

Remote dry ice blaster cleaning as a maintenance technique turbine blades in wind farms

Limpieza remota con blasteo de hielo seco como técnica de mantenimiento de álabes de turbinas en parques eólicos

Díaz-Herrera, Sebastián^{*a}, Cruz-Gómez, Marco Antonio^b, Mejía-Pérez, José Alfredo^c and Castillo-Pensado, Juan Luis^d

^a  Benemérita Universidad Autónoma de Puebla •  NLN-7761-2025 •  0000-0006-8130-8016 •  2132021

^b  Benemérita Universidad Autónoma de Puebla •  S-3098-2018 •  0000-0003-1091-8133 •  349626

^c  Benemérita Universidad Autónoma de Puebla •  G-3354-2019 •  0000-0002-4090-8828 •  473808

^d  Benemérita Universidad Autónoma de Puebla •  NOF-1935-2025 •  0000-0002-1172-4843 •  670346

SECIHTI classification:

Area: Engineering

Field: Engineering

Discipline: Mechanical Engineering

Subdiscipline: Mechanical design

 <https://doi.org/10.35429/JTO.2025.9.22.2.1.16>

History of the article:

Received: September 19, 2025

Accepted: December 10, 2025

*  [\[yadira.lopez@utna.edu.mx\]](mailto:yadira.lopez@utna.edu.mx)






Abstract




Wind energy, a zero-emission renewable energy source, has implemented increasingly larger turbine blades for greater production on land and offshore. The objective of this research was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. On the other hand, wind turbine blades with excellent aerodynamics increase their performance up to 6% annually. However, those without this technology will experience greater downtime, impacting their efficiency and profitability. A mixed analysis was performed to evaluate cleaning and maintenance methods for wind farm blades, identifying advantages and disadvantages through quantitative and qualitative methods. An analysis of existing blade cleaning methods was the trigger to propose an alternative remote cleaning method that meets the objectives of sustainable development and the circular economy. The optimization of this technology will be the subject of future work.

Resumen

La energía eólica fuente de energía renovables cero emisiones han implementado alabes de turbinas cada vez más grandes para mayor producción en tierra como mar adentro. El objetivo de esta investigación fue proponer un método criogénico de limpieza y mantenimiento remoto para alabes de aerogeneradores. Por otro lado, Los alabes de aerogeneradores con excelente aerodinámica aumentan su rendimiento hasta 6% anualmente, Sin embargo, los que no cuenten con esta, experimentaran mayores tiempos muertos impactando su eficiencia y rentabilidad. Un análisis mixto fue realizado en la evaluación de los métodos de limpieza y mantenimiento en alabes de parques eólicos, identificando ventajas y desventajas por métodos cuantitativos y cualitativos. Un análisis de los métodos existentes de limpieza de palas fue el detonante para proponer un método alternativo de limpieza remota que cumpla con los objetivos del desarrollo sustentable y la economía circular. La optimización de esta tecnología será motivo de trabajos futuros.

Remote dry ice blaster cleaning as a maintenance technique turbine blades in wind farms.		
Objectives	Methodology	Contribution
Propose cryogenic cleaning as a maintenance technique for wind turbines.	A focus was used on countries with the greatest development in wind farms and their characteristics.	The advantages offered by cryogenic cleaning in terms of operational efficiency, significant reduction in downtime, and environmental sustainability are highlighted.
		

Cryogenic cleaning, wind farms, operational efficiency

Limpieza remota con blasteo de hielo seco como técnica de mantenimiento de álabes de turbinas en parques eólicos.		
Objetivos	Metodología	Contribución
Proponer la limpieza criogénica como técnica de mantenimiento a turbinas eólicas.	Fue utilizado un enfoque en los países con mayor avance en parques eólicos y las características de estos mismos.	Se destacan las ventajas que ofrece la limpieza criogénica en temas de eficiencia operativa, reducción considerable de tiempos de inactividad y sostenibilidad ambiental.
		

