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Risk Assessment of Wind Farm Development in Ice Proven Area

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ABSTRACT

There many risks associated with wind farms operating in cold harsh areas, a number of these risks is caused by icing. Atmospheric and super-structure icing can cause ice accretion on wind turbines' structure, and lead to public safety risks caused by ice throw and the failure of wind turbine's components. Other risks can affect wind farm's maintenance crew and their activities. Such risks are caused by snow accumulation and forming of sea ice, which can lead to limiting the access to wind turbines, and reducing their availability and the overall power production of the wind farm.

Snow accumulation and ice accretion on wind turbines specifically and the wind farm generally induce different types of risks. Therefore, an analysis should be carried out to determine how the different types of icing and snow accumulation affect each part of a wind turbine and wind farm. A risk matrix is usually utilized to determine the rank of these risks and prioritize them, which will help in the decision-making process for risk mitigation.

KEYWORDS: Wind Farm Safety; Public Safety; Icing Types; Icing Effects; Risk Matrix.

1. INTRODUCTION

The global average capacity of installed wind power throughout the past couple of years exceeded 50 GW per year, where 2015 marked a record-breaking year in which the global installed wind power capacity exceeded 60 GW (Sawyer, 2016). It is expected that the growth of installed wind power will exceed 840 GW by 2022, this will be supported by an increased growth in the installed capacity of offshore wind turbines, which only represented 3.5% of global installed capacity in 2017 (Sawyer, 2017). (Figure 1) illustrates the projected wind power capacity in Gigawatt (GW) to be installed during the following four years until 2022. It is noticed from the figure that the cumulative installed wind power capacity will grow at nearly a constant rate of 10% until 2022.

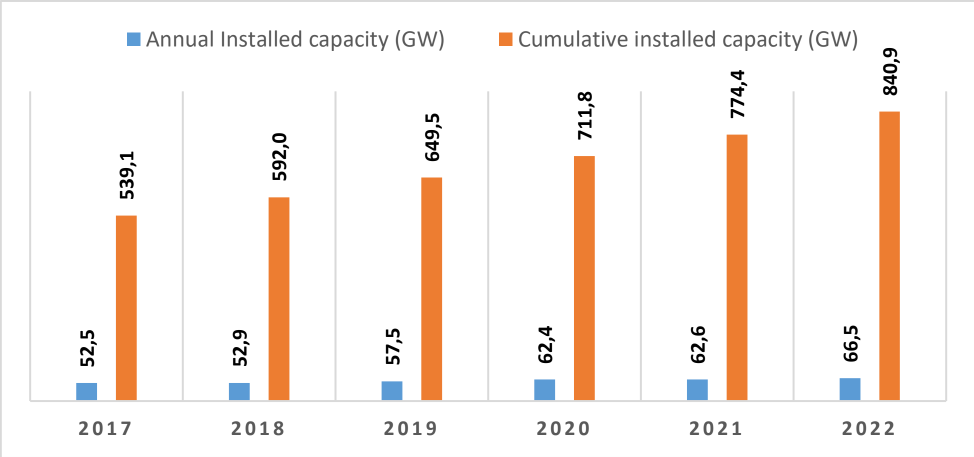

Figure 1. Annual and cumulative wind power forecast, reproduced from (Sawyer, 2017)

Air density in the arctic is higher compared to the other regions. According to (Tammelin and Säntti, 1996), air at -30 ºC is almost 27% denser than at 35 oC. Knowing that power output of a wind turbine is proportional to air density, the available wind power in Arctic is almost 10% higher than in other regions (Fortin, Perron et al., 2005). This fact makes the northern part of Norway a suitable place for further wind farm investments, such as such as Kvitfjel/ Raudfjel Wind Park located to the south of Tromsø, Norway and will be launched in November 2019. Kvitfjel wind farm consists of 67 wind turbines; the capacity of each wind turbine is 4.2 MW, which means a 281 MW of wind farm total capacity (Analyse, 2018). To develop an effective and safe offshore wind farm, the available experience of onshore wind farms plays an important role. For example, this information can be used to identify the potential hazards, possible failures, human performance, life cycle cost as well as inspection and maintenance efficiency.

