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Review of Key Technologies and Engineering Applications of AI-Enabled Intelligent De-Icing Robots

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Abstract: Affected by global extreme climates, ice-covering disasters occur frequently, posing a significant threat to the safe and stable operation of power transmission lines, wind turbine generators, high-speed railway contact nets, and airport infrastructure. The traditional ice removal methods generally have problems such as high risks associated with high-altitude operations, low ice-removal efficiency, and insufficient adaptability to extreme conditions. Based on this, this paper comprehensively reviews the research progress and engineering applications of AI-enabled intelligent de-icing robots, thereby providing theoretical guidance and technical support for future technology optimization and large-scale engineering applications. Focusing on the "perception–decision–execution" technical framework of intelligent de-icing robots, the key technologies, including multi-source information fusion perception, intelligent ice-condition identification, autonomous path planning and motion control, reinforcement learning-based decision-making, and composite de-icing actuators, are comprehensively analyzed. Typical engineering applications in power transmission lines, wind turbine blades, high-speed railway catenary systems, and civil aviation airports are also reviewed and evaluated. The integration of artificial intelligence technologies significantly enhances the environmental perception, autonomous decision-making, and adaptability of intelligent de-icing robots under complex operating conditions, enabling the transition from manual operation to autonomous de-icing. These technologies effectively improve operational safety, efficiency, and intelligence levels. At present, intelligent de-icing robots have been successfully applied in the power, transportation, and renewable energy sectors, demonstrating promising engineering performance. Intelligent de-icing robots have become an important technological approach for improving the anti-icing and de-icing capabilities of critical infrastructures and exhibit broad application prospects. However, significant challenges remain in complex environments, adaptability to extreme operating conditions, energy supply and endurance, and the establishment of technical standards. Future research should focus on multi-robot collaborative operation, digital twin-enabled maintenance, cloud-edge collaborative intelligent control, green low-carbon de-icing, and blockchain technologies to further promote the autonomous, intelligent, and large-scale engineering deployment of intelligent de-icing robots.

1. Introduction

Ice accumulation is one of the major natural disasters that threaten the safe operation of critical infrastructure such as power grids, transportation, and energy systems. Under conditions of low temperatures, high humidity, and complex weather patterns, ice layers can easily form on the surfaces of power transmission lines, wind turbine blades, high-speed rail catenary systems, and airport facilities. This leads to increased equipment loads, heightened structural vibrations, and degraded operational performance; in severe cases, it can trigger circuit trips, tower collapses, equipment damage, or even widespread service outages [1]. According to relevant statistics, the massive ice disaster that struck southern China in 2008 alone caused over a thousand kilometers of power transmission lines to collapse, resulting in direct economic losses of over 100 billion RMB, while tens of millions of people suffered from electricity interruptions [2]. In the wind power sector, ice accumulation on blades can cause a significant reduction in annual power generation—up to 30% to 50%—which significantly impacts the utilization rate of renewable energy [3]. As a lifeline for national economic development, the normal operation of the power infrastructure system ensures the stable growth of the national economy. In the transportation sector, icing on airport runways and high-speed rail catenary systems directly jeopardizes transportation safety and can easily lead to serious public safety issues such as flight delays and train service suspensions [4].

Currently, ice control primarily relies on four traditional methods: manual de-icing, thermal de-icing, mechanical de-icing, and chemical de-icing. Although these methods can address basic icing issues, they generally suffer from shortcomings such as high safety risks, high labor costs, and relatively high energy consumption. Furthermore, they are difficult to adapt to complex operating conditions and cannot meet the development requirements for intelligent operation and maintenance of infrastructure. With the advancement of robotics technology, intelligent de-icing robots have gradually become essential equipment for ice management. By integrating mobile platforms, sensor systems, and de-icing actuators, they enable automated de-icing operations on target facilities [5].

Continuous advancements in artificial intelligence technology have opened new avenues for the development of intelligent de-icing robots. Through technologies such as deep learning, multi-sensor fusion, reinforcement learning, and cloud-edge collaboration, these robots can autonomously perceive their environment and identify icing conditions while simultaneously planning routes and dynamically adjusting operational strategies. This frees them from the limitations of manual remote control, enabling fully autonomous operations throughout the entire process. In particular, artificial intelligence technology demonstrates significant advantages in target recognition, dynamic path planning, adaptive control, and collaborative operations, serving as the core driving force behind the intelligent development of smart de-icing robots [6].

