Sea ice and icing risk for offshore wind turbines

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Abstract

There are two important issues related to wind turbines performances in offshore sites that locate in cold climates: sea ice (flows, driving ice, land-fast ice) and the presence of atmospheric icing (due to water in the air as in-cloud operation, rainfall and sea sprays) which may potentially lead to ice formation on turbines' structures. Icing of rotor blades and some other wind turbine components have effect on the design of turbines, the safety of O&M personnel and the overall economics of a wind energy project.

In offshore conditions ice pack or floating blocks on the sea surface cause additional static and dynamic forces on the turbine structure. The effects of sea ice occur as a mechanical shocks and increased vibrations that may result to additional operational loads.

The presence of sea spray, associated with atmospheric icing, determines complex icing phenomena that are highly dependent on the elevation of the turbine rotor over the sea level and on the size and type of wind turbine. Therefore a risk analysis needs to be performed to assess the life reduction and the hazard of ice shedding which is relevant to neighbour turbines and O&M personnel.

Ice mitigation systems should comprise cold weather packages, anti-icing/de-icing devices and systems reducing the actions of sea ice. The design of such systems should be integrated in the design of the turbine to assess the economic benefit of their operation in cold climates and to set limits for continuous operation during icing periods.

The paper presents a general framing of the icing phenomenon for wind turbines in offshore sites and a procedure for analyzing the risk of ice pieces shedding from the turbines A general scheme of a procedure for the integrated design of ice mitigation systems for wind turbines is also presented and discussed.

KEYWORDS: offshore wind turbine, cold climate, icing, risk analysis, anti-icing.

NOMENCLATURE:

H_{tower}	tower height
LWC	liquid water content in air
MVD	average droplet diameter
$m_{ice,avg}$	ice fragment average mass
$m_{id,avg}$	average mass of ice accretion per day of icing conditions
N	number of detached ice fragments per year
n_{idy}	number of days of icing per year
P_y	strike probability
r	blade radial coordinate
R_b	blade length
S_{cov}	covered surface area
T	recurrence period
Greeks	
ω_R	blade rotational speed
ρ_{air}	air density
ρ_{ice}	ice density

1. INTRODUCTION

Several wind energy parks will be built at sites where the synergic effect of the metrological conditions and sea/ocean processes of cold environment will pose important constraints for a cost effective and reliable development of the wind energy production. The operating environment of large offshore wind turbines results to be more challenging in such sites compared to that of today's cold climates onshore sites.

Sets of new and highly efficient technological concepts need to be developed to open the ice-bound waters of northern Europe to the wind energy exploitation in the medium and long term. Here the wind potential is huge; for example in the Gulf of Bothnia alone over 50 GW could be installed in the next years [1].

At sites having ambient temperature below zero Celsius degrees and humid environment for large periods of the year, icing will represent an important threat to the durability of wind turbines for two main reasons: the effect of icing on structures (atmospheric and sea sprays) and the mechanical actions of sea ice (sea ice and glacial ice).
High water vapour content and sea spray could cause important water condensation and ice growth (see figure 1).

Figure 1: Iced rotor blade.

Icing of wind turbine affects three different aspect: the design (aerodynamics, load, control system, material), the safety (ice throw, unbalance, over power, fatigue), and the cost-effectiveness (annual energy output expectations, wind measurements, design life duration, wind turbine equipment). Icing also affects wind sensors, both in resource estimation and controlling the turbine. The experience on inshore sites teaches that heavy icing can result in a total stop of the turbine and that the ice can last considerably longer on the blades than the time at which icing conditions occur. As a consequence, at harsh sites annual power loss may grow up to 20-50 % [2,3,4,5].
In detail, ice can cause:

- inefficient or inoperative wind measuring equipments (both during wind assessment and turbine operating phase);
- rapid performance degradation;
- increased noise level;
- increased fatigue on wind turbine and foundations;
- down time due to excessive vibrations;
- risk of ice throw (maintenance personnel and near structures safety);
- additional troubles (site accessibility, site data communication);
- limited length of "weather window" during project installation;
- possibly more complicated building permission granting process.