2. ICE TYPES AFFECTING WIND FARMS

Ice accretion can be categorized into atmospheric icing and super structure icing caused by sea water sprayed on the wind turbine's structure during low temperatures, forming ice on it. Onshore structures like wind turbines and power lines are affected by atmospheric icing. Offshore stationary structures like offshore wind turbines and oil drilling platforms are affected by both types of icing (Battisti, Fedrizzi et al., 2006). Moreover, a third category of ice can be added to this classification of ice types affecting offshore wind turbines, which is land-fast and floating frozen sea water applying static and dynamic loads on the foundation and the tower of the wind turbine. (Figure 2) shows the classes of ice affecting onshore and offshore wind farms. Following is an analysis regarding which of the main components (Foundation, Tower, Nacelle and Blades) of a wind turbine operating under icing conditions are mostly affected by the different types of icing. The analysis is summarized in (Table 1). Moreover, different aspects of effects and risks are furtherly discussed in section 3.0.

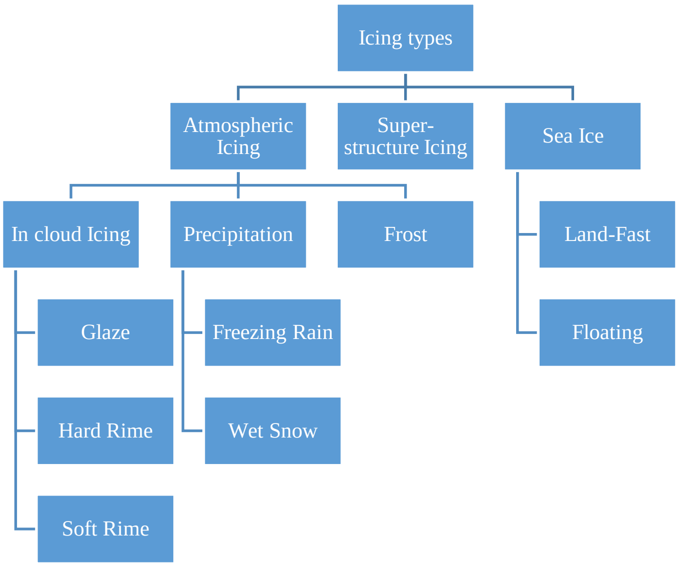

Figure 2. Ice types affecting onshore and offshore wind turbines

2.1. Atmospheric Icing

The process of atmospheric icing formation is that super cooled water particles in the form of droplets and drizzle or rain at temperatures ranging between -15 C^0 and 0 C^0 are found in the atmosphere (Ingvaldsen, 2017). These particles freeze immediately upon hitting a surface exposed to the atmosphere. Atmospheric icing can be divided into three types: In cloud icing, precipitation and frost (Parent and Ilinca, 2011).

The main types of interest when it comes to ice build-up or ice affecting wind turbines' structure and performance are in-cloud icing and precipitation icing. Frost has very low density and persistency and is believed to not cause any problems to wind turbines (Dalili, Edrisy et al., 2009). Therefore, frost is excluded from the following analysis and from Table 1.

2.1.1. In-cloud icing

includes rime ice and glaze ice. Several factors like liquid water content (LWC), median volume diameter (MVD) of water droplets, wind speed, pressure, temperature, etc. determine the form of in cloud icing (Parent and Ilinca, 2011).

Glaze ice: often associated with precipitation, and can be witnessed mostly on flat surfaces such as the top of the nacelle. It forms when portion of water droplets does not freeze immediately upon impact, but runs back on the surface and freezes later. The resulting ice density and hardness is very high (Parent and Ilinca, 2011), which makes it difficult to remove. Glaze can also, with the presence of wind, accumulate on vertical surfaces, which means it can accumulate on the tower and blades when facing the wind direction.

Rime ice is the most common type of in-cloud icing, and is classified into soft rime and hard rime. Soft rime has lower density and adhesion than hard rime. Hard rime is more difficult to remove. The probability and frequency of rime ice formation depends on the geographical location and elevation of the wind farm. Rime ice accumulates on objects facing the wind like the wind turbine's blades and tower, smaller diameter objects have higher collection efficiency of rime ice, such as cables, stair case railings and lattice structures which is a form of offshore wind turbines' towers (Ryerson, 2011).

