Comparative Analysis and Selection Methodology for Wind Turbine Blade Ice Protection Systems for Different Climatic Zones

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Abstract: - This paper presents a comparative methodology for evaluating and selecting wind turbine blade ice protection systems for cold-climate operating conditions. Passive, active, and hybrid technologies are classified, including resistive electric heating, hot-air systems, icephobic coatings, and combined solutions. A multicriteria evaluation framework based on the TOPSIS method, using min–max normalization, is proposed. The framework considers energy, economic, operational, and technological criteria, including annual energy production gain, system energy consumption, capital and operating costs, technological maturity, climatic applicability, and integration and maintenance complexity. The methodology is tested for three generalized icing scenarios differing in icing duration and severity. The results show that the preferred technology is scenario-dependent: hot-air systems are preferable under occasional icing, whereas resistive electric heating becomes more advantageous under regular and severe icing. Passive coatings are insufficient as standalone protection measures.

Key-Words: - wind turbine, blade icing, ice protection system, TOPSIS method, multicriteria evaluation, cold climate.

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1 Introduction

A significant share of wind turbines operate in cold-climate regions, where icing conditions and prolonged subzero temperatures occur regularly [1], [2], [3]. Ice accretion on blades degrades the rotor's aerodynamic characteristics, reduces annual energy production, and increases operational risks, [4], [5]. According to the IcingBlades project, blade icing is the largest individual contributor to energy production losses among the considered causes (Figure 1), [6].

In addition to energy losses, icing causes rotor imbalance, increased dynamic loads, and more unplanned shutdowns. It also complicates maintenance and reduces the accuracy of measurement and control systems, [4], [5], [7]. Ice throw from rotating blades poses additional risks to personnel and infrastructure and generally reduces the availability of wind energy facilities in cold climates, [8], [9].

The practical importance of reliable wind turbine operation under low-temperature and icing conditions is related not only to reducing production losses, but also to the expanding use of wind energy in autonomous power supply systems for remote consumers. For such systems, the integration of wind turbines can reduce power shortages, fuel consumption, and diesel generator operating hours; in addition, wind turbines can be used as power sources for electric heating systems at oil production facilities, [10], [11]. Under these conditions, wind turbine operability during icing becomes important not only in terms of energy efficiency, but also in terms of infrastructure reliability.

To mitigate the consequences of icing, passive and active protection technologies are used together with operational control strategies, including derating and temporary shutdowns when icing is detected, [1], [12]. Active thermal systems, primarily electrothermal heating and hot-air circulation inside blade cavities, are the most widely deployed in industrial applications. Such systems are usually divided into anti-icing systems, which prevent ice formation, and de-icing systems, which break up and remove already formed ice deposits, [4], [13].

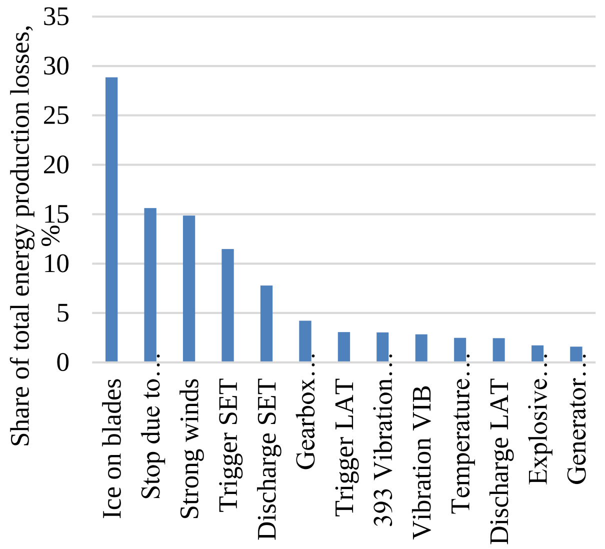

Fig. 1: Relative contribution of different causes to total energy production losses
Source: [6]

Existing studies in this field mainly focus on icing process modeling and on evaluating the effectiveness of individual technologies, particularly electric heating and operational derating, [14]. However, many studies are limited to energy-related indicators or the required heating-system power, whereas operational applicability, operating constraints, and life-cycle economic efficiency are considered only fragmentarily.

This study aims to develop a methodology for the comprehensive evaluation, comparative analysis, and selection of wind turbine blade icing protection systems for different operating conditions in cold climates. For the subsequent analysis, three generalized engineering icing scenarios, denoted as S1–S3 and differing in duration, severity, and expected energy production losses, are considered.

In the present study, a scenario-dependent approach is proposed for selecting wind turbine blade ice protection systems based on the multicriteria ranking of alternative solutions. In contrast to a static comparison of technologies, this approach links the selection of a protection system with icing severity, expected energy production losses, system energy consumption, capital and operating costs, technological maturity, integration complexity, and climatic applicability. This makes it possible to formulate technology selection recommendations for different operating conditions rather than a single universal ranking of protection systems.

The proposed approach includes the following main elements:

1) A classification of passive, active, and hybrid blade ice protection technologies is developed.

