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“Economic viability analysis for icing blades detection in wind turbines”

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LIFE CYCLE COST MODEL FOR ICE DETECTION IN CONDITION MONITORING SYSTEMS FOR WIND TURBINES

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Abstract

Reliability, availability, maintainability and safety (RAMS) of wind turbines in cold climates are closely related to ice accretion. The deterioration of RAMS of the wind turbines involves costs such as Operation and Maintenance costs and energy losses. Systems to monitor the condition of the wind turbines play a key role in the wind energy industry to decrease the costs mentioned above. In this research is presented an economic study of the life cycle cost (LCC) for ice condition monitoring systems in wind turbines. In particular, it is studied the economic feasibility of different commercial ice detection systems through a LCC model when wind turbines are exposed to different scenarios. To date, the scientific literature does not collect any study about the LCC for ice detection systems using different annual rates of return, and providing a map with numerical solution. The study is extended including a bank loan for a real point of view. The findings of this study reveal the ice detection systems that are more profitable and the selection criteria to decide the use of a bank loan. Finally, it is shown that predictive costs are much smaller than corrective cost reaching a reduction of these corrective costs with the ice detection systems.

Keywords: Life Cycle Cost; Condition Monitoring; Maintenance Management; Wind Turbines; Ice Accretion.

1 INTRODUCTION

Wind energy is the renewable energy that presents the highest growth in last years [54]. The increasing production and installation of this type of energy is due to the renewable policies based on the targets of Kyoto Protocol and the European Horizon 20-20.

Wind farms have been located in areas with suitable wind characteristics, where in some cases the presence of ice is common.. Wind farms located in these regions present problems related to icing and cold climate such as energy losses, mechanical failures, downtimes, problems to access for human resources, measurement errors or safety hazards among others.

The research project IcingBlades [53] based on the analysis and solution develop for the ice accretion on the blades of the wind turbines is taken into account in this work. The project analyzed 517 wind turbines, with a total installed power of 682 MW, finding that 18,966 MWh were lost in a period of 29 months due to the presence of ice in blades. Figure 1 shows the main causes of the production energy losses, being the highest the ice on blades. These energy losses involves an increment of the operation and maintenance (O&M) costs.. In Spain, with more than 21,000 MW installed, this phenomenon would be equivalent to more than 550 GWh of power losses (about 45 million € every 29 months). These production losses would be equivalent to the energy consumption of 200,000 households and savings of 658,682 tons of CO₂ [53].

Figure 1. Power losses due to different alarms in ICINGBLADES [53].

The effect of ice in wind turbines causes the reduction of millions of euros due to power losses [1]. Therefore, the reduction of the O&M costs and the improvement of the reliability, availability, maintainability and safety of wind turbine in icing conditions are necessary. For this purpose, the wind energy industry is focused on the development and installation of condition monitoring systems (CMSs) to detect the favourable conditions for ice accretion on the blades and lead to reduce its effects.

CMS is the most effective technology to minimize the O&M costs, to increase reliability and the lifetime of components, to improve safety and to decrease the downtimes of wind turbines [2][3]. An analysis to show the improvements of maintenance scheduling using CMS for onshore and offshore wind farms is developed in [4]. The benefits of CMS on wind power systems are demonstrated in [5] by the application of probabilistic methods and sensitivity analysis.

In this work is proposed a novel maintenance management research based on the economic feasibility for different typologies of ice detection systems through a life cycle cost (LCC) model applied to a real case study. It is necessary to remark that to date any similar study about the LCC of ice detection in CMS has been found by the authors. The proposed study is developed taking into consideration the costs of investment, the operation and maintenance costs and the energy losses of a real wind farm. The LCC model, for different ice detection systems, is based on the net present value (NPV) and finally, a bank loan is included for a real case study. Additionally, to complete the study, different scenarios have been proposed and analysed to obtain a range of different solutions.

The work has been structured as follows: In section 2 is presented the basis of the origin of ice, the wind turbine stages during ice accretion and the problems caused by ice in these machines. Section 3 illustrates the different methods for ice detection on a wind turbine and the different commercial typologies of ice detection most used in CMS. The novel maintenance management research LCC approach developed is included in Section 4. The results found for the case study are presented in Section 5, and finally, the conclusions are presented in Section 6.

2 BACKGROUND AND STATE OF THE ART

The locations for onshore wind farms are usually in elevated areas such as hill tops [6]. Unfortunately, these locations are often exposed to freezing temperatures. For example, wind farms of high mountains in North America, North Europe, China or Russia have several problems due to ice leading to power generation losses and costs [20]. The study developed in reference [21] estimated that 20% of the wind farms will be installed in

areas with high probability of icing. The WECC project (Wind Energy in Cold Climate) [21] analysed the ice effects and the energy generation in wind turbines. This section collects the literature review for the origin of ice, ice accretion on wind turbines and its main problems.

2.1 Origin of ice

The weather conditions for ice development depend on parameters such as temperature, wind speed, relative humidity or air density, among others. The characteristics of ice (colour, strength...) are influenced by the parameters specified in the ISO 12494, 2001 (Atmospheric icing of structures) [7]. A classification of different types of icing is presented in [29]: In-cloud icing; precipitation and hoar frost.

- *In-cloud icing* appears when the atmospheric temperature is below 0°C and the humidity is high. Super-cooled water droplets hit the surface of the structure and frozen at the time of impact. The major problem is the accumulation of different layers of this kind of ice.
- The *precipitation* cause is related with freezing rain on surfaces below 0°C or wet snow. Precipitations can produce higher damages than other types of ice.
- *Hoar frost* occurs when the water vapour solidifies on a cold surface.