2.1.1 Precipitation

Consists of rain or snow freezing upon impact with below zero C° surface, forming freezing rain and wet snow. The accretion rate from precipitation can be much higher than in-cloud icing. Wet snow and freezing rain accumulate mostly on all components of a wind turbine, especially on horizontal surfaces such as top of the nacelle. In case of severe precipitation, snow can add considerable weight to the wind turbine's structure. Snow and freezing rain accumulate also on the wind turbine's foundation and wind farm's roads, which makes it even more challenging for maintenance crews to reach wind turbines and perform the needed maintenance. Moreover, snow occurs during sea-spray icing and can enhance superstructure ice accumulation (Ryerson, 2011).

2.2. Super structure icing:

In an open sea where offshore wind turbines are installed, ice accretion becomes a complex phenomenon as both types of icing i.e. atmospheric and superstructure icing take place. However, the intensity of superstructure ice accretion on wind turbine blades depend highly on the elevation of the wind turbine above sea level and the type and size of the wind turbine. In case the offshore wind turbine elevation was relatively low, sea water can spray on the blade's tip when it is pointing downward, and if air temperature was below freezing, ice accumulates on the lower part of the tower and the blade tip. Sea spray ice can form on the wind turbine of up to 16 meters above the sea surface. However, it is expected that waves can carry sea spray above that limit (Battisti, Fedrizzi et al., 2006).

Table 1. Wind turbine main components affected by different types of icing

		Atmospheric Icing				Super Structure Icing (Sea Spray Ice)	Sea Ice
		In-Cloud Icing		Precipitation			
Configuration	Component	Glaze	Rime	Wet Snow	Freezing Rain		
Onshore Wind Turbine	Blades	✓	✓	✓	✓		
	Tower	✓	✓	✓	✓		
	Nacelle	✓		✓	✓		
	Foundation			✓	✓		
Offshore Wind Turbine	Blades	✓	✓			✓	
	Tower	✓	✓			✓	✓
	Nacelle		✓	✓	✓		
	Foundation					✓	✓

3. ICING EFFECT ON WIND TURBINE AND WIND FARM

Ice effects on a wind farm can be categorized into four main aspects:

- Mechanical equipment performance
- Operation and maintenance crew performance
- Wind farm accessibility
- Public safety risks

3.1. Mechanical equipment performance

Generally, an equipment performance is a function of reliability, maintainability (how easy the failed component can be repaired), which are both main factors comprising the availability performance of an equipment such as a wind turbine. Therefore, fast and frequent maintenance is important in keeping the wind turbine functioning and in minimizing the loss of power production. (Figure 3) shows the relationship between production performance and availability and functional performance.

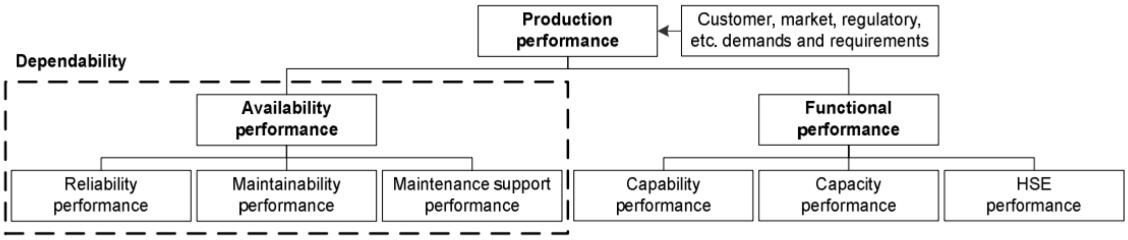

Figure 3: Production performance concept (Barabadi, 2011)

Wind turbine is complex system which is build up from different subsystems and components. Different types of the ice may affect the performance of these components in various ways. Icing may i) reduce reliability of wind turbine's components, ii) decrease their maintainability and iii) affect the accuracy of measuring devices, such as anemometers, wind vanes, temperature sensors and ice detectors. For example, 30% wind speed-reading error was recorded during the assessment phase of a site prone to icing conditions (Laakso, Holttinen et al., 2003).

Ice accretes on different parts of a wind turbine creating mass and aerodynamic imbalance, increases the structural loads on the turbine significantly, shortens the wind turbine's components' lifetime and increases blade generated noise (Elin Andersen, 2011). However, the most critical part of a wind turbine that can be affected by different types of the ice is the blade. Ice accretes differently from one blade design to another. The accretion process of ice is not uniform along the same blade; most accretion takes place on the tip and leading edge of the blade due to the existence of stagnation point there, see (Figure 4).