2) A set of quantitative and qualitative criteria reflecting the energy, economic, operational, and technological characteristics of protection systems is formed.

3) A procedure for multicriteria ranking of alternative solutions based on the TOPSIS method is proposed.

4) The applicability of the methodology is demonstrated for typical wind turbine operating scenarios with different icing severity.

2 Classification of Wind Turbine Blade Ice Protection Systems

Wind turbine blade ice protection systems are based on two fundamental strategies: preventing ice formation on the surface and removing already formed ice deposits. Both strategies can be implemented either by passive methods, which rely on material properties and surface conditions, or by active systems requiring an external energy supply, primarily thermal energy, [15], [16]. A generalized classification of the solutions considered in this study and used later to define the set of compared technologies and formulate the evaluation problem is shown in Figure 2 (Appendix).

2.1 Passive Systems

Passive systems affect the processes of ice adhesion and retention and, as a rule, do not require energy input during operation, [17]. The main approaches include:

1. Chemical agents. Antifreeze compounds applied to the blade surface reduce the freezing point of water and decrease the probability of ice formation. However, due to their limited duration of action, the need for regular reapplication, environmental constraints, and dosing complexity, such solutions are generally regarded as auxiliary and are rarely used in industrial wind power applications, [18].

2. Coatings. Hydrophobic and icephobic coatings reduce ice adhesion and water droplet retention, thereby decreasing icing intensity and facilitating ice removal. At the same time, under prolonged and severe icing events, they usually do

not provide complete icing prevention, and their properties may deteriorate under ultraviolet radiation, erosion, and freeze-thaw cycles, [19]. Photothermal and dark coatings additionally increase solar radiation absorption and may be useful under light icing and sufficient solar exposure; however, their applicability under severe icing conditions is limited, [20].

3. Structural-passive solutions. This class includes approaches based on changing blade and rotor position to reduce the probability of ice adhesion or facilitate ice shedding, as well as geometric solutions aimed at improving water runoff and reducing moisture retention. In the literature, such methods are usually considered auxiliary and are still at an early stage of development; their effectiveness for large wind turbines has so far been confirmed only to a limited extent, [21].

According to the literature, under regular and severe icing conditions, passive methods are more often regarded as auxiliary measures or elements of combined protection, since their standalone effectiveness is usually insufficient to ensure an acceptable level of annual losses, [17], [20].

2.2 Active Systems

Active systems use an external energy source to prevent ice formation and/or remove already formed deposits, [8]. In industrial practice, thermal solutions operating in anti-icing and de-icing modes are the most widely used.

In the anti-icing mode, the surface temperature is maintained above the freezing point under icing conditions, usually by means of continuous heating. In the de-icing mode, already formed ice is periodically broken and removed by cyclic or pulsed heating and, in some cases, by mechanical action.

According to published data on wind turbine operation in cold climates, the total additional energy consumption associated with ice protection and related operating modes may amount to several percent of annual energy production, while the contribution of the heating system itself usually represents only part of this balance, [22].

2.2.1 Electric Heating (Resistive Heating)

Heating elements in the form of films, wires, carbon inserts, or woven carbon heaters are embedded into the near-surface layers of the composite blade or applied to its outer surface, mainly in the leading-edge region, [23]. In the anti-icing mode, the system maintains the surface temperature at about 0 °C, whereas in the de-icing mode it ensures the formation of a water film at the “ice-surface” interface, followed by ice shedding under the action of aerodynamic and inertial forces.

According to published studies, the required power and energy consumption of resistive heating depend on climatic conditions, blade size, and the selected heating layout and, for modern wind turbines, usually amount to several percent of annual energy production, [22], [24]. The technology is characterized by a fast response and efficient heat transfer to the near-surface layer, [25]. Its main limitations include increased structural complexity, higher requirements for lightning protection and cable infrastructure, as well as the risks of composite overheating and secondary icing caused by refreezing of the runoff water.

2.2.2 Hot-air Systems

In systems of this type, heated air is circulated through the internal cavities of the blade, transferring heat through the blade wall to the icing zone. In industrial implementations, particularly those developed by ENERCON, heating is provided by a heating unit installed in the blade root with air recirculation; the system is used to accelerate ice melting and reduce icing-related downtime. ENERCON technical materials also note that, when the risk of re-icing is low, de-icing may be performed while the rotor is rotating, whereas if ice accretion continues, the turbine is stopped, [26].

In practice, hot-air systems are used primarily in the de-icing mode; however, in some implementations, their operation may approach anti-icing, depending on the installed power, blade design, and control algorithm. Field data, SCADA-based evaluations, and technical reports on commercial systems confirm that such solutions can significantly reduce energy production losses at icing-prone sites and, therefore, should be regarded as industrially applicable rather than purely experimental technologies.

The performance of hot-air systems is determined by heat transfer conditions, the internal geometry and length of the blade, temperature distribution along the span, installed thermal power, ambient air temperature, wind speed, and icing intensity. Review studies on wind turbine icing protection technologies note that such systems are often sufficient under light and moderate icing conditions, whereas under more severe regimes, including prolonged and intense icing events at low temperatures, their effectiveness may decrease, and de-icing often requires turbine shutdown, [25], [27].