The most common cause of ice appearance in wind turbines is the frost. It seems compact at first sight but is quite fragile. Frost grows in all parts of the wind turbine but the onset occurs in the leading edge of the blades, owing to the incident velocity (which is an important factor in the growth of ice) [27]. Figure 2 illustrates examples of ice on wind turbines.

Figure 2. Ice on a 150kW wind turbine blade in Grenchenberg, Switzerland [8]

2.2 Wind turbine phases during ice accretion

Wind turbines do not operate properly when the ice accumulation reaches a limit (fixed by normative) and, consequently, the machines is necessary to stop. Wind turbines can be divided into mitigated wind turbines (with systems to prevent or remove the ice accumulation) and non-mitigated wind turbines (without any system to avoid the ice). The phases for the ice accumulation process are showed in Figure 3. In the first stage (pre-icing) the wind turbine is working properly because there is not ice growth. In the following stage icing is starting but the wind turbine would operate until its operational limit. In the third stage, the ice accumulation continues and the turbine needs to stop to prevent possible damages. Finally, in the fourth stage (post-icing) the turbine continues stopped until the complete removal of ice.

Figure 3. Stages of a non-mitigated wind turbine during the ice accretion process [28]

The mitigated wind turbines have a system to deal with ice accretion and its stages are depicted in Figure 4. The objective for these ice prevention or removal systems is the reduction of the wind turbine downtimes. The first stage is similar than the previous case (pre-icing), i.e. the wind turbine is working properly because there is not ice growth. In the second stage (icing), the ice growth is controlled by the system installed to do not reach the operational limit, reducing the downtimes necessary to remove the ice from the turbine. In the third phase the wind turbine has reached its operational limit and is stopped until the complete removal of ice. In this case, the downtimes are smaller than the non-mitigated machines. Finally (post-icing), the wind turbine can operate regularly [28].

Figure 4. Stages of a mitigated wind turbine during the ice accretion process [28]

2.3 Problems related to icing and cold climate in wind turbines

The ice accretion on wind turbines, especially in blades, make potential problems that reduce the efficiency of the machine. The most important problems caused by icing and cold climates are [20]:

- *Power losses by the reduction of aerodynamic efficiency.* Energy losses begin with the appearance of a small amount of ice on the blades. The presence of ice modify the aerodynamics of the blades by increasing the coefficient of friction and making turbulences, vibrations and noise, as well as a lower number of turns. Figure 5 illustrates how the power generation decreases in periods of ice growth at a given speed.

Figure 5. Power losses regarding air speed [22].

- *Loads on turbines.* The icing on blades makes loads on the turbine. Icing causes an increase of mass, drag coefficient, imbalance of the rotor and vibrations. In the case that vibrations exceed a certain value, the turbine must stop due to possible damages, generating losses.
- *Influence in the lifetime of the components.* The fatigue due to loads reduces the life expectancy of the components of the wind turbine such as blades, hub, gearbox, shafts, etc. When the loads are much higher than expected the turbine must stop.
- *Increased noise generated by blades.* The drag coefficient of the blades increases due to icing blades, therefore, the noise level of the turbine is higher than the normal operation.
- *Changes in blade surfaces by ice accretion.* The accumulation of ice is due to the collision of water droplets at low temperature with the solid surface of the blades. These drops produce a frozen layer which may influence the efficiency of the wind turbine. This frozen layer modifies the thickness of the boundary layer and thus the air transition characteristics of the blade [23]. Figure 6 shows the icing phenomenon in two different blade profiles. In blue colour is represented the blade profile using a system for ice removal and, in red colour is illustrated the blade profile under normal conditions. Note that the second figure suffers more aggressive climate conditions (higher ice growth) [24]. The highest accumulation of ice is on the leading edges (see points 0,0 of both graphs in Figure 6).

Figure 6. Blade profiles with ice accretion [23].

- *Safety hazards.* The ice fragments can break off of the blades and can impact against the ground or other objects. The distance that the fragments could reach depends on the ice mass and the speed of rotation of the blades [27], as it can be shown in Figure 7.

Figure 7. Distance of impact of ice fragments [25].

- *Measurement errors.* In the icing process, the anemometers, temperature sensors and wind vanes are exposed to icing conditions, showing measurement errors higher than 40% [8].

3 CONDITION MONITORING SYSTEMS TO DETECT ICE ON A WIND TURBINE

Condition monitoring system (CMS) has recently emerged as a new technique employed by the wind energy industry to improve the reliability, availability, maintainability and safety (RAMS) of the wind turbines reducing the O&M costs. CMSs are installed in the wind turbine to monitor the state of the components by a set of sensors. The effectiveness of CMS depends on the technique applied, the number and type of sensors and, finally, the associated signal processing to extract the useful information from the different signals. Different techniques have been applied to different components of the wind turbine. Techniques such as vibrations for the gearbox, acoustic emission for bearings or structures of blades, ultrasonic testing for towers or blades, oil analysis for hydraulic systems, thermography for electronic and electrical components, etc. are nowadays employed in wind turbines [51]. The ice detection has not been implemented in the CMSs for wind turbines installed today. The ice detection needs to be included in the CMS of the wind turbines to reduce the energy losses and to improve RAMS. For this porpoise, this work is focused on ice detection systems. Ice prevention and ice removing systems are not included in the scope of this research.