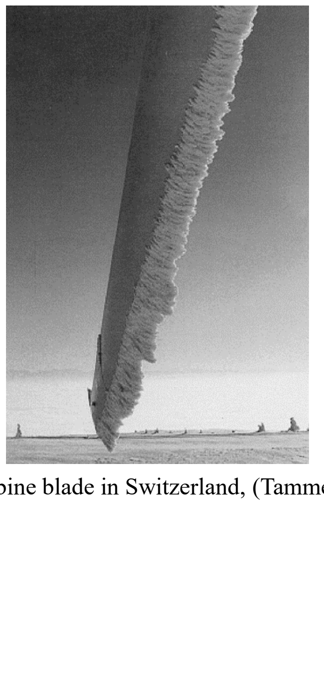

Figure 4. Iced turbine blade in Switzerland, (Tammelin, Bˆhringer et al., 2000)

Ice accretion leads to increase in blade's surface roughness and increasing the drag coefficient, leading to reduction in power production, which can be in range of 20-50% under sever icing conditions (Laakso, Talhaug et al., 2005). Continuing in operation under sever icing conditions and heavily accreted ice will harm the wind turbine and decrease its fatigue life as the wind turbine's components are subjected to excessive loads, which can be up to 50% of the blade's weight (Alsabagh, Tiu et al., 2013). Therefore, wind farm operators tend to shut down the wind turbine until the accreted ice is removed. Stoppage of the wind turbine can happen without the interference of the operator as the heavily accumulated ice can slow down the rotation of the blades to a point where the rotational speed reaches zero. (Figure 5) shows the percentage of main causes resulting in wind turbines' downtime in Finland between the year 1996 and 2008 for 72 wind turbines. As this figure shows, 4% of down time is caused by icing, (Stenberg and Holttinen, 2010). Icing increases the probability of failure of components and shortens the lifetime of the wind turbine, which is approximately 20 years (Echavarria, Hahn et al., 2008). Therefore, it is important to focus on icing issues and solutions.

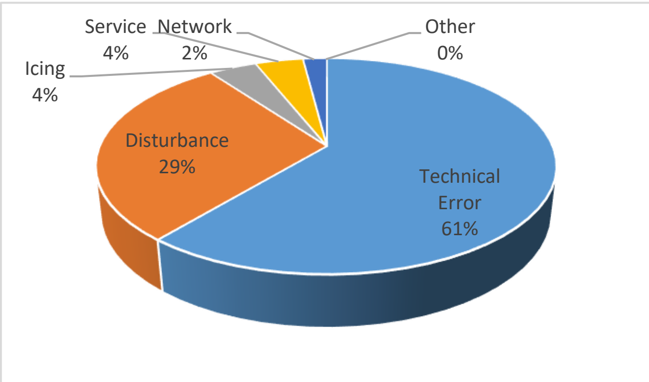

Figure 5. Percentage downtime causes, redesigned from (Stenberg and Holttinen, 2010).

Not only accreted ice on wind turbine's structure affects it, but also static and dynamic loads on offshore wind turbine's tower and foundation caused by land-fast and drifting sea ice pieces or even ice fields is another effect of icing. Drifting ice masses can hit the wind turbine's tower at velocities even higher than 1 m/s, causing damages to the tower and the foundation of the wind turbine through increasing the overturning moments (Battisti, Fedrizzi et al., 2006). Moreover, floating ice pieces hitting the tower increase the vibrations in the wind turbine's structure and can damage the tower due to the brittle behavior of low carbon steel that the tower is normally made of. In addition, sea ice accumulation can increase the corrosion process of the tower and the support structure (Morcillo, Chico et al., 2004). Also, in some cases the sea water around an offshore wind farm freezes completely, such state can last for several months, and will block the access to the wind turbines for maintenance purposes for a long periods of time and will therefore influence the output power from the wind farm.