Cold weather packages of turbine manufacturer are typically adopted for cold climate sites. The aim of the technical solutions is to widen the operating temperature range of a selected wind turbine. Usually manufactures refer to the standstill temperature i.e. the temperature which the turbine can withstand while not operating and also to the lowest operating temperature. These temperatures reflect the turbines capability to withstand low temperatures in terms of material selections, and design philosophy. Therefore a collision between an ice pack and the turbine tower at temperatures below the standstill temperature might be disastrous because of the brittle behaviour of low carbon steels (i.e. typical tower material) [6].
On the other hand, at sites with a high probability of icing - e.g. several weeks per year – systems that ensure the operation of turbines are needed in order to avoid long stoppages during icing weather events. Many sites in northern Europe offer wind speeds during the icing season that are relatively high, so that long down times due to iced rotor blades may cause severe production losses. An active or passive de-icing or anti-icing system for the rotor blades is then recommended [7,8].

De-icing and anti-icing systems are still under development and have been tested on prototypes or small serial production lines. Blades heating systems are currently used at in Finland, Sweden, Switzerland [2,4]. Despite of these advancements, only little experience with anti-icing and de-icing systems is available, compared to the large number of turbines that are erected world wide. In fact, from the economical point of view, the installation of heating systems on wind turbines is not always recommended; if icing occurs only a few days to a week per year, the turbine is simply switched off when icing conditions take place [9]. Therefore, the interest of the manufacturers is put on technologies capable of reducing the amount of power and energy used for icing prevention purposes.

Passive systems such as black coloured coated blades have not offered solution to the ice problem up to now and in addition may induce large blade thermal stresses during hot summer periods [7].

Thermal anti-icing systems are at the moment the most used systems to face moderate icing. The selection and design of those systems shall be based on the consistent evaluation of the heat fluxes that the blades exchange with the environment during icing events. The computation presents a high degree of complexity due to the dependency of the heat fluxes on a great number of variables, both climatic and machine dependent. Only two codes are at the moment available to evaluate the thermal power and energy requirements for wind turbine blades: the TURBICE developed by the VTT [10] and the TREWICE developed by the DIMS [11].

Battisti et al. [12], demonstrated that three-bladed turbines with a rated output between 1 and 6 MW, require an anti-icing power for the rotor ranging from 10 to 15 % of the machine's rated output, depending on environmental conditions, turbine size and type. When the anti-icing power for turbines of different sizes is considered, the ratio of anti-icing power to machine's rated output is lower for larger turbines than for smaller ones. The estimation of the anti-icing power for different types of machines with nearly the same rated output (one, two or three bladed HAWT) shows that the anti-icing power decreases more or less proportionally to the number of blades when respectively three-bladed, two-bladed and single-blade machines are compared. Figures of heating power in the range of about 5-15% of the turbine's rated power were found for three bladed smaller size turbines [2,4].

Ice throw risk in a form of ice shedding may pose a major safety hazard in certain environments. This may affect the safe operations of the turbines in wind parks because of the possibility of being hit and damaged by ice pieces. Operator personnel during turbine maintenance could be also seriously injured by ice throw. The diameter of the ice risk zone is dictated by the mass and size of the ice fragments, and turbine functional parameters [13,14].

Figure 2: Floating sea ice pushed from wind to shore at bay of Bothia.

It is well recognized from field experiences that offshore wind turbines suffer from sea ice actions much less at the areas where sea ice is mostly land fast ice compared with that of the drifting ice. For land fast ice the structure is typically surrounded by more or less uniform ice. The ice sheet interacting with the turbine structure produces a wide range of deformation states, each generating different reactions on the structure [15]. Static loads are induced by a stationary contact of the ice with the turbine tower, and the surface forces arise from loads applied by a combination of winds, currents drags and thermal expansion, which push slowly the ice cover against the structure. The tower behaves as a single isolated pinning point resisting the applied driving force, which can be more or less distributed over the tower surface. Weather conditions, applied force level and icing-deicing cycles of the interface determine the uniformity of the mutual ice-structure contact. Thick ice in cold seawaters may sometimes induce the pile-up phenomenon, as a result of an irreversible damage of the offshore cantilever structure systems. Some amount this "pack ice" occur every winter, typically spring time when sea ice starts to move, at bay of Bothia as shown in figure 2.