The first step to avoid icing is to detect it, then the systems to prevent or to remove the ice will be activated. This section presents the ice detection techniques. Preventative and ice removal techniques are introduced and classified into active and passives approaches. The passive procedure is based on the physical properties of the wind turbine blades to prevent and de-ice (special coatings, black paint, chemical products, etc.). The active approach is based on external equipment which consumes power. It is divided in anti-icing and de-icing techniques. Thermal [46], air layers [45] and microwaves [47][49] are techniques of anti-icing. Heating resistance [48], warm air and radiators [48], electro impulsive/expulsive [45] and pneumatic flexible boots [50] are techniques for de-icing. Some of these techniques have been tested in laboratories but not yet in wind turbines [26], e.g. based on boots which blows up to break up the ice. The pneumatic flexible boots are mounted over the blades. When ice increases from 6 to 13 mm the system is activated and breaks up the ice. The boots are blown up compressed air. When the ice is thrown away by centrifuge and aerodynamic forces, the boot comes back to his original position by a vacuum that eliminates the imperfection on the surface.

3.1 Ice detection methods for wind turbines

Wind turbines should have a correct ice detection system to predict when the ice appears on the structure. Measurements are usually done on the nacelle or in a location into the wind farm, which generates false alarms because the ice volume varies radially and across the blade. These measures are usually carried out in operating conditions providing overestimated values.

There are methods that detect certain parameters to find out the favourable conditions for the development of ice, e.g. the size of the droplets in suspension and the water concentration in the air, together with the temperature and wind speed. The main parameters that indicate the risk of freezing are the relative humidity and the air temperature [7].

Ice detection helps to increase the safety, reduce downtimes, increase reliability, availability and energy production, and decrease the costs associated with failures caused by icing blades. Methods to detect the ice on a wind turbine are classified as direct and indirect [26].

Direct techniques are those in which the measurement of ice is carried out on the surfaces of the wind turbine analysed, being the most important:

- *Damping of ultrasonic waves.* This technique analyses the measurement of the damping of an ultrasonic signal. The sensor sends and receives a signal through a wire guide (that has low acoustic attenuation) which is measured to determine if there is any variation in the signal produced by the appearance of ice (damping phenomenon) [9].
- *Measurement of frequency in resonance.* This method uses an oscillating probe to determine the appearance of icing in the wind turbine. The frequency of this probe decreases when ice is growing [26].
- *Vibration measurement of a diaphragm.* The capacitance between the coil and a doped silicon diaphragm is measured. A change in the capacitance is produced by the appearance of ice on the wind turbine [10].
- *Change of electric properties.* The detection of ice is determined by the change of the capacitance between two electrodes. This change is due to the modification of the relative permeability produced by the presence of thin layers of ice [11].
- *Temperature change measurements.* This method uses multiple temperature sensors. One of them is isolated and the rest will be in contact with the airflow. The ice accretion is determined by comparing the measurements of these temperature sensors [26]. In some cases the sensors are heating to reach a

determinate temperature stabilized. The presence of ice increases the time to heat and stabilizes the temperature.

- *Optical measurements.*
 - *Direct measurement of the reflected light.* The light reflected or emitted from a source is measured. The presence of ice makes a variation in the reflected light [26].
 - *Infrared spectroscopy.* The appearance of ice growth in a surface is determined by measuring the absorption and reflection of infrared light [12].
 - *Reflection from inside of surface.* The total internal reflection could occur when light cross from a medium with high refractive index to a lower refractive index. If there is not ice on the point where total internal refraction is produced, the light will be reflected. However, light will cross when ice or water appears on the surface [13].
- *Measurement of ice loads.* ISO 12494 indicates how to measure the growth of ice [7]. There is a rod spinning at a constant speed. When the air hits the rod, the least amount of ice grows on the front side. This probe will measure the weight of the ice.

The indirect techniques for ice detection include the data acquisition and comparison with historical data. This comparison helps to determine the appearance of ice on the wind turbine. The most important indirect approaches are the following:

- *Difference in expected and real power output.* This method is based in the comparison between the real power output and the theoretical expected power output. If the weather conditions are favourable to icing and the real power curve is lower than the theoretical one, the development of ice is expected (see Figure 5) [22].
- *Heated anemometers.* The ice is detected by comparing signals from heated and unheated anemometers. The ice will appear in the unheated anemometer. A comparison of the wind speed from both anemometers will be done, since one is in perfect operating condition and the other will have a low rotating speed [14].
- *Dew point and temperature.* This method detects the ice accretion when the dew point and the air temperature are similar [26].
- *Noise measurements.* The noise level produced by the blades in operation with ice is measured and compared with those in working conditions without ice [15].
- *Change in resonant frequency of the wind turbine blade.* The ice growth is detected by the analysis of the vibrations of the rotor blades and comparing with historical dataset in the same conditions [26].

- *Probability frost maps.* The ice detection is done analysing the forecast offered by different webs, companies, etc.

3.2 Commercial Ice Detection Systems

This section presents the main commercial ice detection systems for CMS used to detect the presence of ice on wind turbines. The most relevant characteristics of these systems are showed in Table 1.