Research on intelligent de-icing robots has primarily centered on structural design, perception systems, motion control, de-icing mechanisms, and engineering applications, yielding a series of achievements in areas such as power transmission lines, wind turbines, high-speed rail catenary systems, and airport de-icing. However, existing studies mostly focus on individual technical aspects or specific application scenarios, and there is a relative lack of systematic research on the key technological framework and engineering application progress of AI-enabled intelligent de-icing robots. At the same time, numerous challenges remain in areas such as robustness in complex environmental perception, adaptability to extreme operating conditions, energy supply and endurance, and coordinated operations among multiple devices.

Based on this, this paper examines the current state of AI-enabled intelligent de-icing robot technology development, constructs a "perception–decision–execution" analytical framework, and systematically reviews progress in key technologies such as multi-source information fusion perception, autonomous decision-making and motion control, and intelligent de-icing actuators. By integrating typical application scenarios such as power transmission lines, wind turbines, high-speed rail catenary systems, and civil airports, it summarizes their engineering application outcomes and existing issues, and outlines future development trends, to provide a reference for the research and engineering application of key technologies for intelligent de-icing robots.

2. Core Technical Architecture of AI-Enabled Intelligent De-icing Robots

Intelligent de-icing robots are not merely mechanical devices, but rather comprehensive intelligent systems that integrate environmental perception, autonomous decision-making, motion control, and de-icing operations.

With the advancement of artificial intelligence technology, key technologies such as machine vision, multi-sensor data fusion, intelligent control, and autonomous navigation have continued to mature, enabling robots to perform intelligent operations in complex environments. The development of intelligent de-icing robots has undergone multiple generations of technological iteration, forming a clear generational evolution path from manual remote control to AI-driven autonomous operation, as shown in Figure 1.

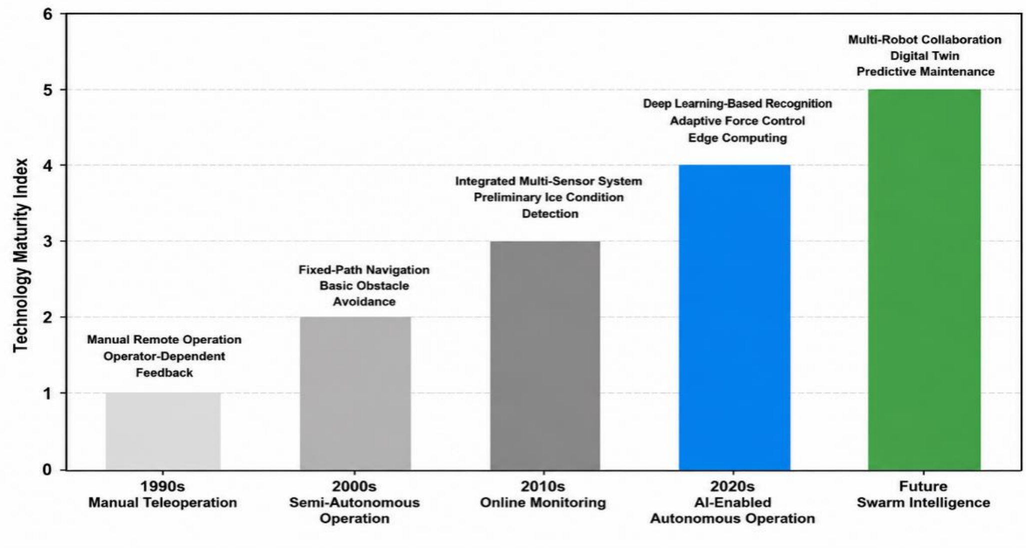

Fig. 1 Technology Evolution Roadmap of Intelligent De-Icing Robots

Currently, AI-enabled intelligent de-icing robots typically employ a three-tier technical architecture consisting of a “perception layer—decision-making layer—execution layer.” The perception layer is responsible for acquiring information about the environment and ice buildup; the decision-making layer handles status analysis, path planning, and the generation of operational strategies; and the execution layer manages motion control and the implementation of de-icing tasks. These three layers operate in concert to form a closed-loop “perception—decision-making—execution” control system, providing technical support for autonomous de-icing operations in complex environments [7].