2.2.3 Other Active Solutions
Other active solutions include air curtains (air blowing), electromagnetic/microwave and dielectric heaters, as well as mechanical and vibrational de-icers (ultrasonic, electro-impulse/expulsive systems, and pneumatic boots), [12]. These approaches may enable lower energy consumption compared with thermal methods; however, for wind power applications, they are still mainly at the laboratory and pilot-development stage, and questions remain regarding durability, scalability, and integration with wind turbine structure and control systems, [21].

2.3 Hybrid Solutions
Hybrid systems combine passive and active protection methods, [28], [29]. Typical concepts include:

– the use of hydrophobic/icephobic coatings together with electric heating to reduce the required specific heater power;

– the use of solar-absorbing coatings combined with internal heating for regions with high solar exposure;

– the combination of local heating in the leading-edge region with less energy-intensive ice removal methods in other areas.

Hybrid solutions aim to reduce the installed power of the active part, lower energy consumption, and improve the effectiveness and reliability of protection under different climatic conditions, including prolonged icing regimes.

2.4 Summary of the Classification and Link to the Subsequent Analysis
The above classification is used below to define the set of compared solutions and formulate the multicriteria evaluation problem. In this study, the following alternatives are considered for subsequent comparison: A1 – resistive electric heating; A2 – hot-air system; A3 – hybrid system (electric heating + coating); A4 – icephobic coating.

At the same time, the comparison is performed primarily at the level of technological solutions. The operational effectiveness of ice protection systems also depends on the control strategy: the system may operate continuously, be activated after ice detection, or be activated based on predictive algorithms using meteorological data and wind turbine operating parameters. In the present study, control strategies are not considered as separate alternatives; however, their influence is partly reflected in the subsequent evaluation through energy consumption, climatic applicability, and integration and maintenance complexity.

A summary description of the alternatives and their qualitative features is provided in Table 1 (Appendix).

3 Methodology for Evaluating the Effectiveness of Heating and Ice Protection Systems
The proposed methodology is intended for the comparative evaluation of wind turbine blade icing protection technologies under various climatic conditions, taking into account energy, economic, operational, and technological factors. For the integrated ranking of alternatives, this study employs a version of the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution), in which min–max normalization of criteria is applied during data preprocessing. This approach enables the transformation of various quantitative and expert-based indicators into a unified dimensionless scale and then compares the alternatives under consideration in terms of their closeness to the ideal solution, [30].

3.1 Alternatives and Performance Criteria
The following icing protection systems are considered as alternatives:

A1 – electric resistive blade heating;

A2 – hot-air circulation system inside the wind turbine blade;

A3 – hybrid system: electrothermal heating + icephobic coating;

A4 – icephobic coating (passive option).

The increase in energy production is evaluated relative to the baseline operating scenario without a dedicated icing protection system.

The alternatives are compared using criteria C1–C7:

C1 – relative increase in annual energy production ΔE_{rel}, % AEP (higher is better). This indicator is defined as the increase in annual energy production relative to the baseline operating scenario without specialized anti-icing measures.

C2 – relative annual system energy consumption E_{heat}/AEP, % AEP (lower is better).

C3 – additional capital costs, $CAPEX_{sys}$, $/kW (lower is better).

Additional investment in the protection system per 1 kW of installed capacity.

C4 – additional operating costs, $OPEX_{sys}$, $/(kW·year) (lower is better).

Annual operation and maintenance costs of the protection system per 1 kW of installed capacity.

C5 – technological maturity and industrial readiness (1–5, higher is better).

This criterion reflects the level of industrial validation, maturity, and predictability of technology performance under icing conditions.

C6 – climatic applicability (1–5, higher is better).

This criterion reflects the suitability of the technology for the considered range of icing conditions (duration, severity, temperature) and the robustness of the expected effectiveness within the scenario.

C7 – integration and maintenance complexity (1–5, lower is better).

Thus, criteria C1–C4 describe the energy and economic performance of the solutions, while criteria C5–C7 characterize the operational and technological properties of the alternatives. To reduce subjectivity, the expert-based criteria are defined using the formalized scales given below.

Criterion C5:

1 – laboratory/conceptual stage;
2 – prototypes/limited testing;
3 – pilot implementations;
4 – commercial implementations on a limited scale;
5 – widely deployed industrial solution with confirmed operational experience.

Criterion C6:

1 – only rare icing episodes near 0 °C;
2 – occasional icing, limited effectiveness under frost conditions;
3 – regular icing at moderate subzero temperatures;
4 – prolonged/intense icing and low temperatures;
5 – severe regimes (long-duration events, down to −25...−30 °C).

Criterion C7:

1 – minimal design changes and simple maintenance;
2 – moderate changes and standard maintenance;
3 – noticeable modification and/or more difficult access;
4 – substantial integration effort and increased service requirements;
5 – high technological and service complexity.