- *LID3300IP Ice Detector Sensor.* This sensor implements the direct technique of measurement of damping of vibrating diaphragm to detect ice growth in wind turbines. It is designed to work in zones with high probability of ice accretion and it is characterized by its easy installation [30].
- *0871LH Goodrich Freezing Rain Sensor.* This sensor is designed to work under moderate and aggressive weather conditions. The technique used by this system is the measurement of the resonant frequency [31].
- *Ice Load Surveillance Sensor.* It can be used in very aggressive cold climates (artic conditions). It is used in wind turbines to detect the appearance of ice accretion [16]. It is designed according to the ISO 12494 specification and based on the measurement of ice loads [7].
- *Ice Meister Model 9734.* This device incorporates an optical sensor on the nacelle. It is based on the direct measurement of the reflected light [17].
- *HoloOptics Series T40 Sensor.* It is an optical sensor designed for the hardest weather conditions which measures both ice growth and the type of ice [32]. It is based on the direct ice detection method of optical measurements. *Sensor WXT-520.* It is a small and lightweight transmitter that measures wind speed and direction, precipitation, atmospheric pressure, temperature and relative humidity [33]. Direct and indirect techniques can be applied in this sensor.
- *Set Vaisala WA25.* The set is composed by an anemometer and a wind vane to determine the wind direction [34], [35], [36], [37]. This sensors set is used for all climates, especially for arctic conditions because it does not freeze. Anemometer and wind vane are heated. Direct and indirect techniques can be applied in this sensor.
- *NRG Ice Free3 Sensor.* This system is composed by a wind anemometer and a wind vane. This system is specially designed to work under climate conditions where probability of ice accretion is high. The installation of this device can be located on the top of the nacelle or in a meteorological centre of the wind farm [38][39][40].
- *Remote Surface state DSC111 sensor.* This device provides an accurate measurement of the presence of ice crystals and is installed in a remote location.

It uses the spectroscopic measuring principle (direct technique) enabling accurate measurement of the amounts of water, ice, and snow in the surface of the wind turbine [41].

- *Blade Control.* This system detects the appearance of ice on blades and it is capable to detect when the ice is removed [44]. Therefore, this systems can be possible to restart the wind turbine automatically at any time, day or night. The technique used by this system is the measurement of frequency in resonance (direct technique) taking into account that the frequency of the natural oscillation decreases in proportion to the increasing mass of ice.

	Ice Detection System	Manufacturer	Condition	Operating Temperature (°C)	Power Supply	Power Consumption	Technique
LID-3300IP	Labkotech	Normal	[-30°:60°]	230V VAC, 50/60Hz	7	Vibration measurement of a diaphragm
			Heating			350
0871LH1 Freezing Rain Sensor	Goodrich	Normal	[-55:71]	[22:29.5]	15	Measurement of frequency in resonance
			Heating			50
Ice Load Surveillance Sensor	Combitech	Normal	[-40:50]	[11:26]	100	Measurement of ice loads
			Heating			2000
Ice Meister Model 9734	New Avionics Corporation	Normal	max 50°C	[12:36]	2	Optical Measurement of the reflected light
			Heating			50
HoloOptics Series T40 Sensor	HoloOptics	Normal	-	[12:48]	1.5	Optical Measurement
			Heating			60
WXT-520	Vaisala	Normal	[-52:60]	[5:32]	42341	Measurement of various climate parameters
			Heating		[5:32]	50
WAA252 Anemometer	Vaisala.	Normal	[-55:55]	24	72	Measurement of Wind Speed
			Heating			1	
	WAV252 Vane	Vaisala.	Normal	[-55:55]	12	50	Measurement of wind direction
			Heating		24	1
IceFree3 Anemometer	NRG Systems	Normal	[-40:60]	-	-	Measurement of wind speed
			Heating		24 CC/CA		
	IceFree3 Wind Vane	NRG Systems	Normal	[-40:80]	1-25 DC	-	Measurement of wind direction
			Heating		24 CC/CA
DSC111	Vaisala	Normal	[-40:60]	9-30 CC	1.9	Infrared spectroscopy (Optical measurement)
			Heating			4

Blade Control	Rexroth (Bosch Group)	Normal				Measurem ent of frequency in resonance
			Heating				

Table 1. Characteristics of the ice detection systems.

4 LIFE CYCLE COST MODEL FOR ICE CONDITION MONITORING SYSTEMS

The literature shows the cost-benefit of CMS in wind turbines, therefore, CMS for wind turbines has a key role for the costs to operate wind farms. In this research, a novel maintenance management research based on an economic study of the Life Cycle Cost (LCC) of different topologies of ice detection systems is presented. It is necessary to emphasize that, to date, this is the first research study that covers the maintenance management of ice detection systems. The model presented in this work takes into account the costs of investment, operation and maintenance and energy losses. In addition, a bank loan amortization is included for a real point of view. On the other hand, to complete the study, different scenarios have been studied: (a) generic study; (b) favorable climate conditions without maintenance modification; (c) favorable climate conditions with maintenance modification; (d) adverse climate conditions without maintenance modification and finally, (e) adverse climate conditions with maintenance modification.

4.1 Life Cycle Cost (LCC)

LCC analysis is used for an economic evaluation of a project in which all costs are considered potentially important to that decision [18]. This analysis had been used in the defense sector, power industries and oil & chemical industries. LCC can be defined as the sum of all recurring and one-time (non-recurring) costs over the full life span, or a specified period, of a particular solution. This analysis is based on the International Standard, IEC 300-3-3, 1996 [52]. The main objective of the LCC study of this work is to determine that ice detection system covers their investment costs and provides certain economic benefits throughout its lifetime. LCC includes direct and indirect initial costs plus any periodic or continuing costs for operation and maintenance [19]. All the costs are usually discounted, and the total to a present day value is known as the net present value (NPV).

The LCC model proposed for the maintenance management research is based in the model described in references [42][43]. In this model, the following assumptions have been considered:

- Property tax, value added tax, etc., and general inflation are constant and included within the annual discount rate.
- Cash required for investment is provided by the enterprise in this case (rather than being borrowed) so the equity rate is 1; the standard LCC model can be written as follows:

$$\mathbf{Y} = \sum_{i=1}^n \mathbf{y}_i = \lambda \sum_{i=1}^n \mathbf{a}_i \mathbf{c}_i^T$$

where $\mathbf{Y}$ is the total cost, $\mathbf{Y} = [\mathbf{Y}_1, \dots, \mathbf{Y}_t, \dots, \mathbf{Y}_T]$; $\mathbf{Y}_t$ denotes the cumulative cost in year t ; the subscript T is the total number of years; $\mathbf{y}_i$ indicates the cost of breakdown in category i ; and λ is the net present value vector (see Annex A).

