SCIEPublish

Review

Icing Models and Mitigation Methods for Offshore Wind in Cold Climate Regions: A Review

Yingjie Gu, Guang Yin *, Marek Jan Janocha and Muk Chen Ong

Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, 4021 Stavanger, Norway; yingjie.gu@uis.no (Y.G.); marek.j.janocha@uis.no (M.J.J.); muk.c.ong@uis.no (M.C.O.)

* Corresponding author. E-mail: guang.yin@uis.no (G.Y.)

Received: 2 July 2024; Accepted: 19 September 2024; Available online: 23 September 2024

ABSTRACT: Offshore wind turbines (OWTs) in cold climate regions have become increasingly significant due to the abundant wind resources with the development of renewable energy. These areas offer considerable potential for the development of OWTs. Generating energy for communities in cold climate regions involves overcoming significant challenges posed by the remote and harsh environmental conditions. This review presents the state-of-the-art research regarding prediction models for ice accretion on wind turbine components. Furthermore, this review summarizes advanced mitigation solutions, such as cold-weather packages and ice protection systems, designed to address icing issues. The present study identifies critical knowledge gaps in OWT deployment in cold climate regions and proposes future research directions.

Keywords: Offshore wind turbine; Cold climate region; Ice accretion; Ice mitigation

1. Introduction

The trend of transition from fossil fuel to green energy and the growing emphasis on sustainable energy solutions have driven offshore wind turbines (OWTs) into the forefront of renewable energy strategies, especially in regions where harsh climates coincide with abundant wind resources as shown by the Global Wind Atlas in Figure 1. As the deployment of OWTs expands into these cold climate zones, maintaining their efficiency and reliability become increasingly challenging. Among these challenges, icing on the turbines becomes a critical threat to the operational safety, energy efficiency, and mechanical integrity of OWTs.

Icing usually occurs when supercooled water droplets in the atmosphere freeze upon contact with the surfaces of wind turbine blades and other components. When the ice accumulation reaches a critical level, it significantly alters the aerodynamic properties of the OWTs' blades and results in a reduction in the power generation. In addition, the mass of the accumulated ice on OWTs increase the mechanical loads, which lead to structural failures. Therefore, it is significant to understand the icing process and develop effective icing mitigation strategies for the efficient and safe operation of OWTs and wind farms in cold regions.

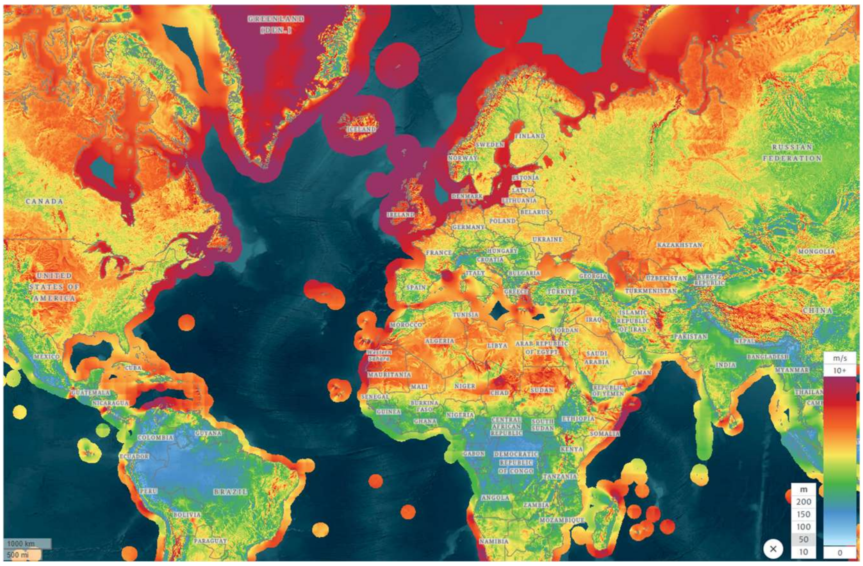

Figure 1. Global wind resources: mean wind speed map at 50 m [1,2].

Several studies on icing problems of wind turbines have been published to date. Fortin and Perron [3], Parent and Ilinca [4], Battisti [5], and Hu et al. [6] provided extensive insights into the occurrence of icing events, and ice mitigation systems were investigated by the latter three. Andersen et al. [7] took a broader perspective, investigating icing problems in wind power, with a focus on production losses and economic aspects. Contreras Montoya et al. [8] studied production losses by reviewing Computational Fluid Dynamics (CFD) based icing models. They summarized that the results of CFD simulation can be affected by the type of ice. Alsabagh et al. [9] and Afzal and Virk [10] conducted reviews focusing on the effect of ice accretion on energy losses and dynamic response of wind turbines. Sunden and Wu [11] presented a review regarding ice detection and ice mitigation techniques, as well as performed ice accretion simulation on an airfoil. Their simulation results indicated that temperature and wind velocity play key roles in influencing ice accretion the most. Wallenius and Lehtomäki [12] explored the potential and challenges of wind energy in cold climate regions, introducing techniques related to ice detection and mitigation. Fakorede et al. [13] reviewed various ice protection techniques and indicated ice protection techniques' efficiency. Lehtomäki et al. [14] gave an introduction to the ice accretion problem on wind turbines in the IEA Task report, covering resource assessment, icing models, ice shedding, ice detection, and mitigation systems. Another IEA Task reported by Bredesen et al. [15] addressed cold-climate topics related to term definitions, ice classification, relevant technologies, operation, and maintenance, as well as health and safety considerations. Madi et al. [16] investigated various combinations of available ice detection and ice mitigation techniques, their effectiveness was accessed. Martini et al. [17] presented a review of blade icing modeling methods, focusing on surface roughness and droplet trajectory modeling.

The objective of this review paper is to provide an overview of existing icing models and their effectiveness in predicting ice accretion on OWTs. In addition, this review also introduces relevant mitigation strategies designed to reduce the hazards of icing. Their effectiveness and applicability are discussed. This paper will provide stakeholders with the knowledge required for improving the performance and safety of OWTs in cold climates. Icing models range from empirical approaches, which can provide fast estimates based on analysis of measurement data and fundamental physics, to numerical simulations which are capable of capturing the complex interactions between the airflow, water droplets, and turbine surfaces. Appropriate selection of icing models for researchers and engineering practitioners should be based on the consideration of accuracy, computational cost, and the operation conditions of OWTs. Their effectiveness and applicability are discussed. The organization of the review paper is as follows: Section 2 will introduce the icing process and the key parameters influencing the process; Section 3 focuses on the comparison and evaluation of different predictive models for icing; Section 4 introduces existing mitigation strategies for icing problems. Discussion and recommendations for future study will be provided in Section 5.

2. Environmental Conditions of Cold Climate Regions

2.1. Cold Climate Regions

Cold climate regions refer to the regions where atmospheric icing occurs frequently, or temperatures drop below the specified operational limits [14]. The cold climate regions consist of two different sub-regions, i.e., low-temperature regions and icing climate regions and their characteristics are shown in Figure 2. Low-temperature regions refer to the regions where air temperature drops below −20 °C for more than 9 days annually or where average annual air temperature is below 0 °C. Icing climate regions, on the other hand, are characterized by instrumental icing occurring for over 1% of the year or meteorological icing lasting for more than 0.5% of the year. Here, instrumental icing in the figure denotes the time frame in which ice is observed on a structure or a meteorological instrument. Meteorological icing denotes the time frame during which meteorological conditions can cause ice accretion.