Dynamic loadings arise from pieces of floating ice or even ice fields which can cover several square kilometres, hitting against the structure with appreciable velocity (even higher than 1 m/s). The duration and the forces exchanged with the tower depend on the kinetic energy of the ice and on its features.
The ice contact areas is an important parameter to determine the foundation sliding resistance, foundation shear bearing capacity and overturning moment at the seabed of a wind turbine structure.
Such loads need to be estimated in order to evaluate the total load to be sustained and in the design of the internal structure members.
Static and dynamic loads cause different response of the structure. Therefore the prevailing sea ice conditions and icing mechanism should be known in advance to properly design the type of foundation and some additional features as:

- barrier or ice collars against the dynamic influences caused by ice (structures can be designed to resist by providing sloping faces to the substructure at sea level. This reduces the ice pressure by inducing bending in the ice and breaking sheets into small pieces);
- cooperating foundations acting together to prevent the movement of the ice cover. The task is to create an artificial zone of "land-fast ice" or to extend the natural land-fast ice zone. In these cases, both static and dynamic forces on the individual foundations remain small.

Floating and pack ice on the water surface and atmospheric icing induce the wind turbine to excessive vibrations. Ice drift and hitting against the foundation might trigger structural vibrations or even damage it by exciting the tower, while structures' icing will excite flapwise the blades but the main effect is felt on the tower [16]. The turbine components need to be resistant to vibration under time-varying environmental or operational loads. Ideally, the wind turbine should incorporate sensors that monitor the environmental loads, including both those due to icing and to the sea ice, and the state of the structure. This concept needs more advanced diagnostic tools to be developed compared to current state of the art ones. Based on this information, semi-active countermeasures are activated automatically to prevent excessive vibrations. A method to mitigate the vibrations could be obtained by embedding damping and smart elements in the supporting structure of the wind turbine. These would be used to reduce the dynamic response and to increase the fatigue life of the structure. Structural damping is almost always an effective solution against excessive vibrations. The foundations of the wind turbines have also an effect on preventing ice induced movements. In appropriate sites, the natural land-fast ice zone can be extended in the wind park such that the static and dynamic ice forces on individual foundations remain small.
Sea ice accumulation on the tower could possibly modify the tower weight and aerodynamic, thus modifying loads on foundations. Moreover, as different researchers showed in [17], the ice accumulation could accelerate the corrosion speed process of the tower and support structure, if current offshore corrosion protection systems are not adopted.
Not last, a general problem for operation and maintenance has to be considered. Where the sea freezes over completely, the access for maintenance purposes may be often completely impossible for periods of up to several months [18]; this is likely to influence the estimates of the offshore energy output.
It is clear from these considerations that cold climates sites in open seas require to consider ice formation a basic factor for site analysis. Ice prevention systems on blades, accurate sealing, load mitigation systems for sea ice, cold weather packages, and diagnostic tools integrated to account for ice loads effects will be a sensible part of the investment and operating costs. Accurate tools for ice risk assessing are thus necessary and the impact on current design ascertained.
It is felt that safety matters will also become a crucial theme for those sites, and certification plans such as regulatory compliance demonstrations for systems against ice will be a mandatory issue in a near future.

2. ASSESSING ICING SEVERITY FOR OFFSHORE SITES

Published reports and studies on offshore sea icing can be hardly used as tools to predict icing severity on offshore wind turbines installations in cold climates, because the ice growth process is highly dependent on wind turbine geometry, and climatic (meteorological-oceanographic) factors. Furthermore, wind turbines for offshore installations have different characteristics compared to those at inland. Tower height, rotor diameters, rotational speeds, materials and foundations adopted in offshore installations differ from that at inland sites; it is important to emphasize that different turbines process identical weather conditions in different way: identical weather conditions lead to different icing conditions on the same turbine in different operating regimes.
Therefore, an analysis of icing risk requires knowledge of both the meteorological conditions conducive to icing and the turbine's geometrical characteristics and operating conditions.

Ice formation in open sea is often a combination of spray and atmospheric icing and their relative importance can vary according to the ocean conditions and the wind turbine components elevation above the sea surface. Usually sprays are reaching just the lower levels structures, like the bottom of the tower and the blade tip during its azimuthally downward pointing. The World Meteorological Organization in 1962 indicated an upper figure of 16 meters above the sea surface for the sea sprays, unless since the sea surface may change its roughness, it is expected that waves can carry sprays up to levels above that limit [19]. For current offshore turbines size, it is expected that sea icing will not cause additional problems for rotor parts.
The meteorological parameters needed as input for ice prevention design have been very precisely recognized from over 50 years of experimental investigations in the aeronautic field. They are principally: liquid water content, water droplet diameter, pressure, temperature, and the horizontal distribution of these variables. Furthermore salinity is fundamental to assess the freezing point of seawater [20].
Meteorological data in open sea remain scarce, unless some data can be collected from oil or gas offshore stations. Data from shores can modestly contribute to assess the actual conditions and determine still a huge area of inaccuracy in assessing the probability and severity of icing events for potential sites. When site developers attempt to assess icing severity, they are faced with the following problems:

1. establishing consistent simultaneous combinations of LWC, MVD, wind speed and temperature, which can occur at a given offshore site;
2. determining how these combinations will affect the rotor, leading to ice accretion (icing severity);
3. assessing the penalties (in terms of both energy losses and components reduced life) associated with icing severity;
4. assessing the energy and power requirement depending on the ice mitigation system adopted (thermal anti/de-icing, mechanical de-icing, etc.).

The information of points 1 and 2 could beneficially take advantage from remote-sensing systems, which can be highly accurate for open sea sites. The problem of meteorological data forecasting is two-fold. Not only are historical data and spatial extrapolation tools needed for wind farm design, but continuously up-to-date forecasts of icing events, their intensity and duration are also essential for wind turbine operation programs.
Existing ground-based systems (airports) could provide an important basis for retrieving the land-meteorological data needed, and together with the characteristics of the wind turbine, to assess the icing intensity of a given site. Long-term scenarios should tend to create a dialogue between ground-based and nacelle-based remote-sensing systems, and satellite-based sensors [8].
The information in items 3 and 4 is important for the economic feasibility analysis of wind turbines planned in cold climates where ice is an issue. A significant advantage in the costs of the supporting structures can be obtained if the simultaneous presence of the operational wind force and an extreme ice force can be prevented.

3. REGULATIONS AND RECCOMENDATIONS

Only a few standards and recommendations exist for offshore wind turbines, and only general indications are given for installations with occurrence of icing on structures and sea ice.
Both Danish and German recommendations [21,22,23], indicate that the whole turbine shall be examined for extreme loads during normal operation where icing is expected. Furthermore, according to the Danish guidelines [22,23] icing shall be included in the fatigue analysis for offshore plants, also if isolated, because ice throw from the rotor blades may pose a risk to the public and staff.
For atmospheric icing on blade, GL standards [21] assume the ice mass forming on the leading edge and increasing linearly from hub to middle blade span. A uniform ice mass distribution is then considered from middle span to blade tip.
For sea ice the Danish recommendations [22,23] require that the foundation of the wind turbine be designed for horizontal and vertical ice loads, including static and dynamic ice loads. Sea ice loads shall be determined (magnitude and direction) by taking in consideration the nature of ice, its mechanical properties, the ice-structure contact area, the shape and size of the structure, and the direction of the ice movements. Loads from possible pile-up in front of the foundations shall be assessed. Such ice loads include the following:

- loads due to rigid covers of ice, including loads due to arch effects and water level fluctuations;
- loads due to masses of ice frozen to the structure;
- pressures from pack ice and ice walls;
- thermal ice pressures associated with temperature fluctuations in a rigid ice cover;
- possible impact loads during thaw of the ice;
- loads due to icing.

The oscillating nature of the sea ice loads shall be considered, including build-up and fracture of moving ice occurrence. When ice breaks up, static and dynamic interactions will take place between the structure and the ice. For structures with vertical walls, the DNV guidelines [23] draw attention about natural vibrations of the structure that will affect the break-up frequency of the ice. Structures can be designed to resist it by providing sloping faces to the substructure at sea level. This reduces the ice pressure by inducing bending in the ice and breaking sheets into small pieces [24].

4. ICE SHEDDING HAZARD

The diameter of the ice risk zone is dictated by the mass and size of the ice fragments and turbine functional parameters Literature on ice shedding from wind turbines appears to be rather slim, also for onshore sites: observations and measurements on ice fragments found on the ground around wind turbines were collected as part of the WECO project [3]. Frank and Seifert [25] performed an experimental campaign to investigate the aerodynamic forces on iced airfoils and ice fragments themselves. On the basis of these results, a first ice throw numerical model was presented by Morgan et al. [26], followed by another work from Seifert et al. [13], in which maps of ice hits probability on the turbine vicinity was proposed.
An investigation is presented here applying a Monte Carlo Method to the ballistic model, which solves the trajectories of ice pieces. Suitable density functions are set for each of the input parameters to the trajectory equation. The input variables are gathered into turbine, wind-and-site and ice pieces characteristics (see figure 3). The output fragments distribution on the surface are presented in terms of strikes probability and recurrence period, as a function of the input parameters: for this purpose, a parametric analysis was performed varying ice pieces mass and shape.

