Andreas T. Aasheim, Special advisor grid/markets, NORWEA

[22] See Appendix B

[23] Carbon chain is a number of carbon atoms joined in a row.

through increased production and give higher capacity availability during the winter period. Øyvind Byrkjedal from Kjeller Vindteknikk was asked if there were any other benefits of AIS, and his answer was; *"There might be minor errors with other components if you have ice-free blades. There may be chances that the other components will be affected by ice and shorten their lifetime*"[24]. By this he proposes that operating with AIS is more beneficial. Ice on wind turbine blade causes aerodynamic imbalance, and may under long periods of exposure increase the loading of components, thus reducing their lifespan. Heavy ice loads may also cause the collapse of measurement towers[25]. The presence of ice may also make maintenance and repairs more difficult. The other issues with ice on the blades are that it would considerably increase the noise levels of a wind turbine (Nordex, 2012). Ice throw from the blades of a wind turbine is a safety issue (Energy & Systems, 2012). This is going to be a major problem in Norway, and NVE is working with a guideline for icing problems in Norway. This guideline is going to look at all the problems that affect the site due to ice.

Results from the Blaiken site show clear improvement of production by having AIS and demonstrated that it is important to consider the system due to the formation of the ice. However, in Blaiken the ice on the blades was difficult to predict and the system was turned on late. The AIS system, which was used in Blaiken communicated when there was already ice on the turbine, instead of when the ice was forming. This makes its operation more similar to that of a de-icing system. If there were reliable forecasting models, which could predict the ice formation a little earlier, it would have been much easier to tackle this problem. It is possible to predict the formation of ice on the blade by looking at numerical forecast data. The downside of this model is that these data necessarily contain much uncertainty because of the meteorological parameters as explained earlier in the thesis, and make it difficult to rely on the information. It is possible to use Labkotec LID ice detector. It is a thread that detects the frequency when ice is accumulated on the wire and records the data. It is located in the nacelle and not in the blade. For this reason, it would not have the same speed as the blade, therefore the ice would not stick to the two components in the same way. The blade will protrude 50 m higher up, and ice formation often

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[24] Interview with Øyvind Byrkjedal from Kjeller Vindteknikk

[25] Interview with Øyvind Byrkjedal from Kjeller Vindteknikk

increases with the height. The system should ideally be installed at the tip of the blade, so that the uncertainty of the data created by the height difference can be eliminated. It is also possible to measure the altitude of the clouds to get a more optimal prediction of ice. In Blaiken, there were some cases where the sensor showed that there was no ice, while ice was detected on physical inspection of the sheets. This might be because, as explained earlier, the top of the blade was touching the clouds while the wire on the nacelle what not affected. However, icing on the blade tips can be prevented by ice-detection sensors (Wind Power Engineering, 2011). To reduce this risk, it is possible to put plaster on the tip of the blades that measure temperature. This operation is relatively cheap. It is also possible to use light laser on the wing, and observe the spread and the reflection of light. This may also cause some problems, because the laser might hit the clouds and reflect back before it hits the turbine. Therefore, this solution is not an optimal solution in foggy conditions.

11.2 Financial

There are different types of risk taken by the developer when it comes to cold weather sites. It is possible to reduce the uncertainty in the parameters, but only to a certain degree. Energy yield calculations for sites where icing condition prevail have a higher uncertainty compared to the same calculations for sites with prevailing “standard” conditions. Icing affects wind measurements and typically causes data losses and irregularities in the readings from the measurement equipment. The first step that the developer should be considering is to do a validated risk analysis by an independent consulting firm that can confirm whether the wind site will likely be affected by icing, and evaluate whether the estimation is greater than 5 % loss due to ice. The second step is to evaluate how many times a site is likely to be affected annually. This will help the developer in calculating whether they should consider a de-icing system or AIS. A de-icing system will have lower cost, but one of its disadvantages is that the turbine must be stopped prior to removal of the ice. The time that is used melting the ice is an expense for the developers and it is characterized as a production loss. The developers might incur large losses where icing is common during the winter season[26]. AIS is thus ideal for regions with regular icing during the winter. AIS will keep turbines operational throughout the icing conditions, rather than shutting them down. In this manner, the developer is producing energy and

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[26] Interview with Øyvind Byrkjedal from Kjeller Vindteknikk

preventing accumulated ice on the blades. AIS normally costs more than a de-icing system[27]. If the availability of a turbine is reduced due to ice by more than 5 % during the winter months, the AIS is more beneficial comparatively.