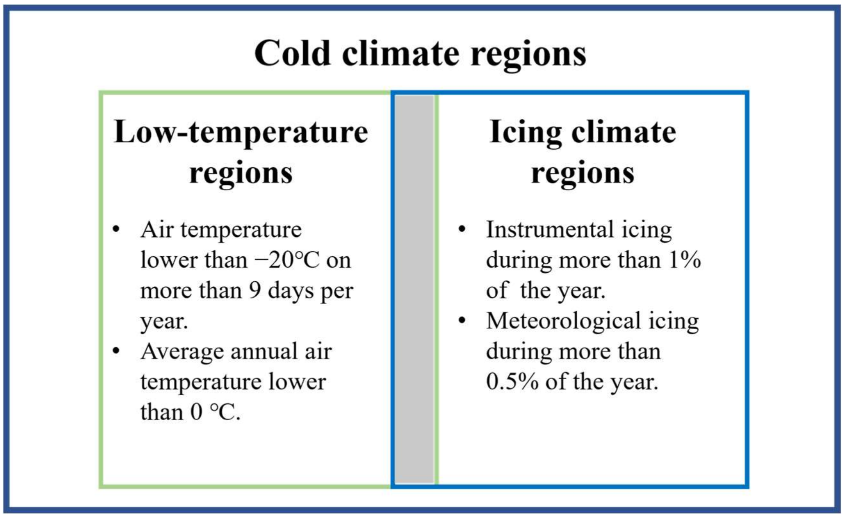

Figure 2. Characteristics of low-temperature and icing climate regions [18].

IEA proposed an ice classification to indicate the long-term ice severities at a given site [14]. Here, the ice severity is defined as the icing frequency resulting from in-cloud icing. The IEA ice classification employs two simplified assumptions. Firstly, it assumes that meteorological and instrumental icing occur simultaneously. Secondly, the classification is applicable to unheated structures. IEA Ice Class 1 presents minimal icing risks at the given site. IEA Ice Class 2 presents a potential for moderate icing risks, whereas IEA Ice Class higher than 2 means substantial icing hazards [6].

Figure 3 shows the IEA Ice Class map WIceAtlas [19]. This map is built based on over 20 years of measurement data to predict icing severities for the next 20 years. It also shows a higher ice class for regions with higher latitude. Countries such as Canada, Norway, Sweden, Finland, and Russia usually experience high icing risks. The study conducted by Battisti [5] indicates that wind power installations in North America and Europe experience high icing risks, affecting 72% and 94% of the total wind turbines, respectively. This matches well with the ice class map shown in Figure 3. The significant risks, including reduced power production, structural failure, and ice throw and fall behaviors, highlight the importance of developing accurate icing prediction models and effective ice mitigation techniques for wind power systems.

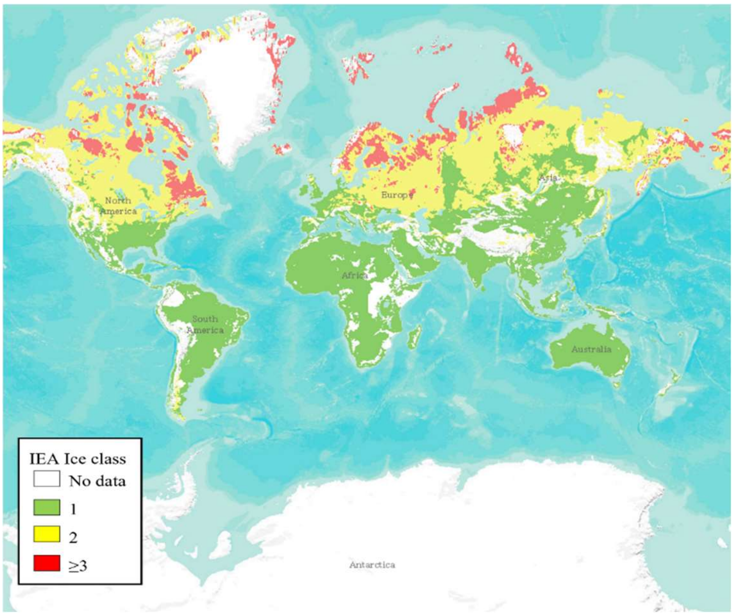

Figure 3. Ice class map provided by VTT WIceAtlas [20].

2.2. Icing Process

2.2.1. Icing Definition and Ice Type

According to Battisti [5] and Mustafa et al. [21], icing on wind turbines occurs as ice shapes accumulate on both stationary and moving parts of the wind turbines. Icing or ice accretion includes both atmospheric icing and sea spraying. The atmospheric icing occurs when supercooled water particles are present in the atmosphere [22]. The sea spraying is induced by seawater splashes on structures or seawater in wind [5]. Based on the formation processes, the atmospheric icing can be generally divided into in-cloud icing and precipitation icing. Both of the two icing phenomena pose significant concerns for the structural health and the operational performance of wind turbines [23]. Supercooled water droplets within clouds or fog can cause the in-cloud icing, which often persists over extended periods. In contrast, freezing rain and wet snow are two main factors leading to precipitation icing [24]. The two main ice types of icing events on OWTs, rime ice and glaze ice are introduced.

(a) Rime ice

Rime ice is characterized by a rough, granular texture, which is a consequence of entrapped air content. When wind turbines are subjected to in-cloud icing, the blade surface experiences the impact of supercooled droplets, leading to immediate freezing upon contact, as shown in Figure 4a. The rapid freezing traps micro-sized air bubbles within the ice, creating voids between ice grains. This phenomenon causes rime ice to exhibit a distinctive milky or white appearance, as highlighted by Fortin and Perron [3]. The formation of the rime ice is influenced by several key factors, including the wind speed, the shape of the structures, the liquid water content (LWC), and the air temperature [24].

(b) Glaze ice

Glaze ice forms at an air temperature ranging from −10 °C to 0 °C, with higher LWC levels and larger sizes of airborne water droplets than those of the rime ice [3]. The formation of glaze ice is shown in Figure 4b. According to Hu et al. [6], this formation process results in the typical appearance of the glaze ice: clear, smooth, transparent, and high density. The adhesion strength of the glaze is larger than that of the rime ice. The formation of glaze ice is primarily influenced by the precipitation rates, the wind speed, and the air temperature [24].

Based on the findings of Hudecz et al. [25], the rime ice tends to have a weaker influence on wind turbine aerodynamic performance, compared to the glaze ice.