3.2. Operator and maintenance crew performance

Ice affects the operator and maintenance crew performance as well as their safety. Icing can decrease worker's visibility and limit the entrance to the wind turbine due to snow accumulation on the roads within the wind farm and at the entrance of each wind turbine. (Figure 6) shows how workers' visibility is unclear during snowy weather conditions in

Fakken wind farm. Snow and ice can cause personnel slipping hazards. Snow can melt and refreeze on lattice structures and hatches (for example the nacelle hatch) (Ryerson, 2011), which makes it even more difficult to open them to perform maintenance. Icing increases the probability of accidents and injuries, and it is a reason for workers to be absent from work due to sick leaves and hospitalization.

Figure 6. Unclear visibility in Fakken wind farm due to snowy weather conditions (ingun, 2013)

Maintenance crews will need to climb up to the nacelle where most mechanical rotating equipment are inside in order to carry out the required maintenance including replacing worn parts, oil and filters change and carry out required inspections. In addition, cleaning blades off accreted ice requires the use of cranes and lift workers to pretty high elevations at which workers are subject to higher wind speeds and lower temperatures. Therefore, they are more prone to falling risks. Moreover, glaze ice and snow accumulate on top of the nacelle, which can undoubtedly be a reason to the risk of slipping, tripping and falling off the wind turbine. Snow accumulated on top of the nacelle can melt and fall down on the wind turbine's vicinity. Ice throw is another risk to wind farm's workers. Pieces of ice either are thrown off an operational wind turbine due to aerodynamic and centrifugal forces or they fall down in case the wind turbine was idle. In both cases ice pieces represent a hazard to personnel, animals, roads and surrounding structures including other wind turbines. With the aid of Monte-Carlo simulation, (Battisti, Fedrizzi et al., 2005) have shown that the odds to be hit by a piece of ice (between 0.18 and 0.36 kg), on a site with moderate icing conditions (5 days per year), is 1 in 10. This is valid for a person walking 10 hours under an operating turbine that uses a de-icing system, considering a total ice accretion of 75 kg/rotor per day.

(Tammelin, Bˆhringer et al., 2000), (Seifert, Westerhellweg et al., 2003) developed two equations (1&2) for measuring the distance of thrown ice pieces from an operational and idle wind turbine:

$$d = 1.5\,(D+H), \text{ when the wind turbine is operating.} \tag{1}$$

$$d = v\,\frac{D/2+H}{15}, \quad \text{when the wind turbine is idle.} \tag{2}$$

Where (d) is the throwing distance, (D) is the rotor blade diameter, (H) is the hub height and (v) is the wind speed at hub height in m/s.

Despite these equations are empirical, they do not consider all necessary parameters to calculate the throwing distance of ice pieces, such as relative wind direction and speed, temperature, humidity, speed of rotation of the blades, and also the initial position and velocity of the ice piece being detached from the wind turbine. All these mentioned parameters can be different from one site to another and from one wind turbine to another. Therefore, the severity of risks evolving from ice throw and ice fall is not the same for all wind farms, and should be thought of during the early stages of the design phase of the wind farm. International recommendations for Ice fall and ice throw risk assessments has been provided by (IEAWind, 2018) in which the development of trajectory models of ice throw and ice fall have been reviewed. Moreover, it is stated that the properties of the ice piece itself should be considered in order to understand the trajectory of a given particular ice piece.

3.3. Wind farms' accessibility:

Onshore wind farms are subject to snow accumulation on the roads and pathways leading to the wind turbines. Snow accumulation on staircase and wind turbine's door can reduce accessibility to the failed components and consequently it will reduce the availability and performance of the wind turbine. Snow drifting on road and against wind farm's buildings can limit movability, and make transportation of personnel and equipment a challenging task. Consequently, specialized vehicles will be needed.

Another solution is to employ a snow removal strategy, shown in (Figure 7). However, a feasibility study to determine which option to use must take place. The feasibility study should include parameters such as the cost of each solution, distance travelled (number of km of access roads), estimated annual snowfall accumulation and frequency, Health & Safety training, etc. noting that a combination of both solutions can be more feasible than depending on only one of them (IEAWind, 2018).