2.1 Intelligent Perception Technology

Intelligent perception is the foundation for enabling autonomous operation of de-icing robots. Its core task is to acquire information on ice accumulation, equipment operating status, and the surrounding environment, thereby providing data support for subsequent path planning, motion control, and de-icing decision-making. In application scenarios such as power transmission lines, wind turbine blades, and railway catenary systems, robots must perform target recognition and status sensing under conditions of low temperatures, high humidity, strong winds, and complex lighting conditions. Consequently, this places high demands on the sensing system's accuracy, real-time performance, and robustness. The classification of key technologies in the perception layer of intelligent de-icing robots is shown in Table 1.

Table 1 Key Technologies Classification for Perception Layer of Intelligent De-Icing Robots

Technology Category	Representative Technology	Core Function
Vision-Based Perception	CNN, YOLO	Ice Accretion Recognition
LiDAR-Based Perception	LiDAR Sensing	3D Scene Reconstruction and Obstacle Detection
Infrared-Based Perception	Infrared Thermal Imaging	Ice Layer Identification and Temperature Monitoring
Multi-Modal Information Fusion	Multi-Sensor Fusion	Enhanced Perception Robustness and Environmental Awareness

Currently, de-icing robots often integrate a variety of sensing devices, such as visible-light cameras, infrared thermal imagers, LiDAR, millimeter-wave radar, and ultrasonic sensors. Among these, visible-light cameras are used to identify targets such as wires and hardware; infrared thermal imagers exploit the differences in thermal radiation between ice and the underlying material to clearly map the extent of ice coverage at night or in low-visibility conditions, thereby monitoring the distribution of ice thickness[8]; LiDAR emits laser beams to create precise 3D point cloud maps, providing the robot with accurate spatial positioning and obstacle ranging capabilities, which are crucial for path planning in complex terrain; meanwhile, millimeter-wave radar has strong penetration capabilities and can operate normally even in heavy snow or dense fog, making it suitable for detecting subtle vibrations in power lines and changes in their distance.

Deep learning-based visual perception technologies are gradually becoming the core sensing methods for intelligent de-icing robots. Convolutional neural networks (CNNs) and the YOLO series of object detection algorithms are widely applied to tasks such as ice-covered target recognition, ice thickness estimation, and equipment status monitoring, enabling rapid identification and localization of ice-covered areas in complex backgrounds. Related research shows that deep learning models trained on large amounts of data from real-world application scenarios achieve an ice accumulation recognition accuracy of over 95%, far surpassing previous simple threshold segmentation algorithms [9]. Furthermore, by utilizing multi-sensor data fusion methods such as Kalman filtering and Bayesian estimation, robots can integrate and complement information from various sensors, thereby establishing a robust and comprehensive environmental perception system that prevents them from becoming disoriented even under severe weather conditions.

Overall, AI-enabled intelligent perception technologies have significantly enhanced de-icing robots’ ability to recognize icing conditions, operational environments, and equipment status, providing a crucial foundation for autonomous decision-making and precise de-icing.

2.2 Autonomous Decision-Making and Motion Control Technologies

Autonomous decision-making and motion control are critical components for enabling intelligent operation of de-icing robots. Their primary tasks include path planning, obstacle avoidance, attitude adjustment, and optimization of operational strategies in complex environments, thereby ensuring that the robots complete de-icing tasks safely and efficiently.

Under traditional control modes, de-icing robots typically operate using preset trajectories or manual remote control, making it difficult for them to adapt to complex and ever-changing on-site environments. With the advancement of artificial intelligence technology, path planning algorithms, reinforcement learning algorithms, and intelligent optimization algorithms have gradually been integrated into the control systems of de-icing robots. Current path planning methods for autonomous mobile robots primarily include graph-search-based algorithms such as the A* algorithm and Dijkstra's algorithm, as well as intelligent optimization algorithms. These methods can dynamically adjust navigation strategies in response to environmental changes, thereby enhancing autonomous operation capabilities in complex scenarios [10,11].