3.2 Indicator Normalization and Criterion Weighting Coefficients

Since criteria C1–C7 differ in units, numerical ranges, and optimization directions (“higher is better” and “lower is better”), they must be transformed to a common dimensionless scale before applying TOPSIS. Therefore, the initial values are normalized, and weighting coefficients are introduced.

Let x_{ij} denote the initial value of criterion i for alternative j. Based on the initial data, the matrix $X = [x_{ij}]$ is formed.

To ensure the comparability of criteria, the values x_{ij} are normalized to the range [0; 1]. Different formulas are used for benefit-type criteria (the higher is better) and cost-type criteria (the lower is better).

For benefit-type criteria, the normalized value r_{ij} is calculated using equation (1):

$$r_{ij} = \frac{x_{ij} - min_j(x_{ij})}{max_j(x_{ij}) - min_j(x_{ij})} \quad (1)$$

For cost-type criteria, the normalized value r_{ij} is calculated using equation (2):

$$r_{ij} = \frac{max_j(x_{ij}) - x_{ij}}{max_j(x_{ij}) - min_j(x_{ij})} \quad (2)$$

For cost-type criteria, the alternative with the minimum initial value of x_{ij} corresponds to $r_{ij} = 1$, whereas the alternative with the maximum value of x_{ij} corresponds to $r_{ij} = 0$.

Thus, after normalization, all criteria are transformed to a common [0;1] scale, where higher values of r_{ij} always indicate more preferable results regardless of the original nature of the criterion.

At the next stage, each criterion i is assigned a weight w_i reflecting its relative importance in evaluating the technology under the considered climatic and operating conditions. The values of w_i are determined by expert judgment based on customer priorities and the operating conditions of the facility. In particular, depending on the scenario, greater weight may be assigned to indicators of energy efficiency, the technology’s resistance to climatic impacts, or the level of capital costs. For the subsequent calculation of the integrated indicator, the criterion weights are normalized according to equation (3):

$$\Sigma_i w_i = 1 \quad (3)$$

The weighted normalized value of criterion i for alternative j is denoted by v_{ij}. It is calculated as the product of the normalized value r_{ij} and the corresponding weight coefficient w_i, as shown in equation (4):

$$v_{ij} = w_i \cdot r_{ij} \quad (4)$$

As a result, the matrix $V = [v_{ij}]$ is formed, whose elements represent dimensionless weighted scores accounting for both the relative position of each alternative and the importance of the corresponding criterion. Qualitative criteria (such as C6 and C7), defined as expert scores on a 1–5 scale, undergo the same normalization and weighting procedure as quantitative indicators.

3.3 Multicriteria Evaluation Procedure based on the TOPSIS Method

To aggregate criterion-specific information and rank the blade protection alternatives, the TOPSIS method is used. The basic idea of the method is that the preferred alternative should be as close as possible to the ideal solution and as far as possible from the anti-ideal solution [30].

Given the weighted normalized matrix V = [v_{ij}], where v_{ij} is the weighted normalized value of criterion i for alternative j, the following steps are performed.

1. Determination of the ideal and anti-ideal solutions for each criterion.

For each criterion i, two reference values are determined:

– the maximum value v_i^+ , representing the best value among all alternatives, is calculated using equation (5):

$$v_i^+ = \max_j(v_{ij}) \tag{5}$$

– the minimum value v_i^-, representing the worst value among all alternatives, is expressed by equation (6):

$$v_i^- = \min_j(v_{ij}) \tag{6}$$

The set of all v_i^+ values form the ideal solution vector in the criterion space, whereas the set of all v_i^- values form the anti-ideal solution vector.

2. Calculation of the distances from each alternative to the best and worst solutions.

For each alternative j, the Euclidean distances to the ideal and anti-ideal solutions are calculated as shown in equations (7) and (8):

$$D_j^+ = \sqrt{\Sigma_i \left(v_{ij} - v_i^+\right)^2} \tag{7}$$

$$D_j^- = \sqrt{\Sigma_i \left(v_{ij} - v_i^-\right)^2} \tag{8}$$

where:

D_j^+ is the distance from alternative j to the ideal solution; smaller values indicate greater proximity to the ideal solution.

D_j^- is the distance from alternative j to the anti-ideal solution; larger values indicate a greater distance from the worst case.

3. Determination of the closeness coefficient to the ideal solution and ranking of alternatives.

For the integrated evaluation of the preference of each alternative j, a closeness coefficient to the ideal solution, k_j, is introduced and determined by equation (9):

$$k_j = \frac{D_j^-}{\left(D_j^+ + D_j^-\right)} \tag{9}$$

The admissible range of the closeness coefficient is given by equation (10):

$$0 \le k_j \le 1 \tag{10}$$

The coefficient k_j indicates the relative closeness of an alternative to the ideal solution. The closer k_j is to 1, the more preferable the alternative is.

The obtained values of k_j make it possible to rank all considered alternatives (A1–A4) in descending order of preference for each specific climatic and operational scenario. Thus, the TOPSIS method provides a formal and transparent aggregation of multiple criteria into a single integrated indicator while retaining sensitivity to both changes in the initial criterion values and the system of weight coefficients.