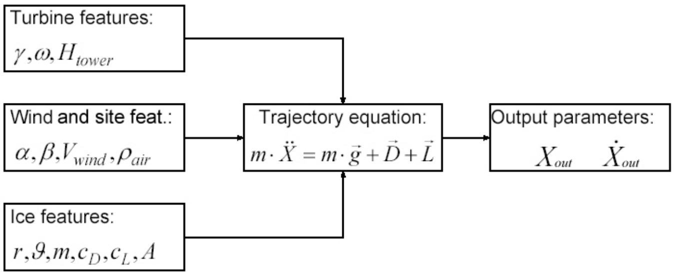

Figure 3: Monte Carlo procedure for the computation of the trajectories.

During the wind turbine operation, the input parameters can assume a large range of values due to variable wind speed and direction, and to the consequent adjustment of the turbine working conditions. Moreover, ice pieces with a variety of masses and shapes can shed from a generic position (r, ω) on the rotor, leading to different lift and drag coefficients for each ice piece. Accordingly, the fragments follow a wide range of trajectories. The Monte Carlo method is used to generate distributions of the input variables, allowing the computation of a number of trajectories. In this way, the landing position and velocity of each considered ice fragment is recorded for a variety of possible combinations of the input parameters. Figure 3 reports a scheme of the computation process. Between 104 and 105 samples were used in each simulation in order to have a sufficiently large database and therefore obtaining repeatable results. More details on the model can be found in [14].
Numerical simulations were performed to predict the ice fragments' distribution on the sea surface around a typical MW-size three bladed offshore wind turbine [27]. In addition to the above-mentioned input distributions, the variables in Table 1 were used for the simulations.

Table 1: Turbine geometrical and operating conditions.

R_b (m)	H_{tower} (m)	ω_R (RPM)	ρ_{ice} (kg/m^3)	ρ_{air} (kg/m^3)
40	70	20	800	1.3

Two sets of ice fragments' thickness and fragment's average masses were chosen. The first, according to Seifert's data [14], indicates respectively 5 cm, and 0,36 kg. The second set simulated the operation of a de-icing system on the rotor blades and figures of 1 cm, and 0,18 kg were accordingly chosen. Finally, different figures of "icing days per year" (days during which icing conditions occur) representative of a "moderate icing" site [3] and a 'severe icing' site were considered for the computations. The number of icing days per year (5 and 90 days per year respectively) was multiplied by the average ice accretion mass per day on the rotor (100 kg/day), and divided by the average mass of the cast ice blocks (0.18 or 0.36 kg) to obtain the annual number of ice strikes:

$$N = \frac{n_{idy} \cdot m_{id,avg}}{m_{ice,avg}} \qquad (1)$$

From this value, the strike probability per year and per square meter P_y is computed from the distribution of the ice fragments on the sea surface. The strike probability is computed in terms of recurrence period, as:

$$T = \left(P_y \cdot S_{\mathrm{cov}} \right)^{-1} \qquad (2)$$

S_{cov} represents the area at the sea surface masked by the "subject" for whom the risk analysis is carried out; in this study, the area of about 15 m^2 corresponds to a small service launch used to reach the turbine.

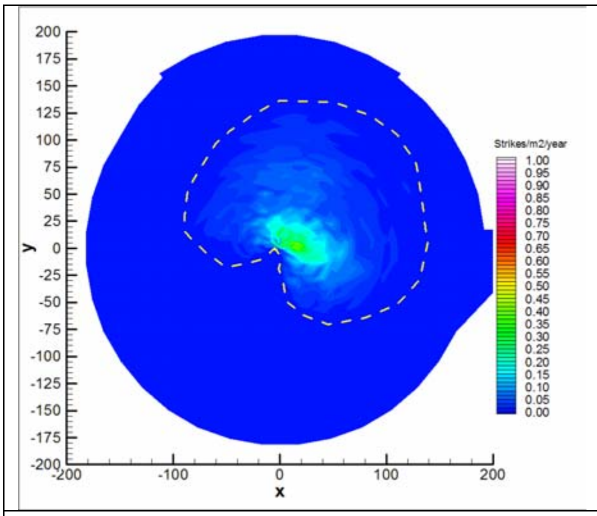

Figure 4: Strike probability for moderate icing site.