Reinforcement learning technology simulates the dynamic interaction between the robot and its environment, enabling the robot to continuously optimize its decision-making strategies in response to environmental changes and thereby improve its autonomous operation capabilities under complex working conditions. Relevant studies indicate that reinforcement learning can effectively address the challenges of autonomous decision-making and dynamic control for robots in unstructured environments, providing new technical approaches for autonomous navigation and optimizing operational strategies in complex scenarios [12]. In power transmission line de-icing scenarios, reinforcement learning algorithms can dynamically adjust operation plans based on the degree of ice accumulation, line structure, and environmental conditions, thereby improving de-icing efficiency and operational safety.

In terms of motion control, de-icing robots generally employ methods such as PID control, fuzzy control, and model predictive control (MPC) to achieve attitude stability and trajectory tracking. Among these, PID control offers advantages such as a simple structure and mature engineering applications; fuzzy control can effectively address system nonlinearities and external uncertain disturbances, and generalized Type-II fuzzy logic control can significantly enhance the disturbance rejection capability of inspection robots [13]; Model predictive control comprehensively considers system constraints and future state changes; when combined with particle swarm optimization algorithms, it can effectively resolve attitude coupling issues under complex wind disturbance conditions, significantly improving trajectory tracking accuracy and system stability during de-icing operations [14]. In recent years, intelligent control strategies combining reinforcement learning with PID control have gradually become a research hotspot, further enhancing the robot's motion control performance in complex environments through autonomous optimization of control parameters [15].

Overall, the introduction of artificial intelligence technologies has enabled de-icing robots to gradually transition from traditional passive control modes to autonomous decision-making and adaptive control modes, effectively improving the robots' motion control accuracy and autonomous operation capabilities in complex environments, thereby laying the technical foundation for the engineering application of intelligent de-icing systems. The classification of key decision-making and control technologies for intelligent de-icing robots is shown in Table 2.

Table 2 Key Technologies Classification for Decision and Control of Intelligent De-Icing Robots

Technology Category	Representative Method	Core Function
Path Planning	A* Search, Dijkstra Algorithm	Optimal Path Planning and Navigation
Intelligent Decision-Making	Deep Reinforcement Learning	Autonomous Decision-Making and Task Planning
Motion Control	Proportional–Integral–Derivative (PID) Control	Stable Motion and Trajectory Tracking
Advanced Control	Model Predictive Control (MPC)	Robust Control in Complex and Dynamic Environments

2.3 De-icing Execution Technologies

The de-icing actuator is a core component of smart de-icing robots responsible for removing ice; its performance directly affects de-icing efficiency, equipment safety, and the effectiveness of engineering applications. Depending on the de-icing mechanism, smart de-icing robots currently primarily employ mechanical de-icing, thermal de-icing, laser de-icing, and hybrid de-icing technologies.

Mechanical de-icing is currently the most widely used method in engineering applications. Its basic principle involves applying mechanical force to the ice layer through scraping, striking, vibration, or rotating mechanisms to cause the ice to fracture or detach. This method offers advantages such as simple structure, high de-icing efficiency, and strong adaptability, and is widely applied in the de-icing of power transmission lines and wind turbine blades [16]. However, mechanical de-icing is prone to generating impact loads, which may cause damage to conductors, insulators, and blade surfaces; therefore, it places high demands on the motion control precision and force control capabilities of the actuators.

Thermal de-icing primarily raises the surface temperature of the iced area through methods such as electric heating, hot-air heating, or microwave heating, causing the ice layer to melt and detach from the target surface. Compared to mechanical de-icing, thermal de-icing causes less structural damage to equipment and is suitable for applications—such as insulators and wind turbine blades—where surface integrity is critical [17]. However, it consumes relatively high amounts of energy, and its de-icing efficiency is significantly affected by ambient temperature, which limits its application in scenarios involving large areas of ice accumulation.

Laser de-icing is a non-contact de-icing technology that uses high-energy laser beams to directionally heat the iced area, causing the ice layer to melt locally and detach. This method features high positioning accuracy, a high degree of automation, and strong adaptability to complex structures, making it particularly suitable for locations that are difficult to reach with traditional mechanical devices, such as insulator strings and complex connection points. At the same time, laser micro- and nano-machining technology can be used to create anti-icing surfaces with superhydrophobic properties, thereby reducing the adhesion strength of ice layers and achieving synergistic optimization of anti-icing and de-icing functions [18].