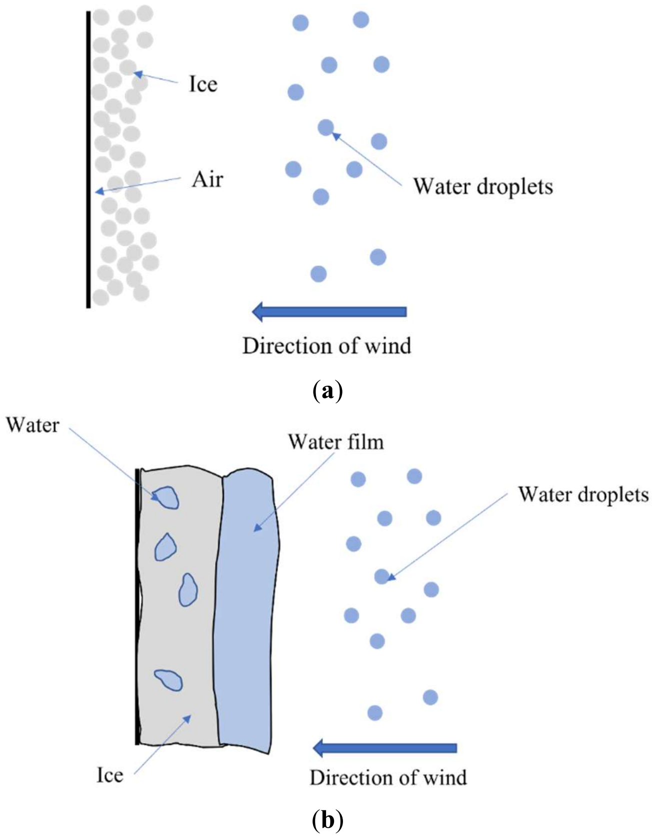

Figure 4. The formation process of ice: (**a**) Rime ice, (**b**) Glaze ice.

2.2.2. Key Parameters

Ambient temperature, LWC, and Median volume diameter (MVD) have a significant influence on the severity of icing phenomena on wind turbines. An overview of these key parameters is presented in the following subsection.

(a) Ambient temperature

In cold climate regions, ambient temperatures often remain below the freezing point. Icing is typically expected to occur between 0 °C and −15 °C. At temperatures below −15 °C, liquid water droplets may freeze and snow formation may occur. This phenomenon reduces the likelihood of freezing rain icing. The droplet size and supercooling extent are also influenced by the ambient temperature [26]. The reduction in ambient temperature can lead to a decrease in the formation probability of supercooled water droplets, which subsequently reduce the icing severity on the turbine.

(b) LWC

LWC is defined as the water concentration in the air. In-cloud measurements indicate a range of the LWC from 0 g/m^3 to 5 g/m^3 [5]. According to Cober et al. [27], the LWC tends to decrease as droplet size increases. As pointed out by Fortin and Perron [3], an increase in the LWC leads to increasing icing severity since the ice shapes that accrete become larger under a higher value of the LWC. A widely accepted classification system for icing severity ranges from light, moderate, severe to extreme, corresponding to the LWC values of 0.04, 0.07, 0.2, and 0.36 $g \cdot m^{-3}$ [28,29].

(c) MVD

MVD represents the median droplet size, which is defined as the droplet diameter below which half the mass (or volume) of water is contained [30]. The median size of droplets plays an important role in affecting droplets trajectories and the efficiency of water collection upon impact on the structures [31]. The increase in the water droplets' diameters leads to a larger inertia than that of small water droplets. Then, water droplets with large diameters follow a straighter path on the structure surfaces, hitting directly on the airfoil leading edge, which leads to a significant ice accretion on the wind turbine blade [6].

3. Advancements in Addressing OWT Icing Problems

3.1. Empirical Models of Ice Accretion

Empirical models for ice accretion prediction are generally developed based on statistical analysis of observed data. Makkonen model is a commonly used ice accretion prediction model, which originally aimed to calculate the ice accretion rate on cylindrical structures [32]. The icing rate is calculated using:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \eta_1 \eta_2 \eta_3 \cdot w \cdot A \cdot v$$

where $\mathrm{d}m/\mathrm{d}t$ is the icing rate per unit projection area; A is the cross-sectional area; η_1 is the collision efficiency; η_2 is the sticking efficiency; η_3 is the accretion efficiency; w is the mass concentration; v is the particles velocity relative to the structure. A detailed explanation of these factors can be found in reference [32].

Several studies investigated turbine icing problems utilizing this model [33,34]. Dierer et al. [34] simulated the ice accretion on two Enercon E-82 turbines using the Makkonen model. Their results revealed that the Makkonen model slightly overestimated the lasting time of the icing event. This discrepancy was attributed to the exclusion of the ice reduction in the model (e.g., ice melting and sublimation). Jolin et al. [33] used the Makkonen model to investigate factors affecting the ice accretion and identified the wind speed and turbine rotor RPM as the main factors.

The predictive accuracy of the Makkonen model relies heavily on the accurate measurements of input parameters (e.g., LWC, MVD, and cloud droplet density). Furthermore, the Makkonen model only considers the growth of ice, excluding both ice melting and sublimation. This limitation may overestimate the severity of the ice accretion [11]. An improved Makkonen model was introduced by Davis [35] to overcome these limitations. The improved model incorporates ice ablation and considers the blade's relative velocity, which is relatively high at the blade tip. Additionally, the rotation of the cylinder described in the original model has been removed to better align with the real wind turbine. These improvements resulted in a more precise representation of the actual conditions experienced by the wind turbine blades.

3.2. Numerical Models of Ice Accretion

Numerical models for ice accretion prediction are based on mathematical equations that describe the underlying physical processes governing the icing. For accurate ice accretion modeling, the computational approach requires a systematic sequence of four key modules: aerodynamic calculations, particle trajectory calculations, thermodynamic analysis, and ice geometry.

Numerical Tools

Several two-dimensional and three-dimensional ice accretion simulation tools have been developed to study the icing problem. The following subsection presents an overview of the most commonly used numerical models.

(a) LEWICE

LEWICE is a two-dimensional ice accretion simulation software [36]. The two-dimensional panel method is used to obtain the flow field. The panel method removes constraints associated with the conformal mapping technique, particularly when dealing with thick airfoils and high angles of attack [37]. The particle trajectory is calculated using the Eulerian method. The atmospheric parameters and the meteorological parameters are used as inputs to simulate the shape of the accumulated ice.

Several studies have been carried out using the LEWICE code [11,36,38,39]. Etemaddar et al. [38] investigated the ice accretion on the NREL 5 MW turbine blade. They combined the LEWICE code with Ansys Fluent. The dynamic responses were simulated using the HAWC2. The study revealed that the ice load increases with the increasing LWC, MVD, and relative wind speed, while the ice load reduces with the increasing blade thickness. Several assumptions were made by Etemaddar et al. [38], such as a uniform atmospheric icing as well as the neglection of the three-dimensional effects and the possibility of the ice detachment from the blade. These assumptions could lead to deviations between the results and the measurements. Sunden and Wu [11] studied the ice accretion on an airfoil using the LEWINT code, which integrates the LEWICE code with a user interface, analysis tools, and automated plotting capabilities. The main factors influencing the ice accretion were found to be air temperature and the wind velocity, as indicated by the results. High-resolution atmospheric data were used as input for the LEWICE code by Montminy et al. [39] to simulate ice accretion on the nacelle. The simulation results showed that, compared to the Makkonen model, the LEWICE model provided much better agreement with the actual camera observations of the ice accumulation on the nacelle. In addition, their study also reviewed that the wind orientation and MVD had a significant influence on the ice accretion prediction [39].