Figure 7. Snow removal employed (IEAWind, 2018)

Accessing offshore wind farms for maintenance and inspection purposes is carried out utilizing a transportation strategy as per (Nielsen and Sørensen, 2011). The strategy implies utilizing three options, taking into consideration that the utilization of these three options is furtherly limited in case of presence of ice:

- *Option 1*: always use boat to perform repairs.
- *Option 2*: repair as soon as possible (ASAP). In case of good enough weather conditions, a boat is used. Otherwise, a helicopter is used. The boat is assumed to require a mean wind speed less than 10 m/s and wave length less than 1.5m. While the helicopter is assumed to operate at wind speeds less than 20 m/s.
- *Option 3*: Risk-based alternative, where the cheapest type of transportation is used

whether it is a boat or a helicopter, assuming perfect weather forecast while performing the repair, which is not the case in reality. This option implies finding the first coming days where repair is possible by boat or helicopter, and the cost of repair and lost production until that day is found for each transport type.

Using a boat only to perform repairs will result in high costs due to high production loss, leading to large total costs, see (Figure 8). When ASAP option is used, most repairs are performed using a helicopter, which is the main contributor to the increase in the total costs of ASAP strategy option. In risk-based alternative strategy, most repairs are performed using the boat. The total costs are smallest for in risk-based option since the cheapest alternative should always be used, given perfect weather forecast.

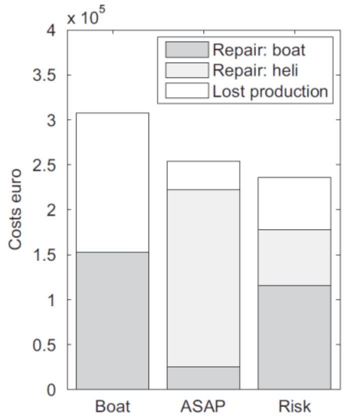

Figure 8. Cost of each transport strategy (Nielsen and Sørensen, 2011)

3.4. Public safety risks:

Wind turbines can cause external safety risks to public and wild life in the wind farm's surrounding area. As mentioned in (section 4.2), ice accreted on wind turbine's blades can detach and break in pieces and fly away, representing a risk to people, cars driving on roads near the wind farm, animals and other nearby public buildings and infrastructures, which can be described as public safety risks. Many countries define a buffer distance, also called setback distances, between wind turbines and existing public roads and infrastructure to reduce the safety risks from wind turbines to them (Larwood, 2005). For example, the setback distance defined in Denmark is four times the wind turbine's height.

Ice and snow accumulation on wind turbine's structure can decrease its fatigue life and might lead to components' failure. Complete or partial detachment of components, such as the wind turbine's blade or the nacelle/ rotor combination and the collapse of the tower are all modes of failure that can be caused by ice and snow accumulation on wind turbines and can result in safety risks to the surrounding area. A fault tree analysis was used by (Brouwer, Al-Jibouri et al., 2018) to describe an analysis of wind turbine failures that can lead to public safety risks. The analysis concluded that the most common failure was complete or partial loss of a blade, which is also the component that is most prone to ice accretion.

Following the snow removal strategy mentioned in (section 3.3) to remove snow off wind farm's roads, snow-blowing machines used for that purpose can increase the traffic around the wind farm and develop hazardous situations for users of nearby roads.

Using anti/de-icing chemicals, in particular glycol compounds (e.g. ethylene, propylene, diethylene, alkylene) to clear ice off wind turbine's blades has many disadvantages. For example, chemicals can create human safety and health problems, cause environmental harms, damage roads and vehicles and may not be cost effective (Back, Meyer et al., 1999). Anti-icing chemical compositions represent a threat to surface and ground water. De-icing chemicals can pollute drinking water, causing some diseases to humans. Also, chemicals increase water's salinity, alter its density, change the physical and ecological properties of lakes, and suppress convective motion of water in spring (Dai, Zhang et al., 2012). In addition, water polluted by ant/de-icing chemicals would harm living plants and animals in the surrounding areas.

4. RISK ASSESSMENT OF ICING EFFECTS ON WIND FARMS

Risk assessment represents an integral part of the risk management process, and it is defined as the overall process of risk identification, risk analysis and risk evaluation (ISO 31000, 2009). In the risk evaluation part, risks are prioritized using a risk matrix, similar to (Table 2).Upon ranking the risk and prioritizing them by comparing their level to other assessed risks, a decision can be made to determine the measures that should be considered to control and mitigate such risks.