The results from Blaiken in Table 10 show that the NPV would have negative value of €3 835,34K if AIS had not been installed on the site. The main concern for the developer is the revenue generated by the wind site. By looking at the worst case for the electricity price, the developer will lose money if the energy prices is lower than LCOE. If the production is lowered due to icing, there will be further loss in revenue. The prices in both cases, best and worst, will have the same impact. By adding the production, the turbine with AIS will give a higher revenue flow.

Above 19% loss due to ice, the NPV would be negative for the site, even if the turbine prices were to be very low. Above 7% loss due to ice, an investment in AIS gives a higher NPV than the turbine without the system. This is the breakeven-point, beyond which the developer starts to earn on the system. This result shows the benefits of investing in the site if the ice loss is higher than 7%. The main risk of investing in AIS is that the system might not work in a cold climate sites. Yet this type of risk may be reduced by providing the developer with a production and availability warranty. With such warranties, the developer may be certain about their minimum production, even in the winter season, and make a more reliable financial portfolio. This will also help the developer in getting financial investors interested in the project and easing access to capital from their banks to invest in AIS.

11.3 Warranty

11.3.1 Economic impact and risk associated with the Warranty for Nordex

Nordex has a standard risk with its technology by providing 10% of the cost of the turbine, as a basic warranty, in case the system does not work as it supposed to[28]. However, in this paper the risk due to technology is not evaluated, instead the number for minimum standard risk of Nordex has been used.

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[27] Interview with Adam Chris, Director of Allianz Specialised Investments

[28] Interview with Paul AlWindi, Lawyer at Nordex

By providing a warranty at the warranted performance level, which is 75% of the standard power curve, Nordex' customer's risk is minimized. It is possible to increase the performance level if the temperature filter within the range of +5°C and -10°C. This will give the Nordex customer security of production which they in turn can provide to potential lenders. The value generated for the developer by increasing the performance level is higher than the risk Nordex is taking. Only by increasing the performance level from 75% (which is the standard power curve) to 80%, the developer is guaranteed to increase their performance by 5-percentage points. This 5 percentage point increase is very valuable for the buyer of AIS, as each percentage point of guaranteed increase in performance makes the developers investment portfolio more attractive for lenders and investors.

11.3.2 The value for the developer of the Warranty

The AIS is a new technology in the market and it is difficult for the developer to fully evaluate the benefits of the system. During the research for this paper, financial investors and developers were interviewed to examine their points of view on the value created by the system.

There are different values that AIS will create for potential developers. One of the values the buyer of AIS will have is a more stable investment portfolio, because the warranty will secure a minimum production income in a certain temperature scale. The warranty will also ease the access to capital for an investment in AIS. The developer will need to roughly certify the production numbers. The warranty will secure the buyers productions number and reduce some degree of risk in their portfolio. This will also give a security of the reliability of the system to the buyer by having a warranty that guarantees the production in given criteria. The CEO of Allianz, Chris Adam was asked which criteria are important in an investment of AIS in an interview and the answer was the technical availability and the increase of energy production in AIS. He also mentions icing loss assumption, energy out-put increase and be able to value icing losses which they corporate[29]. The same question regarding the investment of AIS in cold climate site was asked the technical director for Impax Asset Management, Jim Lower, and his reply was:

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[29] Interview with Chris Adam, Director of Allianz Specialised Investments

"*When people start to see the results from the performers, then the industry will come along. Lenders and developers will be more comfortable. In Europe there are not so many opportunities as they thought, for installing icing equipment. The climate is different, and only in the north the system is needed'*[30]. This shows that the warranty provides a positive impact on the financial investors and it will help the developer when they are working with their financial portfolio.

11.4 Advantages and disadvantages of the suggested of warranty for developers and for Nordex.

The system is new in the market and it is imperative to gain developer trust. It is also important that the warranty is formed in such a way that the supplier does not take all the risk. If the supplier of the system feels that they are taking the whole risk it will decrease their interest to offer the warranty. The warranty should be valuable for both parts and share the risk between the supplier and buyer.

The advantages of a warranty are that it gives the extra value to the buyer to secure the production numbers and have a more secure cash flow. It will also give a security for implementing a new technology that does not has so much historical data. The disadvantage of the warranty for the buyer is that they have to pay for it. The buyer has to decide if the value of the warranty is worth the cost.

For Nordex the advantages of a warranty are that it would increase buyer's confidence to invest in the system and will make it easier to sell the product for Nordex. It will also make it easier to win the developer's trust. The disadvantage of the warranty is if the technology of the system fails and Nordex have to pay for damages. The failure will cost Nordex huge amount of money and reduce their developer's expectation to their products.