For the case study considered in this work, $n = 4$ is assumed (Ice detection system investment: $i=1$; Ice detection system operation: $i=2$; energy production and energy losses by ice detection system: $i=3$ and; maintenance and maintenance reductions by ice detection system: $i=4$). Now, if the term a_{ij} indicates the number of times that the unit cost c_{ij} is incurred, the matrix $\mathbf{A}$ and $\mathbf{C}$ can be described as $\mathbf{A} = [\mathbf{a}_1, \dots, \mathbf{a}_4]$, and $\mathbf{C} = [\mathbf{c}_1, \dots, \mathbf{c}_4]$, where $\mathbf{a}_i$ and $\mathbf{c}_i$ are one dimensional arrays of length 3, i.e. $\mathbf{a}_i = [a_{i1}, a_{i2}, a_{i3}]$ and $\mathbf{c}_i = [c_{i1}, c_{i2}, c_{i3}]$. The values that compose the matrixes $\mathbf{A}$ and $\mathbf{C}$ are the following:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \\ a_{41} & a_{42} & a_{43} \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \\ c_{41} & c_{42} & c_{43} \end{bmatrix}$$

A detailed description of the different costs is developed next.

4.1.1 Investment cost ($\mathbf{c}_1$)

The ice detection system investment cost, $\mathbf{c}_1$, is related to the costs of capital. These costs include the general investment costs defined by c_{11} , the installations costs defined by c_{12} and other costs (regulatory approval, initial testing, etc) denoted by c_{13} . Ice detection system investment costs are performed only once, at the beginning of the life cycle. Finally, the number of times incurred in these costs are $a_{11}=1$, $a_{12}=1$ and $a_{13}=1$.

4.1.2 Operation cost (c_2)

The operation cost of the ice detection system, c_2 , is related to the costs incurred by the technical operation process in a period of time. The most significant costs included in this term are the general operation costs of the ice detections system, defined by c_{21} , and the maintenance costs of the ice detection system, defined by c_{22} . Maintenance costs are performed once a year, $a_{22} = 1$, while operation costs are carried out monthly, therefore $a_{21} = 12$. Finally, $c_{23} = 0$ and $a_{23} = 0$.

4.1.3 Energy production and energy losses by ice detection system (c_3)

The cost due to production losses is given by the difference of production losses employing and not employing the ice detection system. The term a_{31} represents the energy losses due to icing in the case that ice detection system is not used. The ice detection system is not totally efficient, only a part of these energy losses is avoided. a_{32} is the energy losses using the ice detection system. The values of c_{31} and c_{32} are given by the electricity price (0.05 €/kWh). Finally, $c_{33} = 0$ and $a_{33} = 0$. The data from the case study used in this calculus are shown in Table 2 [53].

Period of Time	01/01/2010 – 01/06/2012 (29 months)
Number of wind turbines.	517
Power.	682 MW
Number of downtimes registered and analyzed.	227.146
% downtime due to ice accretion.	14,05 %
% downtime due to ice accretion (areas with high probability of ice growth).	18,49 %
Electricity price.	0,05 €/kWh

Table 2. Data from ICINGBLADES project for the achievement of energy production and losses employing ice detection system.

4.1.4 Maintenance reduction costs by ice detection system (c_4)

This term is the difference between the total maintenance costs with and without ice detection system per wind turbine and per year. c_4 is composed by:

$$c_4 = c_{41} - c_{42}$$

where:

- c_{41} : *Maintenance cost without ice detection system.* This term is composed by the sum of preventive costs (PC) and corrective costs (CC) of the wind turbine. Preventive costs correspond to the number of inspections carried out to check the state of the blades. On the other hand, corrective costs are decomposed in the following four items: (a) blade surface repair; (b) onsite structural repairment of the blade; (c) structural repairment just down the blade; and (d) structural repairment down the nacelle (using cranes).

$$c_{41} = PC + CC$$

being:

$$PC = \sum_{i=1}^n (CPT_i \cdot NPT_i)$$

$$CC = \sum_{i=1}^n (CCT_i \cdot NCT_i \cdot FR_i)$$

where:

- CPT_i = Cost of preventive task i .
 - NPT_i = Number of preventive tasks i in a year.
 - CCT_i = Cost of corrective task i .
 - NCT_i = Number of corrective tasks i in a year.
 - FR_i = Failure rate of the component involved.
- c_{42} : *Maintenance cost with ice detection system:* It is composed by preventive costs and corrective costs as follows:

$$c_{42} = PC \cdot (1 - \alpha/100) + CC \cdot (1 - \beta/100)$$

where α represents the percentage of reduction of inspections with ice detection system and β denotes the percentage of reduction of failures.

- $c_{43} = 0$.

Finally, $a_{41} = 1$, $a_{42} = 1$, $a_{43} = 0$, being $c_4 = PC \cdot \alpha/100 + CC \cdot \beta/100$.

4.2 Procedure for the study of the LCC for the Different Ice Detection systems

The LCC model described above has been applied to the following ice detection systems: Ice Load Surveillance Sensor, NRG IceFree3, BladeControl, 0871LH Goodrich and HoloOptics. Additionally, to complete the study, different scenarios have been taken into account varying the climate conditions and the probabilities of reduction of energy losses and maintenance costs: (a) generic study; (b) favorable climate conditions without maintenance modification; (c) favorable climate conditions with maintenance modification; (d) adverse climate conditions without maintenance modification and; (e) adverse climate conditions with maintenance modification. A description for the different scenarios is explained next (Table 3 shows the values assumed for each scenario).