In summary, the LEWICE code is capable of performing more realistic ice accretion predictions than the Makkoen model. The limitation is that this model has only been validated in a high Reynolds number regime (Re > 2 × 10^5) [36,40]. In addition, this code cannot accurately predict the glaze ice and the mixed ice.

(b) TURBICE

TURBICE is a two-dimensional simulation program for the ice accretion [41]. The program is capable of simulating the rime icing and the glaze icing. This program simulates the flow field around airfoil cross-sections using the panel method, and the trajectory of particles is calculated using the Lagrangian droplet tracking technique.

Several studies have been carried out using the TURBICE program to simulate the ice accretion on the blades [25,42]. Homola et al. [42] observed a reduction in the lift coefficient across all scenarios with varying droplet sizes and temperatures. The results of CFD simulations suggest that the horn-type glaze ice shape leads to a substantial decrease in lift and an increase in the drag coefficient of the blade. Hudecz et al. [25] studied the impact of ice accretion on a NACA 64-618 airfoil. They compared the results obtained from the TURBICE program with the actual ice profiles from wind tunnel tests. The simulation results are in good agreement with the actual results. The study found a nearly linear relationship between the lift and drag coefficient of the airfoil. Furthermore, the mixed ice condition of both rime and glaze ice had a significant influence on the performance of turbine compared to the purely rime ice condition. The presence of mixed ice conditions could potentially reduce the accuracy of the prediction results obtained by the TURBICE program.

(c) FENSAP-ICE

FENSAP-ICE is a three-dimensional ice accretion simulation software that considers the main ice processes. A flow solver based on Reynolds-averaged Navier–Stokes (RANS) is employed to solve the flow field. The impingement is calculated using the Eulerian method. The growth of ice is modeled by solving partial differential equations (PDEs).

Manatbayev et al. [43] studied ice accretion on a vertical-axis wind turbine using the FENSAP-ICE program, considering the centrifugal and Coriolis forces. The predicted ice shapes on the blades were validated against experimental results and showed good agreement. The results indicated that, when compared to the glaze ice condition, the impact on aerodynamic performance is relatively minor in the case of the rime ice condition. This is attributed to the smooth ice shape generated by the rime ice condition on wind turbine blades. Yang et al. [44] predicted the ice accretion on a 5 MW OWT. The flow field was calculated using Fluent. The dynamic response was simulated using FAST and Orcaflex. The predicted ice shape closely matched the measurements from wind tunnel tests. The study identified that the changes in the wind speed moderately influenced rime icing, and temperature variations had limited effect. The results of the FENSAP-ICE program match well with the experimental data. Moreover, differences between the results of the LEWICE and the FENSAP-ICE could be insignificant [40,45].

3.3. Prediction Models for Energy Loss Caused by Icing

Due to the nonuniform ice accretion process, icing events can change the mass and shape of blades or other components. Consequently, this imbalance of mass due to the ice accretion and the locally changed aerodynamic properties of the blades can cause increased local loads on turbines, reducing the turbine's power efficiency. Tammelin et al. [46] pointed out that annual energy production can decrease by 20–50% under severe icing conditions compared to that under ice-free operating conditions. A study involving 517 turbines with a combined capacity of 682 MW showed that, the total produced energy experienced a loss of 18,966 MWh over 29 months due to the turbine blade icing [47]. Dalili et al. [23] estimated that approximately 20% of the performance is lost annually at sites with severe icing occurrence for the operations in stall-regulated and variable-speed modes. Swenson et al. [48] established a statistical power loss prediction model based on field measurements to estimate the icing-induced energy losses.

The most common tools for energy loss prediction caused by icing are the two-dimensional CFD-BEM (Computational fluid dynamics-Blade element momentum) method and the three-dimensional CFD method. For the first method, the ice accretion and aerodynamic coefficients are simulated using CFD. Then, the aerodynamic coefficients are used as input data for the BEM model to obtain the power curve. The procedure is shown in Figure 5. Notably, the BEM theory assumes that no aerodynamic interaction exists between blade sections and three-dimensional effects are not taken into consideration. The two-dimensional CFD-BEM method has a lower computational cost than the three-dimensional CFD method. Yet, this method may underestimate the aerodynamic coefficients and power output. The underestimation of the aerodynamic coefficients may be due to neglecting spanwise flow, which fails to predict the flow separation [8].

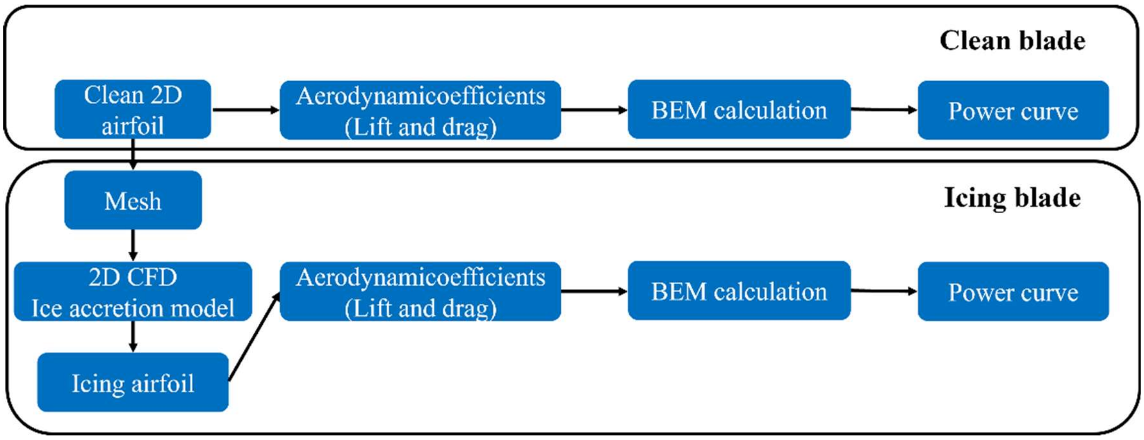

Figure 5. The procedure of the energy loss prediction with coupled CFD-BEM method.

Despite the high accuracy of the three-dimensional CFD method, its applications are limited by the high computational costs. In addition, studies on energy loss using the three-dimensional CFD method are conducted in a quasi-steady state (i.e., the water and air phases in two-phase flow are calculated using a steady solver). Thus, the performance of wind turbines under an unsteady state is still unknown. Moreover, to improve the computational efficiency, the analyses of energy loss usually focus on one blade, which does not consider the interaction among the blades. Switchenko et al. [49] compared the results of the two-dimensional and three-dimensional CFD simulations of a complex icing event. The two-dimensional simulations produced results comparable to the three-dimensional ones, but with low computational cost. As pointed out by Sagol [50], the simulation result of three-dimensional CFD closely match the experimental results, while the two-dimensional simulation results showed a deviation of 25% in the calculated torque of the blade. Sagol [50] also indicated that the three-dimensional CFD simulation takes more than 10 times longer than the two-dimensional CFD simulation.

In summary, the two-dimensional CFD method has a lower computational cost compared to the three-dimensional method, providing a significant advantage when dealing with long-time and complex icing events where computational resources are limited. Although the results from the two-dimensional CFD method are generally comparable to those of the three-dimensional method, the latter may still be preferred where higher accuracy and the capture of the three-dimensional effects are crucial.