With the advancement of artificial intelligence (AI) technology, hybrid de-icing technology has gradually become a research hotspot. This technology integrates visual recognition, intelligent decision-making, and various de-icing methods to autonomously select the optimal de-icing strategy based on ice thickness, location, and environmental conditions. For example, thermal de-icing can be used for areas with light ice accumulation, while areas with heavy ice accumulation can employ a combination of mechanical and thermal de-icing, thereby comprehensively optimizing both de-icing efficiency and equipment safety. Relevant studies indicate that the combined use of electric heating and ultrasonic de-icing can effectively improve ice detachment efficiency and holds promising prospects for engineering applications [19]. The introduction of artificial intelligence enables de-icing robots to dynamically adjust operational parameters based on real-time environmental information, thereby enhancing their autonomous operation capabilities and de-icing effectiveness in complex environments.

Overall, different de-icing technologies each have distinct characteristics in terms of operational efficiency, energy consumption, equipment adaptability, and engineering costs. In the future, for engineering applications, hybrid de-icing technologies integrated with artificial intelligence will become a key development direction for intelligent de-icing robots. De-icing execution technologies are evolving from single-method approaches toward the integration of multiple technologies, and the introduction of artificial intelligence provides new technical support for optimizing de-icing strategies and implementing hybrid de-icing modes [19]. A comparison of de-icing execution technologies for de-icing robots is shown in Table 3.

Table 3 Comparison of De-Icing Execution Technologies for De-Icing Robots

De-Icing Method	Working Principle	Working Principle	Limitations	Typical Applications
Mechanical De-Icing	Mechanical Fracture and Removal of Ice	High efficiency and mature technology	May induce mechanical impact and structural stress	Transmission Lines and Wind Turbine Blades
Thermal De-Icing	Ice Melting by Thermal Heating	Minimal structural damage and simple control	High energy consumption	Insulators; Wind Turbine Blades
Laser De-Icing	Localized Laser Heating	Non-contact operation and high precision	High equipment cost	Precision Structures and Sensitive
Hybrid De-Icing	Multi-Technology Collaborative De-Icing	High adaptability and intelligent operation	High system complexity	Intelligent De-Icing Robots

3. Typical Engineering Application Scenarios and Practical Results

With the continuous development of artificial intelligence, machine vision, autonomous navigation, and intelligent control technologies, intelligent de-icing robots have gradually transitioned from the laboratory research stage to the engineering application stage, demonstrating promising prospects for application in areas such as power transmission lines, wind turbines, rail transit, and civil aviation support.

3.1 De-icing Applications on Power Transmission Lines

Power transmission lines are the primary application scenario for intelligent de-icing robots. Ice accumulation on power lines can lead to increased additional loads on conductors, deterioration of insulator insulation, and excessive stress on towers—all of which pose potential hazards and seriously threaten the safe and stable operation of the power grid. Utilizing intelligent de-icing robots to conduct inspections for ice accumulation and perform automated de-icing has now become a key technical measure for disaster prevention and maintenance of power transmission lines.

Currently, walking-type de-icing robots for overhead lines are the predominant type; these robots can attach themselves to overhead ground wires and move autonomously to remove ice. Take the ±800 kV Ultra-High Voltage Direct Current (UHV DC) project as an example: in the frigid mountainous regions of western Sichuan at an altitude of 4,000 meters, manual de-icing was previously nearly impossible. However, de-icing robots equipped with AI sensing systems can operate continuously in temperatures as low as minus 30 degrees Celsius and effectively clear severe ice buildup over up to 20km, thereby ensuring the unimpeded flow of power along the "West-to-East Power Transmission" artery. Furthermore, drone de-icing technology has been widely adopted. Drones equipped with robotic arms or blowing devices can rapidly fly to fault areas to perform emergency de-icing operations. The Kice-500 flying de-icing robot developed by State Grid Hunan Electric Power can complete the entire process—from startup to identification to de-icing—without any human intervention, demonstrating the transition of power grid operation and maintenance toward intelligent operation.[20].