Scenario 1: Generic study.

In this scenario, all the ice detection systems have the same probability values of reduction of energy losses and reduction of maintenance. The investment costs of the different ice condition monitoring systems can be compared in this scenario.

Scenario 2: Favourable climate conditions without maintenance modification.

In this scenario, all the wind turbines are operating in favourable climate conditions. In this case, the percentage of downtimes due to ice accretion is assumed to be a 14.05% of the total wind turbine downtimes [53]. Additionally, the values for the probability of reduction of energy losses are not the same for the different ice detection systems (depending on the type and the technique used by each ice detection system).

Scenario 3: Favourable climate conditions with maintenance modification.

This scenario is based on Scenario 2 modifying the values of percentage of reduction in blade inspections and failure of the blades (preventive and corrective costs respectively). These values depend on the ice detection system used.

Scenario 4: Adverse climate conditions without maintenance modification.

In this scenario, all the wind turbines are operating in adverse climate conditions. The percentage of downtimes due to ice accretion is now assumed to be 18.49% of the total wind turbine downtime [53]. Additionally, the value of reduction of energy losses is not the same for the different ice detection systems (depending on the method implemented for ice detection).

Scenario 5: Adverse climate conditions with maintenance modification.

This scenario is based on Scenario 4. Additionally, the values of the corrective and preventive costs are modified depending on the ice condition monitoring system used.

<div>Scenarios</div> <div>Ice Detection Systems</div>		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
		Generic study	Favourable without maintenance modification	Favourable with maintenance modification	Adverse without maintenance modification	Adverse with maintenance modification
Ice Load Surveillance Sensor	% reduction in energy losses	40	50	50	35	35
	% reduction in preventive maintenance	75	75	75	75	65
	% reduction in corrective maintenance	40	40	50	40	40
NRGIceFree3	% reduction in energy losses	40	25	25	30	30
	% reduction in preventive maintenance	75	75	60	60	50
	% reduction in corrective maintenance	40	40	30	30	20
BladeControl	% reduction in energy losses	40	30	30	45	45
	% reduction in preventive maintenance	75	75	70	70	60
	% reduction in corrective maintenance	40	40	35	35	25
0871LH Goodrich	% reduction in energy losses	40	60	60	50	50
	% reduction in preventive maintenance	75	75	85	85	70
	% reduction in corrective maintenance	40	40	55	55	45
HoloOptics	% reduction in energy losses	40	55	55	40	40
	% reduction in preventive maintenance	75	75	80	80	70
	% reduction in corrective maintenance	40	40	45	45	35

Table 3. Percentage reductions for the different ice detection CMS and the different scenarios.

5 RESULTS

The LCC presented in this work has been applied to the different ice condition monitoring systems for the different scenarios described above. For example, in the application of the case study for Ice Load Surveillance Sensor (for one wind turbine), the values that compose the matrices $\mathbf{A}$ and $\mathbf{C}$ used in the different scenarios are the following:

- Scenario 1: Generic study

$$\mathbf{A}^T = \begin{bmatrix} 1 & 12 & 15179.88 & 1 \\ 1 & 1 & -9107.93 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{C}^T = \begin{bmatrix} -8858 & -295.27 & 0.05 & 14751 \\ -106.3 & -70 & 0.05 & -7590.6 \\ -3543.24 & 0 & 0 & 0 \end{bmatrix}$$

- Scenario 2: Favourable climate conditions without maintenance modification.

$$\mathbf{A}^T = \begin{bmatrix} 1 & 12 & 15179.88 & 1 \\ 1 & 1 & -7589.94 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{C}^T = \begin{bmatrix} -8858 & -295.27 & 0.05 & 14751 \\ -106.3 & -70 & 0.05 & -7590.6 \\ -3543.24 & 0 & 0 & 0 \end{bmatrix}$$

- Scenario 3: Favourable climate conditions with maintenance modification.

$$\mathbf{A}^T = \begin{bmatrix} 1 & 12 & 15179.88 & 1 \\ 1 & 1 & -7589.94 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{C}^T = \begin{bmatrix} -8858 & -295.27 & 0.05 & 14751 \\ -106.3 & -70 & 0.05 & -6475.5 \\ -3543.24 & 0 & 0 & 0 \end{bmatrix}$$

- Scenario 4: Adverse climate conditions without maintenance modification.

$$\mathbf{A}^T = \begin{bmatrix} 1 & 12 & 19976.94 & 1 \\ 1 & 1 & -12985.01 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{C}^T = \begin{bmatrix} -8858 & -295.27 & 0.05 & 14751 \\ -106.3 & -70 & 0.05 & -7590.6 \\ -3543.24 & 0 & 0 & 0 \end{bmatrix}$$

- Scenario 5: Adverse climate conditions with maintenance modification.

$$\mathbf{A}^T = \begin{bmatrix} 1 & 12 & 19976.94 & 1 \\ 1 & 1 & -12985.01 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{C}^T = \begin{bmatrix} -8858 & -295.27 & 0.05 & 14751 \\ -106.3 & -70 & 0.05 & -6475.5 \\ -3543.24 & 0 & 0 & 0 \end{bmatrix}$$