4. Solutions for Icing Mitigation on OWT

4.1. Cold Weather Packages

Cold weather packages, which provide heating to turbine components, can mitigate the negative effects of icing events and expand the operating temperature range of the wind turbines, as illustrated in Figure 6. Battisti [5] pointed out that cold weather packages are seldom provided for small and micro wind turbines, which are typically designed to remain stationary under extreme conditions.

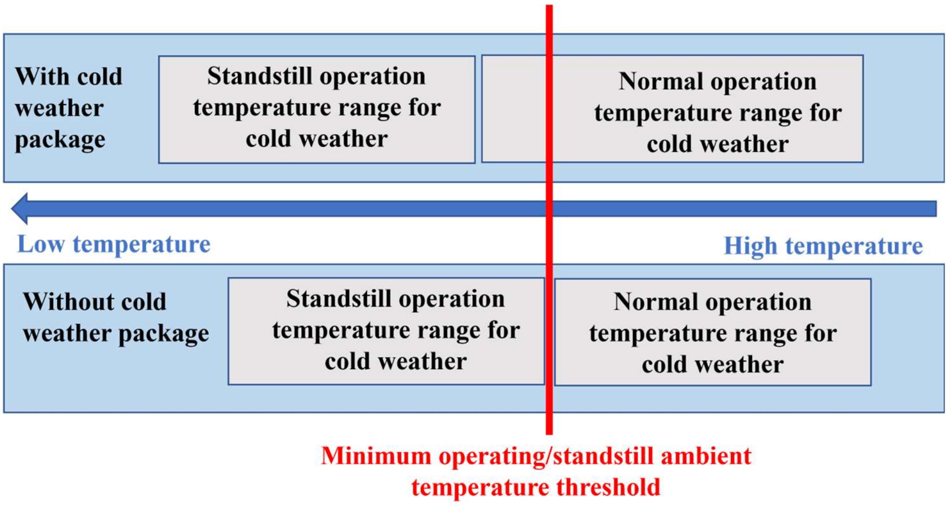

Figure 6. The performance of wind turbines in cold climates with and without cold weather packages.

Hu et al. [6] summarized that, for wind turbines with a capacity larger than 1 MW, the minimum operating temperature without the cold weather package is −10 °C, while the minimum survival temperature without the cold weather package is −20 °C. If the cold weather package is employed, the minimum operating temperature is −30 °C, while the minimum survival temperature is −40 °C. Figure 7 shows the typical composition of cold weather package.

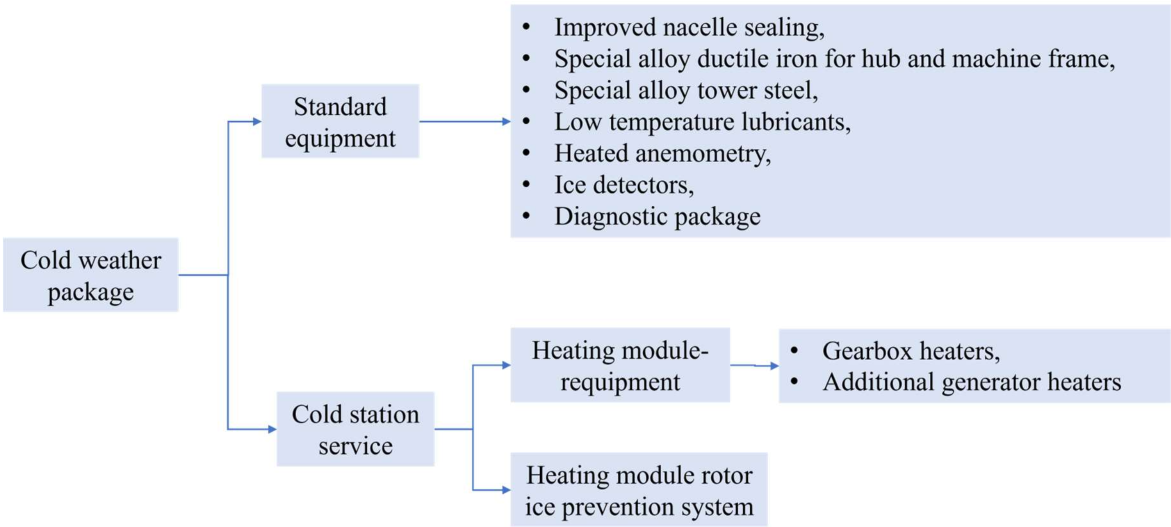

Figure 7. Typical composition of the cold weather package [5].

4.2. Ice Protection Systems

Ice protection systems include anti-icing systems and de-icing systems. Here, the anti-icing systems aim at preventing ice formations during the operation of turbines. The de-icing systems are used to remove ice that has already accumulated to a certain extent. The main difference between an ice protection system and a cold weather package lies in their objectives. The cold weather packages enable turbine components to function in low temperatures, whereas ice protection systems specifically address icing events on wind turbines.

Fakorede et al. [13] performed a comprehensive comparison of the performances of different ice protection systems, as shown in Table 1. The microwaves and thermal coating techniques are energy efficient, particularly in mitigating moderate icing events. However, they may be less suitable for heavy icing. The resistive heater and hot air injection techniques may not provide complete coverage for all blades. The power consumption of the resistive heater and hot air injection techniques is higher than that of microwaves and thermal coating techniques. Additionally, the heating resistance techniques are equipped with lightning protection system, while the other techniques are not. The hot air injection techniques, however, are unaffected by lighting.

The principles, advantages, and disadvantages of these ice protection systems are listed as following:

Table 1. The comparison of ice protection systems [13].

Ice Protection Systems	Effectiveness (1–5)	Cost (1–5)	Energy Consumption (1–5)	Lightning Protection System
Ice-phobic coating	2	2	N/A	Not equipped
Black paint	1	1	N/A	Not equipped
Heating resistance	4	4	3	Equipped
Hot air injection	4	5	4	Not affected
Pneumatic technique	5	4	1	Not equipped
Ultrasonic technique	5	3	2	Not equipped

(a) Ice-phobic coating

Ice-phobic coating is commonly used to minimize ice adhesion strength on blade surfaces. Erosion and pitting may negatively affect the effectiveness of this technique. This may further lead to increasing blade surface roughness. Assessing the durability and reusability of these coatings is crucial. The ice-phobic coating technique was applied by Ørsted in a wind pilot project located in Jämtland, Sweden [7]. The observations made during the pilot test indicated that the application of the ice-phobic coating alone was insufficient for effective anti-icing [7].

(b) Black paint

Black paint can be used to heat the blade during daylight. This technique can complement ice-phobic coating, which is suitable for wind parks where icing events are infrequent, or sunlight exposure is sufficient. Maissan [51] combined the black paint and the ice-phobic coating on the turbine blades with heaters, resulting in improved power production compared to using heaters alone. However, the black paint alone is often insufficient to prevent ice accretion [52].

(c) Heating resistance

Heating resistance technique creates a water film to induce ice shedding through the centrifugal force [53]. This energy consumption of this technique is relatively low compared to the overall energy production of the turbines [54]. The heating power is generally adequate, though challenges arise with the supercooled rain [55]. Direct heating provides nearly 100% thermal efficiency [56]. Furthermore, the energy demand of the heating resistance technique does not increase with the blade size [55].