3.2 Applications in Wind Turbine Blade De-icing

Ice accumulation on wind turbine blades is becoming increasingly prevalent in high-altitude and high-latitude regions. Ice buildup on blades reduces power generation, causes uneven loads, and consequently leads to turbine vibrations. To address this issue, wall-climbing de-icing robots have been developed.

These robots rely on vacuum suction or magnetic adhesion technology to firmly attach to the surface of fiberglass blades—which can be up to tens of meters long—and are equipped with heating and scraping devices to remove ice and snow from the blade surface. Artificial intelligence plays a decisive role: using visual SLAM technology, the robots independently perform positioning and navigation on the complex curved surfaces of the blades, and plan the optimal cleaning route, eliminating repetitive labor. Furthermore, through force-control algorithms, the robot can automatically adjust scraping force to thoroughly remove hardened ice layers without damaging the protective coating on the blade surface. Actual measurement results show that after robotic de-icing, the power generation efficiency of wind turbines can recover to over 98% of the normal range, significantly optimizing the economic returns of wind farms [21].

3.3 De-icing Applications in Rail Transit and Civil Aviation Facilities

In rail transit, ice accumulation on high-speed rail catenary systems directly interferes with current collection by pantographs and, in extreme cases, can even cause train service suspensions [22]. To address this issue, rail-mounted de-icing robots have been deployed. These robots travel along the tracks, and their robotic arms are equipped with rotating brushes or hot-air nozzles to remove ice from the surfaces of catenary wires and insulators. Using artificial intelligence algorithms, these robots can automatically adapt to train schedules, efficiently performing tasks during maintenance windows without damaging the catenary system.

In the civil aviation sector, aircraft de-icing is a critical component of flight safety. Traditional de-icing vehicles rely entirely on manual operation, resulting in low efficiency and inconsistent quality. However, AI-powered autonomous de-icing robots operate differently: they use LiDAR to identify aircraft models and locations, independently plan spraying routes, and precisely control the amount and direction of de-icing fluid sprayed, thereby optimizing de-icing efficiency while significantly reducing chemical waste and its environmental impact. Research from the Technical University of Denmark shows that automated de-icing systems can reduce the de-icing time for a single aircraft by 30 percent and save 25 percent on de-icing fluid usage [23]. A comparison of typical engineering applications for intelligent de-icing robots is shown in Table 4.

Table 4 Comparison of Typical Engineering Applications of Intelligent De-Icing Robots

Application Scenario	Iced Object	Primary Technologies	Advantages	Challenges
Power Transmission Lines	Conductors	Vision-Based Perception, Mechanical De-Icing	Mature technology and widespread deployment	Complex terrain and harsh operating environments
Wind Turbines	Wind Turbine Blades	Thermal De-Icing, Intelligent Control	High level of automation	Severe environmental conditions
Railway Catenary Systems	Contact Wires	Mechanical De-Icing	High operational safety	Limited working space
Airport Facilities	Aircraft and Ground Equipment	Laser De-Icing	High precision and non-contact operation	High implementation cost

Overall, intelligent de-icing robots have been put into practical use in scenarios such as power transmission lines, wind turbines, and railway catenary systems, demonstrating excellent de-icing performance and operational efficiency. The introduction of AI technology has significantly enhanced the robots' ability to identify icing conditions, make autonomous decisions, and adapt to complex environments. However, due to factors such as extreme weather conditions, energy supply capacity, and equipment reliability, intelligent de-icing robots still face certain challenges in their large-scale deployment.

As these engineering applications continue to be implemented, the related market has experienced explosive growth. Taking the power industry as an example, according to a QYResearch survey, the global de-icing robot market is projected to be approximately $360 million in 2025, reaching $559 million by 2032, with a compound annual growth rate (CAGR) of 6.5% from 2026 to 2032[24]. This clearly demonstrates that the market has a strong demand for and recognition of AI-powered intelligent de-icing technology, as shown in Figure 2.