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[30] Interview with Jim Lower, Engineering Consultant, Impax Asset Management

12.0 Conclusion and recommendation

The objective of this paper was to assess the value of AIS. In this regard it was imperative to tackle the major question of “how much ice loss should occur before the NPV of the investment in AIS is positive?” Two major points of the analysis are the price of the system and annual loss due to ice. Moreover, the price of the turbine and loss due to ice will vary across sites. This is one of the reasons a standard estimation is difficult to make. Despite such difficulties, estimations from my analyses shows that beyond a predicted 6 % loss due to icing, an investment in AIS will have a positive NPV. Therefore, it is recommended to install the system in sites where more than 6% production loss due to ice is predicted. The results show that the NPV for the investment in AIS at Blaiken site is €1 674,47K with 8 % loss due to ice if the cost of the system is 10% of the turbine price[17]. Data from the reference turbines shows that without the system, the loss would have been 25%, and the NPV was calculated to be – €3 835,34K. The production data from Blaiken shows that the investment in AIS is a considerable financial gain for the project. The system will also produce other benefits like reduction in noise level and ice throw, which are important factors to consider when making an investment decision.

The interviews with Nordex’ potential customers indicated that they sought a technical guarantee that would ease the access to loans and investment capital. An AIS warranty is showed to be one of the best ways to decrease developer risk and to ease access to capital. The warranty will further help the buyer of the AIS in making a more reliable portfolio and reduce uncertainty related to production loss due to ice.

To optimize the warranty, the developer should get a customized warranty based on the site and project. The developer should adopt in-site prospecting, using portfolio analysis techniques with multiple icing maps if possible and consulting with a firm that can evaluate the site for icing. By demanding proof of performance and control strategy in icing conditions from the turbines, manufactures can lower turbine-specific uncertainty on standard turbines. This warranty design may help in reducing the annual energy production (AEP) uncertainties, potentially ease access to capital and reduce the cost of financing sites.

Individually designed warranties for each site is recommended, as the different sites will have different conditions of icing. The sales engineers should investigate the site properly in order to mitigate the risk of overestimating the production loss, and making Nordex sign a contract of warranty which contains unsustainably high risk. The warranty should cover availability and production deviations from the power curve. The warranty period should not extend the time it takes to repay the system while the liquid damages should not exceed the price of the system. Warranties should cover at least the percentage of ice loss that the developer need before the investment in the system returns a positive NPV. This percentage will depend on the individual project and should be calculated on an individual basis.

Future recommendations

Based on the results and conclusions in this report, the recommendations for further research is to design a detailed warranty by doing an analysis of the financial risk Nordex is taking by providing a warranty to developers, comprising a combination of availability and power curve warranties. The power curve in the AIS warranty should be somewhere between the standard power curve and the maximum power curve provided with AIS. Availability would have to be covered by the warranty, for the customer of AIS to have the technical security included.

This research was not included in this paper, as there was not enough data available; moreover, the analyses needed to make final recommendations on the subject falls outside the boundaries of this project. Finite recommendations on warranty design will be easier once the system is implemented in several sites and there is enough data on the productivity and availability of the system.

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APPENDIX

APPENDIX A

Nordex Standard Availability Warranty

During the term of the Agreement the contractor warrants that the average technical availability of the wind park, A (wp), will not be less than specified in the table 1. The warranty start on the Substantial Completion Date, if a Supply and Installation Agreement has been entered into, or on the beginning of the term of the Agreement, if no Supply and Installation Agreement has been entered into, and will be calculated on a yearly basis for a preliminary settlement and in each case on a three yearly basis for a final settlement (Measurement Period). If the term of the Agreement does not correspond to a multiple of three years, then the last Measurement Period shall reduce to the remaining time period after expiry of the last three year Measurement Period.

Table 13 Calculation of the technical Availability of the WTG

Operating year after the Substantial Completion Date, respectively after the beginning of the term of the Agreement (as applicable)	**Availability**
1	93%
2-10	97%
11-15	96%

The determination of the technical availability will be based on the data collected by the WTG Control System or control unit within each WTG.

The technical availability of an individual WTG, $A(wtg)$, is calculated as follows:

$$A(wtg) = \frac{T_{total} - \left(T_{stop} - T_{fm}\right)}{T_{total}} \times 100\%$$

where:

$A(wtg)$	Technical availability for one WTG (in percent).
T_{total}	The time (in hours) for the respective Measurement Period.
T_{stop}	The time (in hours) during the period of T_{total} for which the WTG is not in operation.
	the time (in hours) during the period of T_{stop} for which the WTG is not or would not be in operation because of the following: ▪ Different conditions based on the agreement between developer and Nordex. ▪ Stops due to icing conditions are not included in the warranty today.