(d) Hot air injection

Hot air injection technique creates a water film between the surface and ice with hot air [52]. In addition, waste heat of the turbine can also be used as a supplement [57]. This technique presents several advantages. Hot air injection technique uses wind turbine waste heat to increase efficiency. It is environmentally friendly and not susceptible to lightning [58,59]. Due to the uneven heat distribution, the thermal efficiency is compromised [57,59]. In extremely low temperatures, the technique's application is limited by the substantial heating power [60,61].

(e) Pneumatic technique

Pneumatic technique uses air chambers to distort the ice [60–62]. This technique, known for its simplicity and efficiency, has many years of experience in the aerospace field. However, its installation can be complex, potentially disrupting the aerodynamics of the blade. Maintenance demands may also contribute to higher costs [62].

(f) Ultrasonic technique

Ultrasonic technique aims to disconnect the adhesion bonds between ice and the surface of the blade [63,64]. This technique provides advantages of low cost and high efficiency. Its effectiveness diminishes during heavy icing events due to output limitations and uncertainties with larger water droplets. Furthermore, its technical structure restricts surface coverage along the blade length [16].

4.3. The Evaluation and Suggestion of Ice Protection Systems

Lehtomäki et al. [14] conducted a benchmark test of several commercial ice protection systems at four sites, involving wind turbine equipment manufacturers Dongfang, Enercon, Nordex Group, and Vestas. The ice protection systems used in this benchmark test were based on the hot air injection technique. The test sites A, B, and D were located in the Nordics, while site C was located in central Europe. The IEA Ice Class of sites A, B, C, and D are 4, 3, 2 and 4, respectively. The benchmark test showed that ice protection systems can protect wind turbines from icing events and reduce energy loss [14].

Fakorede et al. [13] summarized several promising ice protection systems based on the icing severity and the size of the wind turbine. It was suggested that the black paint and active pitch control are suitable for wind turbines that are less than 3 MW, and the resistive heaters can be applied to wind turbines that are higher than 3 MW.

5. Discussion and Future Work

Challenges and risks arising from icing hinder the commercial deployment of OWTs in cold climate regions. To review the icing problem of OWTs, the authors have taken into account the environmental conditions of cold climate regions and recent advancements in addressing these issues.

In the aspect of the environmental conditions of cold climate regions, the terms and concepts related to cold climate regions, icing events, and sea ice are introduced. The physical mechanisms and key parameters of ice accretion are reviewed. Lower ambient temperatures, higher LWC, and MVD tend to increase the severity of icing events, thereby negatively influencing the OWT performance in cold climate regions.

In the aspect of the advancements in addressing OWT icing problems, a summary of icing prediction models for OWT is presented in Table 2. Empirical formula models can provide faster runtime than numerical models, though they may sacrifice accuracy. However, both types of models exhibit distinct limitations. For example, the Makkonen model does not consider real blade geometry and ice ablation processes. On the other hand, numerical models often require a high computational cost and may be restricted in their application scope. The two-dimensional CFD-BEM methods have higher computational efficiency than the three-dimensional CFD methods when dealing with long-time and complex icing events while the three-dimensional CFD methods can capture three-dimensional effects with a high accuracy. To mitigate icing on OWT, solutions such as cold weather packages and ice protection systems are implemented.

Table 2. Overview of icing prediction methods for OWT.

Model or Code	Main Inputs	Ice Type	Evaluation of the Model and Code		Reference
			Efficiency	Summarized Features	
Makkonen model	Cross-sectional area, LWC, relative velocity, wind speed, cylinder diameter, droplet diameter, temperature	Rime ice, Glaze ice	High	• Primarily suitable for estimating ice accretion on a rotating cylinder rather than on a turbine blade • Not consider the ice ablation • Short run time	Makkonen [32]
iceBlade (Improved Makkonen model)	Cross-sectional area, LWC, relative velocity, wind speed, cylinder diameter, droplet diameter, temperature	Rime ice, Glaze ice	High	• Consider the ice ablation • Provide short-term icing forecast • A better representation of the blade • Short run time	Davis [35]
LEWICE	Temperature, pressure, wind velocity, LWC, relative humidity, droplet diameter	Rime ice, Glaze ice (low accuracy)	Low	• Only validated in a high Reynolds number regime (Re > 2 × 10^5) • Cannot predict glaze ice and mixed ice accurately • More realistic ice accretion predictions than the Makkoen mode	Wright [36]
TURBICE	MVD, LWC, wind speed, rotating speed, pitch angle, air temperature, air pressure and icing time	Rime ice, Glaze ice	Low	• Cannot predict mixed ice • Differences between the results of LEWICE and FENSAP-ICE are moderate	Makkonen et al. [41]
FENSAP-ICE	MVD, LWC, relative velocity, attack angle, air temperature, air pressure, icing time	Rime ice, Glaze ice	Lowest	• Three-dimensional CFD solver contains all ice processes	Habashi et al. [65]

To promote and accelerate the deployment of OWTs in cold climate regions, the following future research directions are recommended:

1. Advanced icing prediction methodology: It is crucial to regularly update icing prediction models to include the geometric details of OWT blades. A comprehensive understanding of the transient behaviors of different types of ice during ice accretion is necessary. Furthermore, integrating empirical formulas with phenomenological coupled icing models is recommended to achieve a balance between accuracy and computational efficiency.

2. More effective solutions: The combination of several ice protection systems is recommended to counterbalance the negative influence of their respective technologies when addressing icing problems. For example, a well-applied pneumatic technique, though expensive, can be combined with a low-cost and relatively moderate ultrasonic technique to reduce costs.

6. Conclusions

The abundant wind resources in cold climate regions provide unique opportunities for deploying and developing OWTs. The harsh environments of these areas pose significant challenges that must be addressed to supply energy to communities effectively. The significance of icing prediction models and mitigation strategies cannot be overstated, as they play a key role in identifying and reducing potential hazards for OWTs in cold climates.

The present review has highlighted the critical importance of accurate icing prediction models and effective mitigation strategies for the deployment of OWTs in cold climate regions. By systematically evaluating existing models, both empirical approaches and numerical simulations have been identified as valuable tools for predicting ice accretion, each offering unique benefits in terms of accuracy, computational efficiency, and adaptability to various operational conditions. The development of these models enhances the feasibility of deploying OWTs in such challenging environments. Moreover, the implementation of the cold weather packages and the ice protection systems can effectively reduce the ice accretion, enabling OWTs to operate at lower temperatures.

In conclusion, OWTs provide a promising solution to fulfill energy needs in cold climate regions while minimizing the environmental impact. By overcoming logistical hurdles and optimizing turbine design and deployment, cold climate regions can look forward to a more sustainable and cleaner energy future.