Limpieza criogénica, parques eólicos, eficiencia operativa

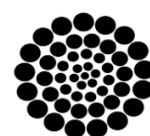
Area: Promotion of frontier research and basic science in all fields of knowledge

Citation: Díaz-Herrera, Sebastián, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo-Pensado, Juan Luis. [2025]. Remote dry ice blaster cleaning as a maintenance technique turbine blades in wind farms. Journal of Technological Operations. 9[22]1-16: e2922116.



ISSN: 2523-6806/ © 2009 The Author[s]. Published by ECORFAN-Mexico, S.C. for its Holding Taiwan on behalf of Journal of Technological Operations. This is an open access article under the CC BY-NC-ND license [<http://creativecommons.org/licenses/by-nc-nd/4.0/>]

Peer review under the responsibility of the Scientific Committee MARVID[®] in the contribution to the scientific, technological and innovation Peer Review Process through the training of Human Resources for continuity in the Critical Analysis of International Research.



RENIECYT

Registro Nacional de Instituciones y Empresas Científicas y Tecnológicas

1702902 SECIHTI

Introduction

A fundamental analysis of the design phase of a wind farm is that of reliability evaluated from a quantitative and qualitative point of view. Fixed offshore wind turbines require a higher economic budget than those located on land, with the increase in water depth due to the complex marine conditions.

Wind turbines installed on floating structures represent a viable solution offering; more flexible construction and installation procedures, insensitive to water depth, higher wind speed, more difficult maintenance procedures, less noise pollution, lower demolition cost. [Aafif et al. \(2022\)](#), [Albatayneh et al. \(2025\)](#), [Chan and Mo \(2017\)](#), [Jamshidi et al. \(2019\)](#), [Kang et al. \(2018\)](#), [Gonzalo et al. \(2022\)](#) and [Saleh et al. \(2023\)](#).

The adverse operating conditions of semi-submersible and fixed floating offshore wind turbines determined that failures have a greater incidence in the support structures, hydraulic system, gearbox, generator, and other systems. These are due to factors such as salt spray, waves, high wind speed, among others. Early fault detection allowed for the implementation of predictive maintenance strategies that can plan actions based on repair times, average repair costs, and average number of personnel required for repairs.

The most critical maintenance systems are corrective maintenance in gearboxes, generators, turbine blades, and hydraulic systems, which require longer downtimes. Maintenance strategies were implemented with cause-and-effect analysis of faults, in a plan to improve the design and optimize maintenance programs.

In semi-submersible and fixed floating offshore wind turbines, it was identified that the mooring system - support structures (mooring line breakage, abnormal tension of turnbuckles, failure of anchor, buoys and fairleads) were the most prone component to failure with a rate of 17%, failures to hydraulic and pitch systems have a failure frequency around 13%, the generator with a frequency 12%, the gearbox and speed train with 8% representing the failures with the highest downtime due to repair that influence the performance of the wind turbine with impacts on the production of the wind farm.

On the other hand, lower incidence failures are electronic components and automatic control systems. [Aafif et al. \(2022\)](#), [Adedeji et al. \(2022\)](#), [Albatayneh et al. \(2025\)](#), [Begun and Schlickewei \(2024\)](#), [Chen et al. \(2021\)](#), [Ding et al. \(2025\)](#) and [Kang et al. \(2018\)](#).

The factors influencing the failure generation of semi-submersible and fixed floating offshore wind turbines are impact by brought or fallen objects, lightning strike, wind, aircraft accident, biological collision, strong waves, storm, typhoon, human error, poor operating environment, insufficient emergency measures.

As a result, collision protection measures, sophisticated weather forecasts, emergency response plans to reduce losses, and periodic detection to ensure the condition of the pillars are required. [Jamshidi et al. \(2019\)](#) and [Kang et al. \(2018\)](#).

Wind energy, a renewable energy source, has implemented increasingly longer and larger composite blades that allow for greater production of viable wind energy for electric power generation.