Figure 8 to Figure 12 show the NPV for different values of the annual rate of return (k) reached by the installation of the Ice Load Surveillance Sensor in a wind turbine and operating in each scenario respectively. Figure 8 illustrates the NPV for wind turbines operating under the generic scenario, the initial ice condition monitoring system investment cost is recovered for all values of k in the 3th year of operation. In the 4th year of operation appear positive values of NPV due to ice detection. Figure 9 depicts the NPV for wind turbines operating under favorable conditions without maintenance modification. In this case, the payback is recovered for all values of k in the 3th year of operation. In the 4th year of operation appears energy production benefits due to ice detection. A time reduction for the payback is achieved in scenario 2 in comparison with the scenario 1 due to the reductions of energy losses. On the other hand, Figure 10 shows the scenario 3, favorable conditions with maintenance modification. It is observed that the payback is recovered for all values of k in the second year of operation. With the increase of the percentage of the probability of the reduction of the corrective costs, the time necessary to achieve the profitability of the ice detection system is reduced. Figure 11 illustrates the results for the 4th scenario (adverse climate conditions without maintenance modification). The initial investment

cost is recovered for all values of k in the second year of operation. The reason is that, under severe icing conditions, higher energy losses are caused by the increase of ice accretion on the wind turbine. In this case, the time interval to make the ice detection system profitable is reduced. Figure 12 shows the NPV for wind turbines operating under adverse conditions with maintenance modification, the payback is recovered for all values of k between the 3th and the 4th years of operation. The higher maintenance costs make that the ice detection system needs more time to be profitable. Finally, comparing all the scenarios, it is observed that savings in maintenance costs and the increase of energy generation using ice detection systems make reductions of the time necessary to recover the investment costs and, therefore, higher economic benefits can be achieved.

Figure 8. Scenario 1 (Generic Study) - NPV for different rates of return in the interval $k=1\%$ to $k=10\%$ and for different years of operation using Ice Load Surveillance Sensor CMS on a wind turbine.

Figure 9. Scenario 2 (Favourable climate conditions without maintenance modification) - NPV for different rates of return in the interval $k=1\%$ to $k=10\%$ and for different years of operation using Ice Load Surveillance Sensor CMS on a wind turbine.

Figure 10. Scenario 3 (Favourable climate conditions with maintenance modification) - NPV for different rates of return in the interval $k=1\%$ to $k=10\%$ and for different years of operation using Ice Load Surveillance Sensor CMS on a wind turbine.

Figure 11. Scenario 4 (Adverse climate conditions without maintenance modification) - NPV for different rates of return in the interval $k=1\%$ to $k=10\%$ and for different years of operation using Ice Load Surveillance Sensor CMS on a wind turbine.

Figure 12. Scenario 5 (Adverse climate conditions with maintenance modification) - NPV for different rates of return in the interval $k=1\%$ to $k=10\%$ and for different years of operation using Ice Load Surveillance Sensor CMS on a wind turbine.

An extension of the case study of the LCC is carry out for the ice detection system assuming that the investment costs are supported by a bank loan with an interest rate of 8% and 10 years. The study includes the NPV results for the five scenarios using a rate of return of $k=5\%$ in the 10th year of operation (see Figure 13). It is observed that the benefits caused by the installation of Ice Load Surveillance start appearing between the second (for scenarios 3 and 4) and the fourth year (scenario 5).

Figure 13. Investment cost supported by a bank loan - NPV results for the five scenarios using a rate of return of $k=5\%$.

A comparison of the NPV results achieved for this ice detection system with and without the application of a bank loan with values of rate of return of $k=5\%$ and $k=10\%$ have been done. It is observed that the option of the investment cost supported by a bank loan is the best option when the values of the rate of return (k) are higher than the interest rate of the bank loan (8%). Also, when the values of the rate of return are smaller than the interest rate of the bank loan, the bank loan is the worst option (see Figure 14).

Figure 14. Investment cost with and without a bank credit using a rate of return of $k=5\%$ and $k=10\%$.

The studies for NRG IceFree3, BladeControl, 0871LH Goodrich and HoloOptics systems through the different scenarios have been developed and the results are

illustrated in Table 4. This table shows a resume of the NPV results for all scenarios using extreme values of rate of return of $k=1\%$ and $k=10\%$. The analysis of the ice detection system taken into account provides the following findings:

- i. The investment, maintenance and operation costs of the Ice Load Surveillance Sensor are high. The investment is recovered between the second and the fourth year depending on the value of the rate of return used ($1\%-10\%$) for all scenarios;
- ii. The device that requires the lowest investment is the NRG IceFree3. This ice detection system requires the smallest time to recover the initial investment (between the first and the second year depending on the value of the rate of return used for all scenarios). Additionally, this ice detection system presents the highest NPV value in the 10th year of operation for $k=1\%$ of all the CMS studied in this research;
- iii. The BladeControl device requires the highest investment of all the ice condition monitoring systems studied. The initial investment is recovered in the 5th year of operation for the scenarios 1 and 2 (using small values of rate of return). On the other hand, for scenarios 3, 4 and 5 and for high values of rate of return the initial investment of the BladeControl is not recovered;
- iv. The initial investment of the 0871LH Goodrich is recovered between the first and the second year for all scenarios;
- v. The HoloOptics sensor has medium investment costs finding similar results that the 0871LH Goodrich sensor;
- vi. After studying the maintenance costs, it is observed that predictive costs are much smaller than corrective cost for the blade of the wind turbines. It is necessary to emphasize the achievement of a great reduction of these corrective costs; and, finally,
- vii. The bank loan support option for the BladeControl device is not viable.