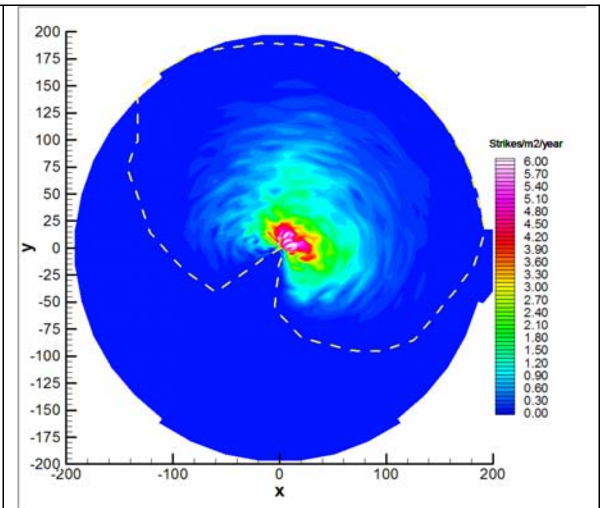

Figure 5: Strike probability for severe icing site.

Figure 4 and figure 5 show the strike probability in strikes/m^2/year for ice fragments of 0.36 kg average mass, and 1 cm thick. Figure 4 refers to a "moderate icing site", while figure 5 represent a "severe icing" site. The simulations carried out by varying the input variables mentioned, showed similar results both in terms of strike probability and recurrence period and therefore they are not shown for seek of brevity.

As can be seen, a much larger number of strikes is revealed in figure 5 (note the different colour scales) as a consequence of the larger quantity of ice formed on the blades. The simulations, however, show similar ice pieces distributions in the two cases, with a major strike probability in the area within 200 m around the turbine. The maximum distance covered by an ice piece is about 250 m.

In a wind farm, the turbines are about 200 m far from each other when they are arranged in a single row, while they locate 500 to 800 m from each other when they are set up in more than one row. As a consequence, a moderate probability exists for a turbine to be struck from an ice piece which is ejected by the nearest turbine, only for turbines located on a single row.

O&M personnel will likely to face higher risk while maintaining the power plant. Different risk areas can be identified in terms of recurrence period in the two figures: the yellow contour indicates a 10-years recurrence period. As can be seen, the chart in figure 4 shows a larger recurrence period contour, as a consequence of the larger number of strikes. In any case, the probability for a maintenance boat to be struck rises higher than 1 in 10 years in an area with a radius of about 130 – 200 m around the wind turbine.

Similar conclusions could be drawn for service helicopters approaching the nacelle. Although typically turbines will be remotely shut down before they are approached by helicopter, elevated risk remain at moderate winds because of ice pieces which, while detached from the rotor at rest, can possibly carried out by the wind.