Calculation of the technical Availability of the wind park

The determination of the technical availability will be based on the data collected by the WTG Control System or control unit within each WTG.

Calculation of the availability of the complete wind park, $A(wp)$, will be based on the availability of the individual WTG, $A(wtg)$, by the following equation:

$$A(wp) = \frac{1}{N}\sum_{i=1}^{N} A(wtg_i)$$

Where:

$A(wp)$	Average technical availability (in per cent) of the wind park.
$A(wtg_i)$	Technical availability (in per cent) of the WTG Numbered i .

N	Number of WTG included in the availability warranty of the wind park.

Acceptance criteria

CONTRACTOR will have fulfilled the warranted technical availability obligation of the wind park if $A(wp)$ is equal or higher than $A(gwp)$. In case $A(wp)$ is less than $A(gwp)$ the CONTRACTOR shall have to pay liquidated damages to the OWNER as set out hereinafter.

Liquidated damages

The following equation for the calculation of the liquidated damages shall be applied:

$$LD = (((E \times A(gwp)) - (E \times A(wp))) \times EP) - IR$$

Where:

LD	Liquidated damages (in EUR) for insufficient technical availability of the wind park.
$A(gwp)$	Warranted technical availability (in per cent) of the wind park.
$A(wp)$	Average technical availability (in per cent) of the wind park.
E	Expected average net energy production (in kWh) for the wind park (as calculated for the respective Measurement Period): [P75 value] kWh If, however, the actual net energy production (in kWh) for the wind park as invoiced by OWNER to the Utility is on average underachieved by more than 10% over a period of 3 or more consecutive operating years, the Parties shall in good faith re-assess and agree to adjust E

	accordingly.
EP	Price of one unit of energy (in EUR/kWh) supplied to the grid as agreed with the Utility, however, not exceeding a net amount of EUR 0.08/kWh.
IR	Insurance reimbursement (in EUR) OWNER has received or will receive from insurance covering insufficient performance, if applicable.

The upper limit of liquidated damages payable by CONTRACTOR to OWNER for insufficient technical availability shall in no event exceed in the aggregate per Measurement Period 100% of the Annual Fee paid by OWNER to CONTRACTOR for services supplied by CONTRACTOR under the Agreement for the respective Measurement Period.

The liquidated damages are exclusive and in lieu of all warranties, expressed or implied, with respect to the availability of the WTG, respectively the wind park. CONTRACTOR shall not be liable for any loss or damage of OWNER resulting from an insufficient fulfillment of the technical availability warranted by CONTRACTOR.

Nordex Standard Power Curve Warranty

The power curve is a tabular or graphical representation of the electrical power produced by the WTG in a range of given wind speeds.

The power curve, which relates to the WTG to be delivered by CONTRACTOR, is measured under the standard conditions according to the latest revision of the standard IEC 61400-12-1 ‘Wind turbine generator systems, Part 12-1: Power performance measurements of electricity producing wind turbines’, hereunder referred to as ‘the IEC standard’.

Prerequisites concerning the power curve warranty

The warranted power curve is subject to the fulfilment of all contractual obligations of EMPLOYER which might have an impact on the power curve of the WTG and applies only if the rotor blades are clean. A general malfunctioning or the unavailability of the WTG is not covered by this power curve warranty.

Warranty

During the Warranty and Defects Liability Period the CONTRACTOR hereby warrants (subject to the general limitations of liability according to the Agreement) that the WTG has / have the capacity of producing electrical power in accordance with the power curve as described in Annex 1 hereto.

Power curve performance testing

The power curve may, at the EMPLOYER's discretion and expense, be verified by performance testing during the Warranty and Defects Liability Period in cooperation with the CONTRACTOR. The performance testing shall be carried out and reported in accordance with the IEC standard taking into account the criteria set forth in Annex 1. The performance testing shall be carried out by an independent and internationally recognized institution acceptable to both parties.

The WTG to be used for the performance testing shall be representative for the wind park and shall be selected by the institution carrying out the measurement. The institution shall confirm that the selected WTG is representative for all WTG in the wind park. The power curve will be measured in free sectors according to the IEC standard, taking into account the actual site conditions as stated and using a calibrated anemometer of the Thies 'First Class', Risø P2546A or Vector A100 type.