	Device (Investment)	ILSS (12507,5€)			NRG IceFree3 (5216€)			BladeControl (15480€)			0871LH (10661€)			HoloOptics (8950€)		
		Recovery	Value 10 th year	Value 10 th year credit	Recovery	Value 10 th year	Value 10 th year credit	Recovery	Value 10 th year	Value 10 th year credit	Recovery	Value 10 th year	Value 10 th year credit	Recovery	Value 10 th year	Value 10 th year credit
Scenario 1: Generic	k=1 %	4 years and 2 months	11.200 €	11.600 €	11 months	32.400 €	32.900 €	7 years and 6 months	3.100 €	4.800 €	2 years and 11 months	16.200 €	16.300 €	2 years and 3 months	19.800 €	20.800 €
	k=10 %	3 years and 6 months	24.000 €	17.900 €	10 months	52.700 €	50.700 €	5 years and 3 months	13.200 €	7.300 €	2 years and 5 months	30.800 €	25.200 €	1 year and 11 months	35.400 €	32.000 €
Scenario 2: Favorable conditions without maintenance modification	k=1 %	4 years and 1 month	11.600 €	12.100 €	12 months	31.700 €	36.100 €	7 years and 10 months	2.700 €	4.300 €	2 years and 10 months	17.100 €	17.300 €	2 years and 2 months	20.500 €	21.500 €
	k=10 %	3 years and 3 months	24.700 €	18.600 €	11 months	51.600 €	56.100 €	5 years and 5 months	12.500 €	6.600 €	2 years and 4 months	32.200 €	26.600 €	1 year and 11 months	36.500 €	33.100 €
Scenario 3: Favorable conditions with maintenance modification	k=1 %	3 years and 1 month	18.500 €	18.900 €	1 year and 5 months	21.500 €	22.000 €	No recovery	-1.900 €	-240 €	1 year and 11 months	29.600 €	29.800 €	1 year and 10 months	25.100 €	26.000 €
	k=10 %	2 years and 6 months	35.200 €	29.200 €	1 year and 3 months	36.000 €	34.000 €	7 years and 3 months	5.500 €	-370 €	1 year and 8 months	51.500 €	45.900 €	1 year and 7 months	43.500 €	40.100 €
Scenario 4: Adverse conditions without maintenance modification	k=1 %	3 years	18.300 €	18.800 €	1 year and 4 months	22.200 €	22.700 €	No recovery	-500 €	1.100 €	1 year and 11 months	29.900 €	30.000 €	1 year and 10 months	25.000 €	25.900 €
	k=10 %	2 years and 5 months	35.000 €	28.900 €	1 year and 2 months	37.000 €	35.000 €	No recovery	-7.600 €	1.700 €	1 year and 7 months	51.900 €	46.300 €	1 year and 7 months	43.300 €	39.900 €
Scenario 5: Adverse conditions with maintenance modification	k=1 %	4 years and 2 months	9.200 €	9.700 €	2 years and 1 month	23.000 €	21.100 €	No recovery	-9.600 €	7.900 €	2 years and 7 months	19.700 €	19.900 €	2 years and 7 months	16.200 €	17.100 €
	k=10 %	3 years and 7 months	21.000 €	14.900 €	1 year and 9 months	13.100 €	13.700 €	No recovery	-6.400 €	-12.200 €	2 years and 2 months	36.200 €	30.600 €	2 years and 3 months	29.800 €	26.400 €

Table 4. Resume of the LCC for all the ice detection CMS and for all the scenarios using a rate of return of $k=1\%$ and $k=10\%$.

6 CONCLUSIONS

The presence of ice on wind turbines greatly affects their reliability, availability, maintainability and safety and it is one of the biggest causes of energy losses. Ice detection systems or ice condition monitoring systems play a key role to reduce the operation and maintenance costs, increase the lifetime of components, increase reliability, improve safety and decrease the downtimes and energy losses of wind turbines. In this research work is presented a novel economic study of the life cycle cost of some commercial ice condition monitoring systems (Ice Load Surveillance Sensor, NRG IceFree3, BladeControl, 0871LH Goodrich and HoloOptics sensors). In particular, the economic feasibility of different ice detection systems is analyzed by a LCC model through different scenarios. The results obtained from the study shows that the NRG IceFree 3 sensor requires the lowest economic investment and provides the highest NPV in the 10th year of operation while the BladeControl system requires the highest investment and provides the worst values. Moreover, the investment cost supported by a bank loan is the best option when values of rate of return (k) are higher than the interest rate of the bank loan (8%). Finally, the study also illustrates that predictive costs are much smaller than corrective cost for the blades of the wind turbines. Therefore, it is necessary to emphasize the achievement of a higher reduction of these corrective costs installing ice detection systems for the blades of the wind turbines.

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Annex A: Net present value

The net present value (NPV) is defined as the sum of the present values (PVs) of the individual cash flows of the same entity. The NPV is defined by the following expression:

$$NPV_t = \frac{CF_t}{(1+k)^{t-1}}$$

where CF_t is the cash flow in year t assuming that all costs are defined using base-year prices, and k is the annual rate of return on investment, referred to as the cost of capital by some researchers. The total discounted cost over t years of life is therefore achieved by the following expression:

$$NPV = -I_0 + \sum_{t=1}^T \frac{CF_t}{(1+k)^{t-1}}$$

being I_0 the initial investment. Additionally, assuming that the previous costs remains constant throughout the lifetime of the project, $CF_1=CF_2=\dots=CF_t=CF$, the NPV factor λ is given as follows:

$$\lambda = \sum_{t=1}^T \frac{1}{(1+k)^{t-1}} = \frac{1}{k} \left[1 - (1+k)^{-T} \right]$$

Considering the above expressions, the NPV value can be calculated as

$$NPV = -I_0 + CF \cdot \lambda = -I_0 + \frac{CF}{k} \left[1 - (1+k)^{-T} \right]$$