4 Application of the Methodology and Results of the Comparative Analysis

4.1 Climatic Scenarios

To demonstrate the proposed methodology, this study considers three wind turbine operating scenarios under cold-climate conditions. These scenarios are constructed with reference to the IEA ice classes and differ in the duration and intensity of icing. Scenarios S1–S3 are not direct reproductions of individual IEA classes; rather, they represent a generalized interpretation of those classes in terms of icing severity and associated energy production losses. In this sense, scenario S1 corresponds to the conditions of the second ice class, scenario S2 to the transition zone between classes 3 and 4, and scenario S3 to severe conditions characteristic of classes 4–5.

S1 (occasional icing): 50–100 h/year, annual production losses without protection systems up to ~3%.

S2 (regular icing): 300–500 h/year, annual production losses up to ~10%.
S3 (prolonged and severe icing): 800–1500 h/year and more, annual production losses up to ~20%.

In this formulation, the scenarios characterize not fixed geographical zones, but typical icing regimes that may occur at different cold-climate sites. Scenario S1 may be characteristic of temperate or coastal areas with occasional icing, scenario S2 of continental and high-altitude sites with regular icing, and scenario S3 of Arctic, high-latitude, or high-altitude conditions with prolonged icing exposure. This interpretation enables linking the selection of an ice protection system to expected meteorological operating conditions while maintaining a unified calculation format for subsequent multicriteria evaluation.

For each scenario, tables of initial criterion values $X = [x_{ij}]$ were formed for alternatives A1–A4. The values of criteria C1 and C2 were derived from published sources, including technical reports, field-operation data from real wind farms, SCADA-based evaluations, experimental studies, and manufacturer-published data. For active heating systems, materials on Vestas and ENERCON systems were used, as they consider wind turbine operation under icing conditions, [26], [31], [32]. For hybrid solutions, review and experimental studies of systems combining icephobic coatings and electrothermal heating were taken into account, including tests under simulated icing conditions on aerodynamic profiles and blade models, [18], [28], [29]. For passive coatings, available field and manufacturer-published data on icephobic coatings were used [33], [34].

Capital costs C3 are expressed in $/kW. For active systems, benchmark estimates of commercial de-icing system costs and published techno-economic assessments of blade heating systems were used [35]. For coatings, publicly available estimates of application cost per turbine were converted to $/kW, [34].

Operating costs C4 are expressed in $/(kW·year). For active systems, C4 was estimated as 2% of the initial system investment, as shown in equation (11):

$$C4 = 0.02 \cdot C3 \tag{11}$$

For coating-based alternatives, periodic coating renewal was accounted for using equations (12) and (13):

$$C4(A4) = \frac{C3(A4)}{\tau} \tag{12}$$

$$C4(A3) = 0.02 \cdot C3(A1) + \frac{C3(A4)}{\tau} \tag{13}$$

where τ is the coating lifetime (years). In the base calculation, τ = 3 years was adopted.

Since the initial criterion values were obtained from sources that differed in turbine types, climatic conditions, and performance assessment methods, they were standardized into a unified set of criteria and generalized across scenarios S1–S3. This makes it possible to compare the alternatives within a single calculation framework and to use the methodology as a tool for preliminary selection of ice protection technologies.

The initial criterion values for scenarios S1–S3 are given below (Table 2, Table 3 and Table 4).

Table 2. Initial criterion values for scenario S1

	A1	A2	A3	A4
C1, %/year	2	2	2.1	1
C2, %/year	0.3	0.5	0.1	0
C3, $/kW	40	10	42.5	2.5
C4, $/(kW·year)	0.8	0.2	1.6	0.8
C5	4	4	3	3
C6	3	2	3	2
C7	4	5	5	2

Source: created by the authors

Table 3. Initial criterion values for scenario S2

	A1	A2	A3	A4
C1, %/year	7.0	6.5	7.5	2.5
C2, %/year	0.8	1.3	0.3	0
C3, $/kW	40	10	42.5	2.5
C4, $/(kW·year)	0.8	0.2	1.6	0.8
C5	4	4	3	3
C6	4	3	4	2
C7	4	5	5	2

Source: created by the authors

Table 4. Initial criterion values for scenario S3

	A1	A2	A3	A4
C1, %/year	14	15	15	4.5
C2, %/year	2	2	0.8	0
C3, $/kW	40	10	42.5	2.5
C4, $/(kW·year)	0.8	0.2	1.6	0.8
C5	4	4	3	3
C6	4	2	4	2
C7	4	5	5	2

Source: created by the authors

4.2 Assignment of Criterion Weight Coefficients

The weighting coefficients w_i define the relative importance of criteria C1–C7 in each icing scenario. Their values differ across the considered scenarios because changes in icing intensity and duration alter the requirements for the protection technology. Under episodic icing conditions, the choice of a solution depends more strongly on economic indicators, whereas under more severe conditions, greater importance is assigned to technological maturity, suitability for operation in cold climates, and the operational robustness of the alternative under consideration.