Monitoring the condition and maintenance of blades prevents damage, detects structural defects, and prolongs the turbine's lifespan in both offshore and onshore environments. [Lopez and Kolios \(2022\)](#), [Danesh et al. \(2025\)](#), [Global Wind Energy Council, \(2024\)](#), [Katsaprakakis et al. \(2021\)](#) and [Saleh et al. \(2023\)](#).

Wind turbine blades can suffer damage such as delamination, spalling, cracks, erosion, fouling, and coating by layers of contaminants, which cause changes in the roughness of the blade surface, negatively impacting aerodynamic performance.

Because of this, it is necessary to evaluate the degradation, performance, and condition to determine reliability and sustainability through technologies such as digital twins (virtual representation of comparison with real-time model update). The evaluation of blade conditions uses techniques and tests under international standards adaptable to each type of inspection and decision-making.

These can be maintenance techniques, tests (ultrasonic, thermography, radiographic, electromagnetic, acoustic emission, shearography), comparison and complementarity between analysis methods for decision-making, and real-time monitoring through technologies with artificial intelligence. [Aafif et al. \(2022\)](#), [Bošnjaković et al. \(2025b\)](#), [Chan and Mo \(2017\)](#), [Danesh et al. \(2025\)](#), [Leon-Medina et al. \(2025\)](#) and [Sheehan et al. \(2025\)](#).

The objective of this research was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. An analysis of existing blade cleaning methods was the trigger to propose an alternative remote cleaning method that meets the objectives of sustainable development and the circular economy. [Lopez and Kolios \(2022\)](#), [Cold Jet Dry Ice Production, n.d., \(2025\)](#) and [Saleh et al. \(2023\)](#).

Turbine blades are manufactured with a load-bearing spar that serves as a structure that provides strength and stiffness to the casing, with thin, pre-twisted walls to counteract compression, tension, and torsion-induced deformations during bending and buckling operation. The wind turbine blade has suction and pressure sides to optimize aerodynamic performance, and these sides are formed at the leading and trailing edges and flaps. Turbine blades must also withstand environmental conditions that include; humidity, fatigue, wind gusts, salinity environments, sand, lightning strikes, rain, hail, dust, ice, and insect contamination, which cause them to gradually develop defects. [Zhang and Tee \(2019\)](#).

How can efficient maintenance programs be achieved that meet the objectives of sustainable development and the circular economy, focusing on wind turbine blade cleaning and improving aerodynamics, directly linked to increased electricity generation and profitability?

For wind turbine blade cleaning monitoring, it is essential to use and develop advanced techniques to meet the need to reduce repair costs through early detection and removal of contaminants, thereby increasing the lifespan of wind turbines.

Therefore, remote-controlled non-destructive methods (visual, optical, ultrasonic, electromagnetic, thermal, and radiographic) have been developed to inspect blades using real-time monitoring databases with machine learning and comparison of classified characterization models for interpretation and decision-making. [Bošnjaković et al. \(2025b\)](#), [\(Cold Jet, 2025b\)](#), [Lopez and Kolios \(2022\)](#), [Danesh et al. \(2025\)](#) and [Sheehan et al. \(2025\)](#).

There are several methods used for the removal of industrial contamination. These methods are divided into physical, chemical, and physicochemical. In this research, dry ice cleaning is an abrasive physical method for the removal of industrial dirt. The cleaning mechanism is based on three main steps: surface subcooling, contamination fracturing due to the decrease in temperature, and dry ice sublimation, with rapid volume expansion that causes the propagation of contaminant cracks and the subsequent removal of dirt.