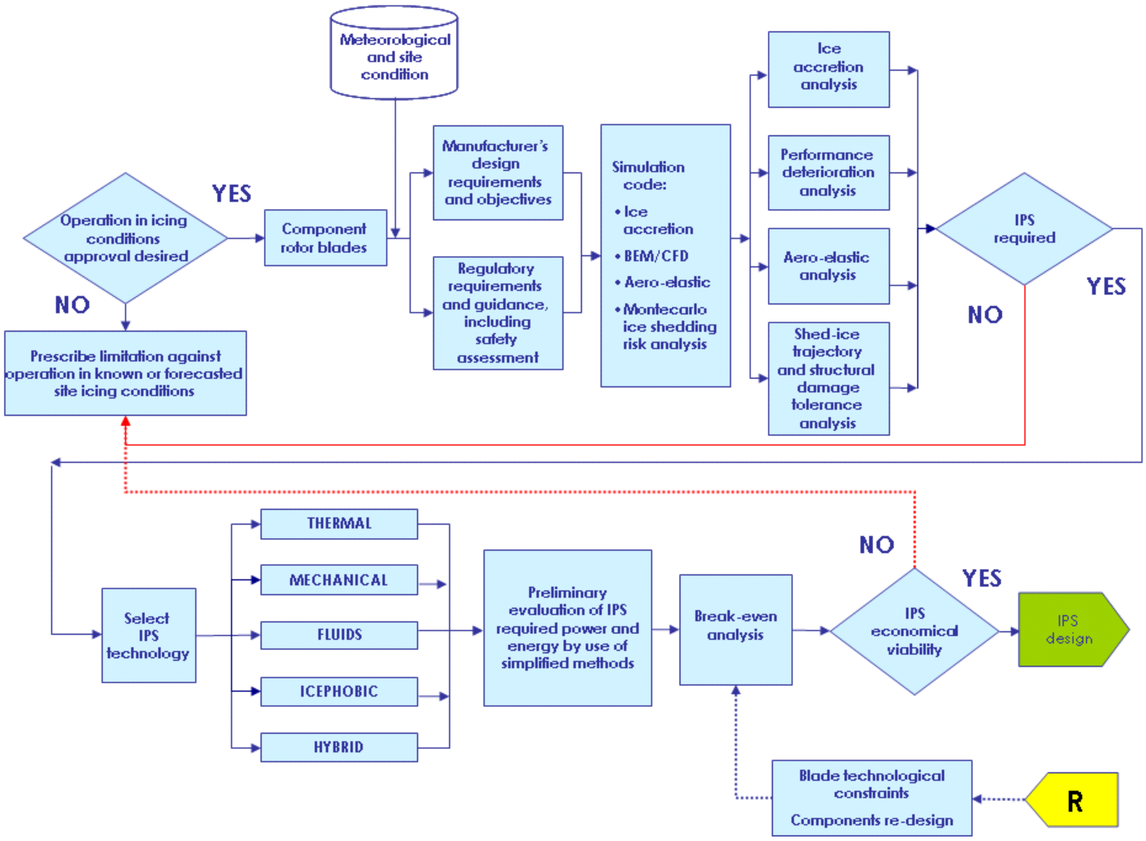

Figure 6: Ice prevention systems integrated design.