In this study, the criterion weights are assigned according to a scenario-based group-weighting logic. For this purpose, the criteria are first divided into three groups: energy-related criteria C1–C2, economic criteria C3–C4, and operational-technological criteria C5–C7. Then, the relative importance of each group is specified depending on the icing scenario, after which the group weights are distributed among individual criteria according to their role in selecting the protection technology. The final set of weighting coefficients is normalized so that $\sum_i w_i=1$.

For scenario S1, characterized by episodic icing, the greatest importance is retained by the energy-related and economic criteria. This is because, under short-duration icing events, the key issue is the investment feasibility of implementing the protection system: the expected increase in energy production should be comparable with the capital and operating costs.

For scenario S2, corresponding to regular icing, the weights are redistributed in favor of criteria C1, C5, and C6. In this case, along with the energy effect, the industrial maturity of the technology and its suitability for stable operation in cold climates become more important. This scenario is transitional between episodic and prolonged icing; therefore, it maintains a balance between energy-related, economic, and operational-technological factors.

For scenario S3, characterized by prolonged and severe icing, the priority shifts toward the operational-technological criteria C5 and C6. Under such conditions, downtime costs, the risk of reduced turbine availability, and the requirements for stable operation of the protection system become more significant than minimizing initial costs. At the same time, criterion C1 remains highly important because the increase in annual energy production is still one of the main indicators of technology effectiveness.

The group structure of the weights used to form the final coefficients is as follows: for scenario S1, the energy-related, economic, and operational-technological criteria have total weights of 0.40, 0.35, and 0.25, respectively; for scenario S2, the corresponding values are 0.35, 0.25, and 0.40; and for scenario S3, they are 0.30, 0.20, and 0.50. Thus, as icing severity increases, the weight of economic factors decreases, whereas the contribution of operational-technological characteristics increases.

The final weights used in the calculations are given in Table 5.

Table 5. Assigned criterion weights

	S1	S2	S3
w (C1)	0.25	0.25	0.20
w (C2)	0.15	0.10	0.10
w (C3)	0.20	0.15	0.10
w (C4)	0.15	0.10	0.10
w (C5)	0.10	0.15	0.20
w (C6)	0.10	0.15	0.20
w (C7)	0.05	0.10	0.10

Source: created by the authors

To verify the robustness of the obtained ranking, a sensitivity analysis based on varying the criterion weights within ±20% while preserving normalization of the weight vector was additionally performed in Section 4.4.

4.3 Results of the Multicriteria Evaluation

Based on the input data presented in Table 2, Table 3 and Table 4 and the weight coefficients specified in Section 4.2, min-max normalization, construction of the weighted matrix, and calculation of the closeness coefficient to the ideal solution, k_j were performed using the TOPSIS method. The larger the value of k_j, the more preferable the corresponding alternative is with respect to the set of criteria considered in a given climatic scenario.

The calculated closeness coefficients and the rankings of alternatives A1–A4 for scenarios S1–S3 are given in Table 6. For clarity, the obtained values of k_j are also presented in Figure 3.

Table 6. Ranking of alternatives by scenario

Alternative	S1	S2	S3
A1	2	1	1
A2	1	2	2
A3	3	3	3
A4	4	4	4

Source: created by the authors

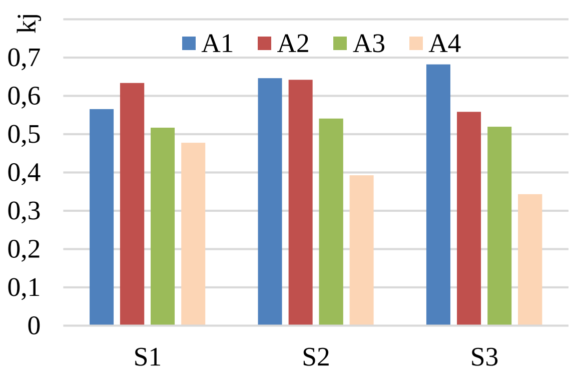

Fig. 3: Values of the closeness coefficient kj for alternatives A1–A4 in scenarios S1–S3
Source: created by the authors.

The obtained results show that the preferred technology depends on the climatic scenario and the adopted weight structure. In all scenarios, the top positions are occupied by active systems A1 and A2, whereas the passive coating A4 demonstrates the lowest values of k_j, with its relative lag increasing as the icing conditions become more severe. This is because, under regular and prolonged icing, the low capital costs and almost zero energy consumption of the coating do not compensate for its limited contribution to reducing production losses and its insufficient climatic applicability as a standalone protection measure.

In scenario S1, corresponding to mild icing conditions, the highest closeness coefficient is obtained for the hot-air system A2 (k_j=0.6338). This result is consistent with the weighting logic adopted for episodic icing, in which the economic criteria C3 and C4 have a substantial influence on the overall evaluation. Under these conditions, the hot-air system proves to be preferable due to its more favorable combination of cost-related indicators and sufficient effectiveness.