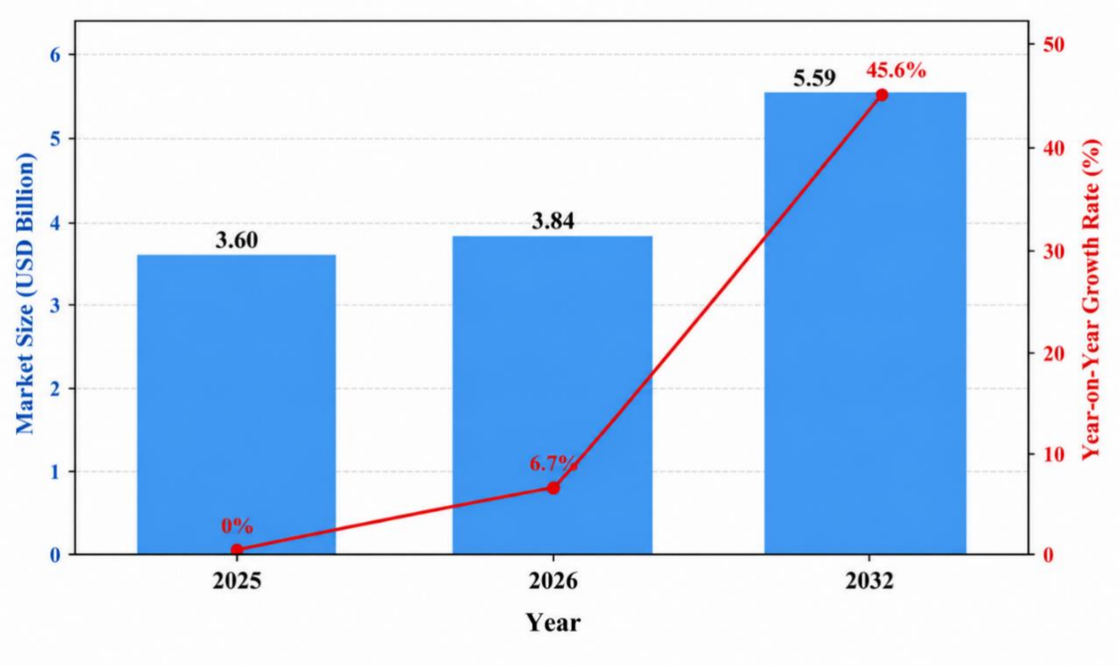

Fig. 2 Market Size and Growth Trends of Global Power Line De-Icing Robots

4. Current Challenges and Technical Bottlenecks

At this stage, AI-powered intelligent de-icing robots have made significant progress, achieving breakthroughs in environmental perception, autonomous decision-making, path planning, and operational control. However, in practical engineering applications, they still face many real-world challenges and technical bottlenecks, which limit their further adoption and application.

Intelligent de-icing robots typically operate in complex environments such as low temperatures, strong winds, rain and snow, and high altitudes, placing high demands on their mechanical structures, electronic components, and power systems. Low-temperature environments can cause lithium-ion battery capacity degradation and reduced output power, affecting the robot's operational endurance. Additionally, extreme environmental conditions such as strong electromagnetic fields and ultraviolet radiation also pose challenges to the robot's ability to operate stably over the long term [25].

In complex scenarios, there are also issues regarding the robustness of perception and decision-making. While AI algorithms perform well in laboratory settings, their performance in real-world natural environments is vastly different. For example, during severe weather conditions such as blizzards, the robot's visual sensors may be obstructed, and the point clouds generated by LiDAR may be disrupted by noise, which directly affects the accuracy of target recognition and status assessment. At the same time, factors such as the swaying of power lines, changes in ice formation, and complex terrain also increase the difficulty of motion control and path planning for robots. Most current reinforcement learning models are trained in simulation laboratories; when deployed in real-world environments, they are prone to the so-called "real-world gap," which can lead to decision-making errors. How to enhance the ability of AI models to cope with extreme disturbances is a major challenge currently facing research [26].

Insufficient energy supply is a key factor limiting the continuous operation of de-icing robots. Constrained by their own weight and load-carrying capacity, the energy storage systems on existing equipment have limited capacity, making it difficult to support continuous de-icing operations over long distances. Although research has been conducted on energy-harvesting technologies such as inductive power transfer and wireless power supply, these still face certain limitations during power-outage maintenance and in complex electromagnetic environments [27]. In the future, for large-scale operation and maintenance scenarios such as power transmission lines and wind farms, it will be necessary to improve energy storage capacity and energy utilization efficiency further to meet the demand for long-term, continuous operation required for autonomous maintenance of extensive networks.