Author Contributions

Conceptualization, Y.G., G.Y., M.J.J. and M.C.O.; Methodology, Y.G., G.Y., M.J.J. and M.C.O.; Formal Analysis, Y.G., G.Y., M.J.J. and M.C.O.; Resources, M.C.O.; Data Curation, Y.G., G.Y., M.J.J. and M.C.O.; Writing—Original Draft Preparation, Y.G.; Writing—Review & Editing, Y.G., G.Y., M.J.J. and M.C.O.; Visualization, Y.G., G.Y., M.J.J. and M.C.O.; Supervision, G.Y., M.J.J. and M.C.O.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Funding

This research was funded by Research Council of Norway grant number 332034 (ImpactWind Sørvest project).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Available online: https://globalwindatlas.info/en (accessed on 20 July 2024).
2. Davis NN, Badger J, Hahmann AN, Hansen BO, Mortensen NG, Kelly M, et al. The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application. *Bull. Am. Meteorol. Soc.* **2023**, *104*, E1507–E1525.
3. Fortin G, Perron J. Wind turbine icing and de-icing. In Proceedings of the 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, Orlando, FL, USA, 5–8 January 2009; p. 274.
4. Parent O, Ilinca A. Anti-icing and de-icing techniques for wind turbines: Critical review. *Cold Reg. Sci. Technol.* **2011**, *65*, 88–96.
5. Battisti L. *Wind Turbines in Cold Climates: Icing Impacts and Mitigation Systems*; Springer: Cham, Switzerland, 2015.
6. Hu H, Gao L, Liu Y. *Wind Turbine Icing Physics and Anti-/De-Icing Technology*; Elsevier: Amsterdam, The Netherlands, 2022.

7. Andersen E, Börjesson E, Vainionpää P, Undem LS. Wind Power in Cold Climate. WSP Environmental. 2011. Available online: https://www.nordicenergy.org/wp-content/uploads/2012/01/wind_power_in_cold_climate_-_final_report.pdf (accessed on 20 September 2024).
8. Contreras Montoya LT, Lain S, Ilinca A. A review on the estimation of power loss due to icing in wind turbines. *Energies* **2022**, *15*, 1083.
9. Alsabagh ASY, Tiu W, Xu Y, Virk MS. A review of the effects of ice accretion on the structural behavior of wind turbines. *Wind Eng.* **2013**, *37*, 59–70.
10. Afzal F, Virk MS. Review of icing effects on wind turbine in cold regions. *E3S Web Conf. EDP Sci.* **2018**, *72*, 01007.
11. Sunden B, Wu Z. On icing and icing mitigation of wind turbine blades in cold climate. *J. Energy Resour. Technol.* **2015**, *137*, 051203.
12. Wallenius T, Lehtomäki V. Overview of cold climate wind energy: Challenges, solutions, and future needs. *Wiley Interdiscip. Rev. Energy Environ.* **2016**, *5*, 128–135.
13. Fakorede O, Feger Z, Ibrahim H, Ilinca A, Perron J, Masson C. Ice protection systems for wind turbines in cold climate: Characteristics, comparisons and analysis. *Renew. Sustain. Energy Rev.* **2016**, *65*, 662–675.
14. Lehtomäki V, Krenn A, Jordaen P, Godreau C, Davis N, Khadiri-Yazami Z, et al. Available technologies for wind energy in cold climates. In *International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP)*; 2018. Available online: https://iea-wind.org/wp-content/uploads/2021/09/Lehtomaki-et-al.-2018-Available-Technologies-for-Wind-Energy-in-Cold-Climates-report-2-nd-edition-2018.pdf (accessed on 20 September 2024).
15. Bredesen R, Cattin R, Clausen N, Davis N, Jordaens P, Khadiri-Yazami Z, et al. Wind Energy Projects in Cold Climates, IEA Wind TCP Recommended Practice 13. Wind Energy in Cold Climates, International Energy Agency. 2017. Available online: https://euagenda. eu/upload/publications/untitled-102011-ea. pdf (accessed on 20 December 2021).
16. Madi E, Pope K, Huang W, Iqbal T. A review of integrating ice detection and mitigation for wind turbine blades. *Renew. Sustain. Energy Rev.* **2019**, *103*, 269–281.
17. Martini F, Contreras Montoya LT, Ilinca A. Review of wind turbine icing modelling approaches. *Energies* **2021**, *14*, 5207.
18. DNV-GL. RECOMMENDED PRACTICE—Extreme Temperature Conditions for Wind Turbines. DNVGL-RP-0363 2016. Available online: https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7B4488CAB8-6944-4117-8171-CC6A1C7BF1A7%7D (accessed on 20 September 2024).
19. Rissanen S, Lehtomäki V. Wind Power Icing Atlas (WIceAtlas) & icing map of the world. In Proceedings of the Winterwind Conference, Piteå, Sweden, 3–4 February 2015.
20. VTT. Available online https://projectsites.vtt.fi/sites/wiceatlas (accessed on 20 September 2024).
21. Mustafa A, Barabadi A, Markeset T. Risk assessment of wind farm development in ice proven area. In Proceedings of the POAC Conferences, Delft, The Netherlands, 9–13 June 2019.
22. Ingvaldsen K. Atmospheric Icing in a Changing Climate: Impact of Higher Boundary Temperatures on Simulations of Atmospheric Ice Accretion on Structures during the 2015–2016 Icing Winter in West-Norway. Master's Thesis, University of Oslo, Oslo, Norway, 2017.
23. Dalili N, Edrisy A, Carriveau R. A review of surface engineering issues critical to wind turbine performance. *Renew. Sustain. Energy Rev.* **2009**, *13*, 428–438.
24. *ISO 12494*; Atmospheric Icing of Structures; ISO: Geneva, Switzerland, 2017.
25. Hudecz A, Koss H, Hansen MO. Ice accretion on wind turbine blades. In Proceedings of the 15th International Workshop on Atmospheric Icing of Structures (IWAIS XV), St. John's, NL, Canada, 8–13 September 2013; pp. 8–11.
26. Gent RW, Dart NP, Cansdale JT. Aircraft icing. Philosophical Transactions of the Royal Society of London. *Ser. A Math. Phys. Eng. Sci.* **2000**, *358*, 2873–2911.
27. Cober SG, Isaac GA, Strapp JW. Characterizations of aircraft icing environments that include supercooled large drops. *J. Appl. Meteorol. Climatol.* **2001**, *40*, 1984–2002.
28. Fikke SM, Ronsten G, Heimo A, Kunz S, Ostrozlik M, Persson P, et al. *COST 727: Atmospheric Icing on Structures: Measurements and Data Collection on Icing: State of the Art*; Meteo Schweiz: Zürich, Switzerland, 2006.
29. Lamraoui F, Fortin G, Benoit R, Perron J, Masson C. Atmospheric icing severity: Quantification and mapping. *Atmos. Res.* **2013**, *128*, 57–75.
30. Campbell SE, Broeren AP, Bragg MB. Sensitivity of aircraft performance to icing parameter variations. *J. Aircr.* **2007**, *44*, 1758–1760.
31. Li H, Roisman IV, Tropea C. Influence of solidification on the impact of supercooled water drops onto cold surfaces. *Exp. Fluids* **2015**, *56*, 1–13.
32. Makkonen L. Models for the growth of rime, glaze, icicles and wet snow on structures. Philosophical Transactions of the Royal Society of London. *Ser. A Math. Phys. Eng. Sci.* **2000**, *358*, 2913–2939.
33. Jolin N, Bolduc D, Swytink-Binnema N, Rosso G, Godreau C. Wind turbine blade ice accretion: A correlation with nacelle ice accretion. *Cold Reg. Sci. Technol.* **2019**, *157*, 235–241.