In scenario S2, characterized by regular icing, the leading position is taken by the resistive heating system A1 (k_j=0.6461); however, the closeness coefficient for alternative A2 is almost identical (k_j=0.6420). The small gap between the two alternatives indicates that this scenario is transitional: the economic advantages of the hot-air system still allow it to remain competitive, but the increasing importance of climatic applicability, technological maturity, and stable system operation gradually shifts the preference toward resistive heating. Consequently, under regular icing conditions, the final choice between A1 and A2 may depend on project-specific priorities, including the acceptable level of capital costs, turbine availability requirements, and the expected duration of icing events.

When moving to scenario S3, corresponding to prolonged icing, the advantage of resistive heating A1 becomes more pronounced: k_j=0.6822 versus 0.5585 for A2. This indicates that under severe conditions, greater importance is attached to the reliable operation of the technology and its climatic applicability under sustained icing exposure. In this case, the role of criteria related to technological maturity, climatic applicability, and stable operation under prolonged exposure to subzero temperatures and ice deposits increases. The higher controllability and local efficiency of heat supply make resistive heating a more preferable solution for severe conditions despite its higher capital costs. As a result, the preference shifts toward the more universal active solution, whereas A2, despite retaining practical effectiveness, receives a lower overall score because of its more limited range of stable application.

In all considered scenarios, the hybrid system A3 ranks third, which allows it to be regarded as an intermediate option between active thermal technologies and passive protection. This result shows that the combination of electric heating and an icephobic coating is a promising intermediate solution; however, within the adopted system of criteria, its advantages in reducing energy consumption do not compensate for its higher integration complexity, the need for coating maintenance, and lower industrial maturity compared with active thermal systems. At the same time, A3 may become a more attractive alternative if coating lifetime increases, maintenance costs decrease, or stricter requirements are imposed on minimizing the energy consumption of the protection system.

The coating alternative A4 consistently remains in fourth place in all scenarios. This does not mean that icephobic coatings have no practical value; rather, it indicates the limitations of using them as standalone protection systems under regular and prolonged icing. Their more rational application area is associated with light icing conditions or with their use as part of hybrid solutions, where the coating reduces ice adhesion and may decrease the required power of the active part of the system.

The TOPSIS results confirm that the choice of an icing protection system depends on the icing conditions at a given site. Using a single universal ranking without accounting for climatic conditions, cost structure, and operational priorities may lead to an impractical technology choice. To verify the robustness of this conclusion, a sensitivity analysis of the effect of variations in weighting coefficients on the final ranking was carried out.

4.4 Sensitivity Analysis of the Ranking Results

The robustness of the ranking was evaluated using a local sensitivity analysis. For each criterion, its weight was varied by ±20% relative to its baseline value, after which the weight vector was normalized while preserving the normalization condition $\sum_i w_i=1$. As a result, 14 additional calculations were performed for each scenario, for a total of 42 calculations across the three scenarios. The results of the ranking sensitivity analysis for scenarios S1–S3 are summarized in Table 7.

Table 7. Results of the ranking sensitivity analysis

Scenario	Number of tests	Ranking changes	Nature of changes
S1	14	2	Swap between A3 ↔ A4
S2	14	5	Change of leader A1 ↔ A2
S3	14	2	Swap between A2 ↔ A3

Source: created by the authors

The analysis shows that, in most cases, changes in criterion weights do not alter the baseline order of alternatives. In 33 out of 42 calculations, the original ranking remains unchanged. The highest sensitivity is observed in scenario S2, whereas for scenarios S1 and S3, the overall conclusions are more robust.

For scenario S1 (occasional icing), the baseline ranking is preserved in 12 of 14 tests. In all cases, the hot-air system A2 remains the leading alternative, indicating the robustness of the conclusion that this technology is preferable under occasional icing. Rank changes are observed only in two cases—when the weight of criterion C1 is decreased and when the weight of criterion C3 is increased—where alternatives A3 and A4 swap positions. In both cases, the first and second positions remain unchanged.

For scenario S2 (regular icing), the baseline ranking is preserved in 9 of 14 tests, which makes this scenario the most sensitive to changes in the preference structure. In 5 cases, the leader changes between alternatives A1 and A2: this occurs when the weights of criteria C1, C2, and C6 are decreased, as well as when the weights of criteria C3 and C4 are increased. This result is expected, since in the baseline calculation, the values of the closeness coefficient for A1 and A2 in scenario S2 differ only slightly. Therefore, the transition scenario between occasional and prolonged icing is most sensitive to changes in operator priorities, particularly in terms of the trade-off between energy effect, climatic applicability, and cost-related criteria.

For scenario S3 (prolonged icing), the baseline ranking is preserved in 12 out of 14 calculations. In all considered cases, resistive electric heating A1 remains the most preferable option, which confirms its advantages under the most severe icing conditions. Changes are recorded only in two tests: when the weight of criterion C5 is decreased and when the weight of criterion C6 is increased, alternatives A2 and A3 exchange positions. At the same time, the leading and the last-ranked positions remain unchanged.