Acceptance criteria

The theoretical annual energy output is calculated by the institution carrying out the measurement both for the warranted power curve according to Annex 1 hereto and the verified power curve. The verified power curve comprises the measured values adjusted with the Project Site-specific measurement uncertainty factors. The project wind distribution to be used for the calculation is indicated in Annex 2 hereto and is based on the information received from the EMPLOYER. The following equations shall be used for the theoretical energy output calculation up to the maximum measured wind speed of the verified power curve:

$$E(gpc) = \sum_{v=0}^{v_{\max,vpc}} P_g(v) \times T(v)$$

$$E(vpc) = \sum_{v=0}^{v_{\max,vpc}} P_v(v) \times T(v)$$

$$P_v(v) = P_m(v) + \sqrt{[U_A(v)]^2 + [U_B(v)]^2}$$

In which:

$E(gpc)$	theoretical annual energy output (in kWh) for the warranted power curve.
$E(vpc)$	theoretical annual energy output (in kWh) for the verified power curve taking account of the Project Site-specific measurement uncertainties.
$P_g(v)$	electrical power (in kW) produced by the WTG at a given wind speed v according to the warranted power curve (Annex 1).
$P_v(v)$	electrical power (in kW) produced by the WTG at a given wind speed v according to the verified power curve.

$P_m(v)$	electrical power (in kW) produced by the WTG at a given wind speed v according to the measured power curve (without taking account of the Project Site-specific measurement uncertainties).
$T(v)$	the time (in hours) during the year that the wind blows with a given speed v according to the project wind distribution (Annex 2).
$v_{\max,vpc}$	the maximum measured wind speed of the verified power curve measured during the performance test (the last complete Wind-BIN in accordance with the IEC standard).
$U_A(v)$	category A uncertainties as identified during the performance testing in accordance with the IEC standard.
$U_B(v)$	category B uncertainties as identified during the performance testing in accordance with the IEC standard.

The verified power curve is in accordance with the warranted power curve if the following condition is fulfilled:

$$E(vpc) \geq E(gpc)$$

APPENDIX B

Other de- and anti-icing systems in the market

Siemens

Siemens has electrically heated carbon fiber foil on the turbines. The system consists three elements. It has an ice detection system, the heating of the blades and a system to control the strategy for de-icing. The system includes power connections at the root and heating element integrated into the blade surface at manufacture control system based on existing sensors. It has full retention of the aerodynamic profile and no effect on nose levels. Their first generation of Siemens de-icing system was installed and tested in 2011 at two wind farms in Sweden. Today, more than 50% of the turbines Siemens supplies in Sweden are equipped with de-icing system. Turbine with this system is available with the company's SWT-2.3-101, SWT-3.0-101, SWT-2.3-113, and SWT-3.0-113 turbines.

Vestas

Vestas de-icing technology use circulation of hot air to heat the blades and melt the ice. It is similar to Enercon's system. The system consists of a heating unit in the hub to distribute hot air throughout the blades, and a control unit which is integrated into the turbine's SCADA system. This system is available for company's V112-3,3 MW turbine, and have installed a prototype in Sweden.

The system is designed to de-ice the outer 1/3 of the blade full chord, and the outer 2/3 of the leading edge towards the tip end, to maximize power curve recovery. This targeted approach does not compromise de-icing efficiency according to Vestas, but is critical in regaining full power curve quickly. It also reduced the risk of run-back icing, and can minimize the danger of ice throws from the blade tip.

Enercon

Enercon has a technology that combines an ice detection system with a fan heater installed at the root of the blade. It circulates a stream of hot air right up to the tip of the blade inside the turbine blades to melt ice after it has formed. The ice detection system works on a specially developed power curve analysis method. Rotor speed, wind speed and other operating values data are analyzed during operation and are plotted into an operating map. Ice build-up on the blades alters the aerodynamic properties and this is shown on the operating map. When certain criteria are fulfilled and ice is detected, the turbine is stopped and the de-icing procedure is initiated. The temperature of the blade surface is heated to 0°C, and the ice build-up is melted. The de-icing procedure can take place while the turbine remains in motion, thawing thin layers of ice at an early stage of formation. If ice continues to form, it becomes essential to stop the turbine while the process takes place.

Table 14 An overview of known anti-and de-icing systems

Turbine	System	Function
Nordex	Anti-Icing For Rotor Blades	Electro-Thermal heating elements
Enercon	Rotor Blade De-Icing System	Warm-air circulation
Siemens	BDI (Blade De-Icing)	Electro-Thermal heating elements
Vestas	Rotor Blade De-Icing System	Electro-Thermal heating elements
Donfang's	De-Icing System	*Uses hot air in the blades and electrically heated carbon fibre film on the blades.*
GE Energy	De-icing System	Warm-air circulation
WinWind	Blade Ice Prevention System	Electro-Thermal heating elements

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no