Based on the expertise of the authors of this paper, a safety rating is assigned to onshore and offshore wind turbine's components as shown in (Table 2). The safety rating represents the impact of each component on the wind farm's safety in case of its failure, or other component-related hazards it can represent to the wind farm. For example, the blade is assigned a safety rating of (10), because of the risk of ice thrown from it, and the failure of it is of high safety concern in case of complete or partial detachment from the wind turbine. Tower collapse is less probable than blade failure and it accumulates less ice and snow, but it is more prone to sea ice collision in case of offshore wind farms, so it is assigned a rate of (9). The foundation is also prone to sea ice collision and so much snow accumulates on it in case of onshore wind farms. However, it is rare that snow accumulation will lead to a foundation failure. Therefore, the foundation is assigned a safety rating of (8). Nacelle/ hub detachment is less probable than blade detachment and the accumulated snow and ice on top of it is less than that on a blade or the foundation. Therefore, it is assigned value of (7). In addition, three important wind farms' safety aspects are considered in the table to investigate the impact of icing on them. Operator and maintenance crew safety and public safety are assigned a safety rating of (10) as they are of highest importance. Wind farm accessibility and logistics is assigned a safety rating of (9).

Each icing type is assigned a rate that represents the expected hazard it could have on the wind farm's safety in total. For example, glaze ice is assigned a rate of (10), because it affects many wind turbine's components like the blade, nacelle and tower and it accumulates on both onshore and offshore wind turbines. Moreover, glaze ice is more difficult to remove than rime ice. Therefore, rime ice is assigned a lower rate, which is (9). Freezing rain and wet snow have lower impact on the structure of wind turbines, but they have high impact on other functions related to the wind farm's safety. Their impact is higher on the foundation and the roads of onshore wind farms. Freezing rain and wet snow are assigned a rate of (8). Super structure icing affects only offshore wind farms. It affects the wind turbine's tower and part of the blades. Therefore, it is assigned a rate of (7). Sea ice affects the tower and foundation of offshore wind turbines and is assigned a rate of (6).

		Safety rating	Glaze	Rime	Freezing Rain	Wet Snow	Super Structure Icing	Sea Ice
	Icing type rating		10	9	8	8	7	6
Wind turbine's structure	Blades	10	100	90	80	80	70	60
	Tower	9	90	81	72	72	63	54
	Foundation	8	80	72	64	64	56	48
	Nacelle/ Hub	7	70	63	56	56	49	42
Wind farms' safety aspects	Operator and maintenance crew performance	10	100	90	80	80	70	60
	Public Safety	10	100	90	80	80	70	60
	Wind farm accessibility	9	90	81	72	72	63	54

Table 2. Risk-matrix comprising impacts of ice types on wind turbine's components and wind farms' safety aspects

5. DISCUSSION AND CONCLUSIONS:

Wind farms operating in ice proven areas experience multiple safety risks induced by different icing types. The effects of different icing types on onshore and offshore wind farms have been investigated and listed in (Table 1). Ice accretion on wind turbines' structure increases its components' failure process and creates risks such as ice throw and detachment of an entire or partial component, resulting in public safety risks. Moreover, ice and snow accumulation on the roads of a wind farm and land-fast and floating sea ice reduce accessibility to wind farms to perform the required maintenance, which affects the availability of the wind turbines and wind farm's overall power production. The effect of each icing type on wind turbine's components and wind farms' safety aspects have been illustrated in (Table 2).

The design of the wind turbine's components and foundation should be resistant to the damages and vibrations caused by ice accretion and sea ice. Cold weather packages and offshore corrosion protection systems have to be adopted. Inspection and maintenance planning should be designed to accommodate limited access to wind turbines due to seawater freezing.

Maintenance crews must receive the required training and work only when their health and psychological conditions are appropriate. Moreover, workers have to use proper equipment and clothing and follow regulations like using safety ropes and cranes and working in pairs, etc. There are techniques used to clean blades off accreted ice, such as the use of drones that can spray de-icing liquid to the blades.

There are other aspects of risks that can be witnessed in wind farms operating under icing conditions, which were not mentioned in this paper such as the effects of icing on wind farm's communication tools, and the effects of accreted ice on wind turbine's blades in increasing noise hazards. Further investigation of the effects of the use of chemical Anti/De-icing systems (ADIS) on the environment can be included.

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