34. Dierer S, Oechslin R, Cattin R. Wind turbines in icing conditions: Performance and prediction. *Adv. Sci. Res.* **2011**, *6*, 245–250.
35. Davis N. Icing Impacts on Wind Energy Production. Ph.D. Thesis, DTU Risø Campus, Roskilde, Denmark, 2014.
36. Wright W. User's Manual for LEWICE Version 3.2. 2008. Available online: https://ntrs.nasa.gov/citations/20080048307 (accessed on 20 September 2024).
37. Thomas SK, Cassoni RP, MacArthur CD. Aircraft anti-icing and de-icing techniques and modeling. *J. Aircr.* **1996**, *33*, 841–854.
38. Etemaddar M, Hansen MOL, Moan T. Wind turbine aerodynamic response under atmospheric icing conditions. *Wind Energy* **2014**, *17*, 241–265.
39. Montminy DP, Roberge P, Lemay J, Ruel J, Bégin-Drolet A. Validation of a numerical ice accretion model on a wind turbine with high-resolution field data. *Cold Reg. Sci. Technol.* **2022**, *201*, 103620.
40. Hann R, Hearst RJ, Sætran LR, Bracchi T. Experimental and Numerical Icing Penalties of an S826 Airfoil at Low Reynolds Numbers. *Aerospace* **2020**, *7*, 46.
41. Makkonen L, Laakso T, Marjaniemi M, Finstad KJ. Modelling and prevention of ice accretion on wind turbines. *Wind Eng.* **2001**, *25*, 3–21.
42. Homola MC, Virk MS, Wallenius T, Nicklasson PJ, Sundsbø PA. Effect of atmospheric temperature and droplet size variation on ice accretion of wind turbine blades. *J. Wind Eng. Ind. Aerodyn.* **2010**, *98*, 724–729.
43. Manatbayev R, Baizhuma Z, Bolegenova S, Georgiev A. Numerical simulations on static Vertical Axis Wind Turbine blade icing. *Renew. Energy* **2021**, *170*, 997–1007.
44. Yang X, Bai X, Cao H. Influence analysis of rime icing on aerodynamic performance and output power of offshore floating wind turbine. *Ocean Eng.* **2022**, *258*, 111725.
45. Beaugendre H, Morency F, Habashi WG, Benquet P. Roughness implementation in FENSAP-ICE: Model calibration and influence on ice shapes. *J. Aircr.* **2003**, *40*, 1212–1215.
46. Tammelin B, Böhringer A, Cavaliere M, Holttinen H, Morgan C, Seifert H, et al. *Wind Energy Production in Cold Climate (WECO)*; Finnish Meteorological Institute: Helsinki, Finland, 2000.
47. Pérez JMP, Márquez FPG, Hernández DR. Economic viability analysis for icing blades detection in wind turbines. *J. Clean. Prod.* **2016**, *135*, 1150–1160.
48. Swenson L, Gao L, Hong J, Shen L. An efficacious model for predicting icing-induced energy loss for wind turbines. *Appl. Energy* **2022**, *305*, 117809.
49. Switchenko D, Habashi W, Reid T, Ozcer I, Baruzzi G. Fensap-ice simulation of complex wind turbine icing events, and comparison to observed performance data. In Proceedings of the 32nd ASME Wind Energy Symposium, National Harbor, MD, USA, 13–17 January 2014; p. 1399.
50. Sagol E. Three Dimensional Numerical Predicton of Icing Related Power and Energy Losses on a Wind Turbine: École Polytechnique de Montréal. Doctoral dissertation, École Polytechnique de Montréal, Montréal, QC, Canada, 2014.
51. Maissan JF. Wind Power Development in Sub-Arctic Conditions with Severe Rime Icing. Northern Review. 2001. Available online: https://thenorthernreview.ca/nr/index.php/nr/article/download/233/226 (accessed on 20 September 2024).
52. Laakso T, Peltola E, Tammelin B. *Wind Turbines in Icing Environment: Improvement of Tools for Siting, Certification and Operation: New Icetools*; Finnish Meteorological Institute: Helsinki, Finland, 2005.
53. Battisti L, Fedrizzi R, Brighenti A, Laakso T. Sea ice and icing risk for offshore wind turbines. In Proceedings of the OWEMES: Citeseer, Citavecchia, Italy, 20–22 April 2006; pp. 20–22.
54. Tammelin B, Säntti K. *Effect of Rime Accretion on Wind Energy Production in the Top Areas of Fells. BOREAS II*; FMI: Pyhätunturi, Finland, 1994; pp. 265–275.
55. Marjaniemi M, Peltola E. Blade heating element design and practical experiences. In *BOREAS IV: Wind Energy Produciton in Cold Climates*; Finnish Meteorological Institute: Helsinki, Finland, 1999; pp. 197–209.
56. Battisti L, Brighenti A, Dal Savio S, Dell'Anna S. Evaluation of anti-icing energy and power requirement for wind turbine rotors in cold climates. In Proceedings of the VII BOREAS Conference: Boreas Conference, Saarisalka, Finland, 7–8 March 2005.
57. Xie T, Dong J, Chen H, Jiang Y, Yao Y. Experimental investigation of deicing characteristics using hot air as heat source. *Appl. Therm. Eng.* **2016**, *107*, 681–688.
58. Gantasala S, Luneno J-C, Aidanpaa J-O. Detection of ice mass based on the natural frequencies of wind turbine blade. *Wind Energy Sci. Discuss.* **2016**, *2016*, 1–17.
59. Ilinca A. Analysis and mitigation of icing effects on wind turbines. *Wind Turbines* **2011**, *4*, 183–214.
60. Seifert H. Technical requirements for rotor blades operating in cold climate. *DEWI-Magazin.* **2004**, 26, 1–13.
61. Shajiee S, Pao LY, McLeod RR. Optimizing the layout of heaters for distributed active de-icing of wind turbine blades. *Wind Eng.* **2014**, *38*, 587–600.
62. Mayer C, Ilinca A, Fortin G, Perron J. Wind tunnel study of electro-thermal de-icing of wind turbine blades. *Int. J. Offshore Polar Eng.* **2007**, *17*, ISOPE-07-17-3-182.

63. Habibi H, Cheng L, Zheng H, Kappatos V, Selcuk C, Gan T-H. A dual de-icing system for wind turbine blades combining high-power ultrasonic guided waves and low-frequency forced vibrations. *Renew. Energy* **2015**, *83*, 859–870.
64. Wang Z. Recent progress on ultrasonic de-icing technique used for wind power generation, high-voltage transmission line and aircraft. *Energy Build.* **2017**, *140*, 42–49.
65. Habashi WG, Aubé M, Baruzzi G, Morency F, Tran P, Narramore JC. FENSAP-ICE: A fully-3D in-flight icing simulation system for aircraft, rotorcraft and UAVS. In Proceedings of the 24th International Congress of the Aeronautical Sciences: International Council of the Aeronautical Sciences (ICAS), Yokohama, Japan, 29 August–3 September 2004; pp. 1–10.