5. Future Trends and Outlook

At present, the de-icing capacity of a single robot is limited. In the future, operations will involve collaborative clusters of multiple robots. Relying on 5G/6G communications and swarm intelligence algorithms, numerous small robots will form a "swarm" that divides tasks and works together to clear large areas of ice buildup [28]. Large-scale power grid de-icing requires the coordination of multi-robot swarms; however, full-scale interaction among a massive number of devices would place a heavy burden on edge computing power. By employing automatic swarm modeling based on a hard attention mechanism—which retains only communication with key neighbors—lightweight swarm control can be achieved. This approach offers outstanding robustness and scalability, providing cutting-edge theoretical support for self-organizing task allocation in air-ground integrated de-icing robots [29].

Digital twin technology and the integration of virtual and real worlds will be applied to de-icing operations and maintenance. By creating high-precision digital models of transmission lines and wind turbines in the cloud and projecting real-time data collected by robots into the virtual space, operations and maintenance personnel can pre-simulate de-icing procedures in a virtual environment, refine operational plans, and even perform remote, immersive control [30]. Predictive maintenance enabled by digital twins has also become feasible. By analyzing historical icing data, icing phenomena can be detected in advance, guiding robots to carry out preventive operations and achieving a shift from "post-event repairs" to "preemptive protection."

Future de-icing robots will be more than just simple de-icing tools; they will evolve into multifunctional integrated O&M platforms that combine patrols, inspections, de-icing, and repairs [31]. While performing de-icing tasks, the robot can use multimodal sensing devices to simultaneously identify issues such as line cracks, corrosion, and loose hardware, enabling an integrated "one-robot-multiple-functions" operational model. This integrated O&M solution not only significantly reduces the overall O&M costs of power infrastructure but also effectively improves equipment utilization efficiency, driving the development of power grid O&M toward greater intelligence and integration.

Against the backdrop of the "Dual Carbon" development goals, anti-icing and de-icing technologies for power equipment are transitioning toward low-carbon and green solutions, with low-energy-consumption technical approaches becoming the mainstream trend in the industry [32]. Combining superhydrophobic coatings, anti-icing materials with low interfacial toughness, and intelligent de-icing robots can establish an operational model that synergizes passive anti-icing with active de-icing, significantly reducing energy consumption during operations. Furthermore, new energy technologies such as solid-state batteries, solar charging, and wireless charging can further enhance the robots' operational capabilities.

In the future, intelligent de-icing robots may also integrate blockchain technology. Blockchain technology has already demonstrated promising application prospects in areas such as energy data management, full-lifecycle management of power equipment, distributed energy coordination, and the Energy Internet; its characteristics—including decentralization, immutability, and traceability—can effectively enhance the data security and coordination efficiency of energy systems [33]. Relying on distributed ledgers and encrypted evidence-preservation mechanisms, blockchain ensures that equipment operation data and operational logs are fully traceable and tamper-proof throughout their lifecycle. This traceability approach can be applied to the operational and maintenance data management of de-icing robot clusters, ensuring the reliability of data interactions among multiple stakeholders [34].

6. Conclusion

Currently, AI-enabled smart de-icing robots integrate multiple technologies—including artificial intelligence, autonomous decision-making, motion control, and intelligent execution—driving de-icing operations from traditional manual methods toward autonomy and intelligence. Smart de-icing robots have already been deployed in sectors such as power grids, wind power, and rail transit, effectively reducing operational risks and improving work efficiency, thereby providing robust support for the intelligent operation and maintenance of infrastructure.

Next-generation intelligent technologies—including cloud computing, big data, the Internet of Things (IoT), mobile internet, and artificial intelligence—will drive technological innovation in anti-icing and de-icing efforts, building an intelligent anti-icing and de-icing control platform characterized by "comprehensive perception of icing trends, holographic visualization of icing scenarios, end-to-end visibility of de-icing decisions, and full control over post-disaster emergency response" [35]. This will achieve full coverage of the power system and usher in a new era of anti-icing and de-icing.

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