Overall, the sensitivity analysis shows that the obtained ranking is sufficiently robust to moderate changes in criterion weights. For scenarios S1 and S3, the choice of the preferred technology does not change, which makes the corresponding conclusions reliable. The highest sensitivity is observed for scenario S2; however, even in this case, the competition is essentially limited to the two active solutions, A1 and A2. The hybrid system A3 and the passive coating A4 do not become leading alternatives in any of the tests. This confirms the main conclusion of the scenario-based analysis: under occasional and prolonged icing conditions, the preferred technology is determined sufficiently robustly, whereas in the transitional scenario S2, the choice between A1 and A2 depends on the project priorities of the operator and the acceptable trade-off between energy benefit, costs, and climatic applicability.

5 Conclusion

This paper presents a methodology for the comprehensive evaluation and selection of icing protection systems for wind turbine blades under various climatic operating conditions. The methodology is based on multicriteria ranking using the TOPSIS method and takes into account energy, economic, operational, and technological characteristics of the solutions. The study also classifies passive, active, and hybrid protection technologies and considers four alternatives for comparison: resistive electric heating, a hot-air system, a hybrid solution combining electric heating and coating, and an icephobic coating.

Applying the methodology to three generalized icing scenarios, S1–S3, showed that the choice of a protection system should be scenario-specific. Under episodic icing conditions, the hot-air system is the most preferable option, whereas under regular and prolonged intensive icing, the advantage shifts to resistive electric heating. In all considered scenarios, the hybrid system occupies an intermediate position, while the passive icephobic coating is inferior to active solutions when used as a standalone protection measure.

The obtained results confirm that the selection of an icing protection system cannot be adequately reduced to a single universal ranking without considering the climatic operating conditions and the operator's priorities. The proposed approach can be used at the stage of preliminary techno-economic justification for selecting a protection technology for sites with different icing intensities, as well as in the comparative analysis of alternative solutions for new and existing wind energy projects.

At the same time, the results should be regarded as a preliminary engineering assessment obtained for generalized operating scenarios. The input parameters were formed based on operational reports, SCADA data, experimental studies, published techno-economic estimates, and expert assumptions. Further work should focus on refining the input parameters using comparable data from real wind farms, expanding the set of alternative technologies, and performing additional analyses of ranking robustness. In addition, the methodology may be supplemented by physical modeling of ice accretion and removal processes, including Messinger-type models, CFD modeling, and thermal analysis, as well as by data-driven models for icing prediction and adaptive control of protection system activation.

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The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.

APPENDIX

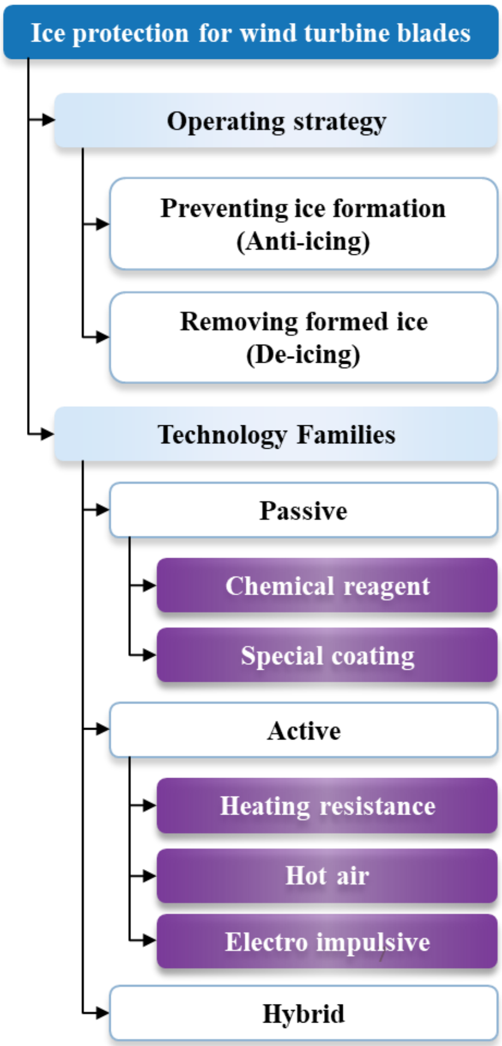

Fig. 2: Classification of wind turbine ice protection systems
Source: created by the authors

Table 1. Summary characteristics of the alternatives considered in the study

Alternative	Technology	Type	Operating mode	Key features
A1	Resistive electric heating	Active	Anti/de	+ high effectiveness and controllability; – more complex integration, lightning protection requirements, risk of secondary icing
A2	Hot-air system	Active	Anti/de	+ no current-carrying elements on the surface; – lower thermal efficiency, higher inertia, limitations under severe climatic conditions
A3	Coating + local electric heating	Hybrid	Anti/de	+ lower energy consumption, broad applicability range; – complexity and coating maintenance requirements
A4	Icephobic coating	Passive	Anti	+ nearly zero energy consumption, low CAPEX; – limited effectiveness under severe icing, coating degradation

Source: created by the authors