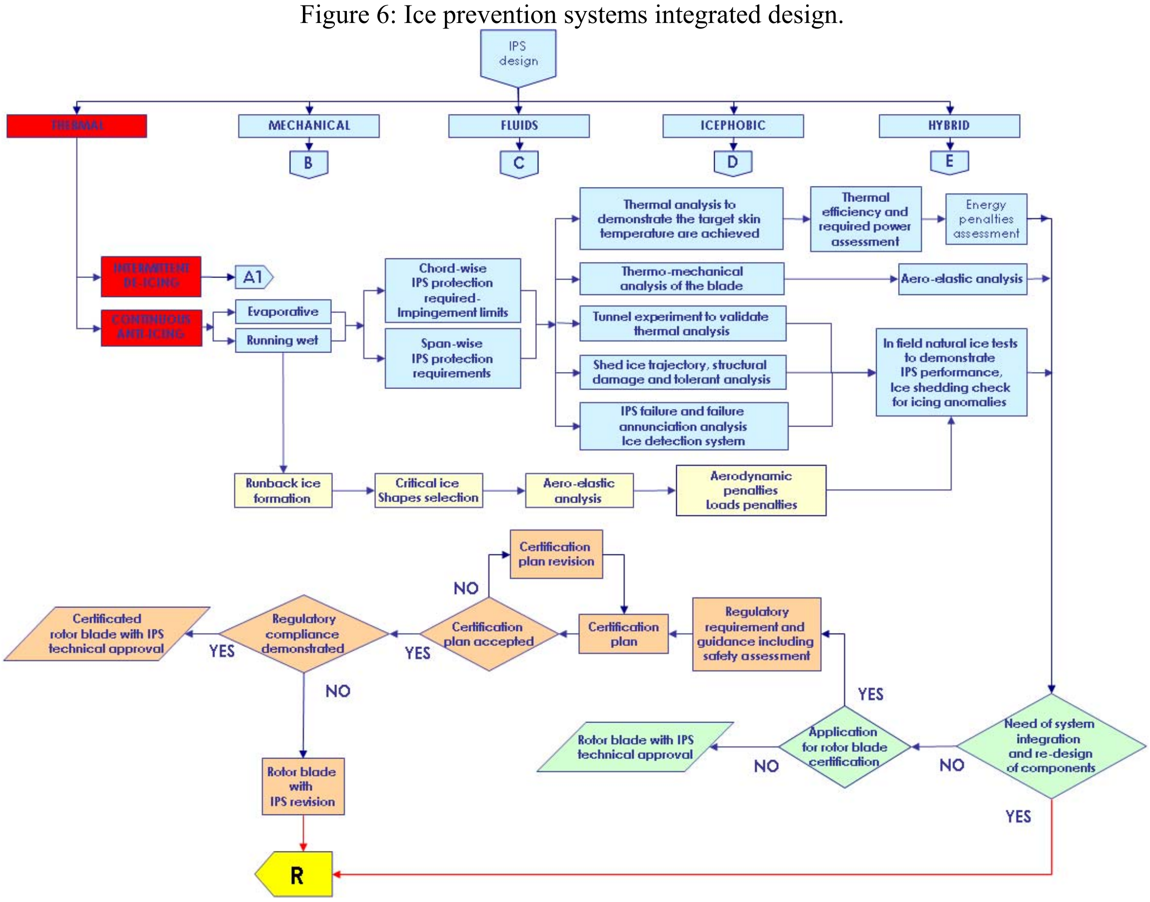

Figure 7: Ice prevention system executive design, verification and certification.

5. A PROCEDURE FOR ASSESSMENT OF ICE PREVENTION SYSTEMS

Ice prevention systems (IPS) on wind turbines cause additional investment and operational costs. A procedure is needed for the assessment of the benefits of such systems. In the following a flow path is described aimed to evaluate the economical viability of ice prevention systems for wind turbines. The procedure requires data and verified tools:

1. the correct identification of the parameters which mainly affect the performance and design characteristics of ice prevention systems;
2. the effect of the selected anti-icing and de-icing strategy on turbine performance, loads and safety;
3. the effect of ice mitigation technology selection on design and costs.

Searching for appropriate structural solutions for IPS should take into account both the actions exerted by sea ice and icing.
In the following only an example of an integrated procedure for icing is presented. The extension to include sea ice effect is straightforward and do not modify the underlying logic.
Figure 6 depicts a possible integrated design path for ice prevention systems applied to the rotor as an explanatory situation.
On the basis of environmental data and technical guidance issues, manufacturer design requirements and objective, the procedure first assigns the boundary conditions for a series of numerical simulations and experimental campaigns. Ice accretion analysis is necessary to provide the new contaminated blade profile shape and the induced performance and load. In this step the aeroelastic code simulations will account for ice accretion on the blades and consequent surface and mass loads. A performance deterioration analysis allows the energy output to be evaluated. Shed-ice trajectory and structural damage tolerance analysis is also an output of the integrated procedure. A technical level decision is now made on the need of ice prevention systems. For light icing, where negligible structural and performance penalties and an acceptable risk for people and goods is evident, no ice prevention system is required and only limitations can be prescribed for in icing operations. If the use of ice prevention systems results to be necessary instead, a preliminary selection of the technology is made on the basis of engineering experience. Five classes of systems are indicated in figure 6: thermal, mechanical, fluids, ice phobic surfaces and hybrid ones. According to the choice, simplified methods are used to evaluate the anti-icing installed power and the energy consumption, and a break-even analysis is carried out to assess the economic viability of the system. In the case the system ends as non-economically worth, only limitations are prescribed for operation in icing conditions. If for instance, the selection of continuous anti-ice technology is confirmed as preliminarily viable, figure 7 indicates the full calculation path for system executive design, verification and certification. Numerical and in-field tests on models are necessary to assess the technical availability and reliability of the ice prevention systems. This step ends with the analysis of the components' re-design. If a major redesign is needed, a new economic break–even is required, otherwise only technical approval path is followed.

6. CONCLUSIONS

The knowledge on how to mitigate the effects of the ice action is of great importance for the future development and reliability of offshore wind installations at such areas in Northern latitudes where sea ice occurs annually. This progress needs multidisciplinary skills in several fields of technology as experience on the wind energy technology, marine technology and ice engineering.
Cost-effective methods need to be developed to measure and to respond to the different ice actions in order to reduce the additional loads that occur in the presence of ice.
Safety issues for operating personnel during maintenance due to ice strikes risk is still an open and unsolved problem.
Integrated design procedures are important to select a proper ice-icing mitigation technology. These procedures could state that major benefit could be obtained by adopting a particular wind turbine class, or a given size for offshore cold conditions.
Current design procedure and certification need therefore to integrate the design of devices to assess the economic sustainability of high latitude off-shore plants.

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