Finally, residual particles are carried out of the cleaning zone by the gas flow. The safety of dry ice cleaning technology is a decontamination method with minimal controlled surface erosion, no secondary residue, no phase change of contaminants, and no massive damage to the morphology of the part. This method is safe, and the material removal rate can be considered almost zero under optimized method conditions, considering that it influences a controlled surface roughness pattern and depends on factors such as: mixture percentages, dry ice particle size, mixing fluid velocity at the nozzle, angle of attack, and application distance, but does not affect the microstructure of the materials and controls the roughness pattern uniformly. The dry ice cryogenic cleaning method meets all specifications for cleaning wind turbine blades in accordance with international regulations, sustainable development goals, and the circular economy. [Admin \(2025\)](#), [\(Global Wind Energy Council, 2024\)](#) and [Todorović \(2025b\)](#). The optimization of this technology will be the subject of future work.

Research methodology

This research adopted a mixed approach, applying both quantitative and qualitative technologies, utilizing systematic processes, as well as records and estimated data.

The objective of this research was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. To this end, the application of the quantitative method was relevant in identifying control variables involved in previous studies evaluating cleaning and maintenance methods for wind farm blades, identifying advantages and disadvantages. An analysis of existing blade cleaning methods was the trigger for proposing an alternative remote cleaning method that meets the objectives of sustainable development and the circular economy. Quantitative indices of wind power generation reports based on mixed records determine that contaminated wind turbine blades decrease their productivity by 2% to 6%. On the other hand, the experiences of wind farm personnel qualitatively identify that damage to wind turbine blades due to contaminants, lightning damage, and wear are the main cause of loss of efficiency in the wind turbine system. This coincides with scientific reports, contrasting the experience and statistics that were considered as the application of the mixed method that allowed the possibility of obtaining results from the estimation of variables, which played an important role in decision-making.

A mixed analysis was performed in the evaluation of cleaning and maintenance methods on wind farm blades, identifying advantages and disadvantages by quantitative and qualitative methods. The operational data resulting from this research determined that, for monitoring wind turbine blade cleaning, it is essential to use and develop advanced techniques to meet the need to reduce repair costs through early detection of contaminants and their removal that allow increasing the useful life of wind turbines.

Therefore, remote-controlled non-destructive methods (visual, optical, ultrasonic, electromagnetic, thermal, and radiographic) have been developed to inspect blades using real-time monitoring databases with machine learning and comparison of classified characterization models for interpretation and decision-making. Finally, using a mixed method, an analysis of the control variables was performed, allowing for an understanding of how to achieve efficient maintenance programs that meet the objectives of sustainable development and the circular economy, focusing on cleaning wind turbine blades that improve aerodynamics directly linked to increased electricity generation and profitability.

This research proposes the cryogenic dry ice cleaning technique after being evaluated based on its technical process variables in a quantitative manner as a physical abrasive method for the removal of industrial dirt. The safety of dry ice cleaning technology was qualitatively evaluated as a decontamination method with controlled surface erosion, without secondary residues, without phase change of the contaminants and it is proposed to evaluate in a mixed way, which does not generate damage to the morphology of the part through digital twins. (Akgül, 2024, Admin (2025b), Albatayneh et al. (2025), Bošnjaković et al. (2025b), Leon-Medina et al. (2025), Li et al. (2022) and Liu et al. (2023).

Classification of faults in wind turbines

The global wind energy market has experienced rapid growth as countries strive to reduce carbon emissions and transition to renewable energy sources. These environments expose turbines to various stressors, such as extreme weather conditions, UV radiation, saltwater corrosion, and abrasive particles, which affect their durability and efficiency. The wind industry is facing increasing pressure to improve turbine longevity and reliability while minimizing maintenance costs. This is essential to ensure the long-term sustainability and profitability of wind energy operations (Aafif et al. (2022), Chan and Mo (2017), (Global Wind Energy Council, 2024) and Saleh et al. (2023).

The ten countries with the largest wind power generation capacity are: China with 460 GW, the United States with 150 GW, India with 60 GW, Germany with 45 GW, the United Kingdom with 39 GW, France with 25 GW, Spain with 20 GW, Brazil with 19 GW, Poland with 15 GW, and South Africa with 12 GW. Albatayneh et al. (2025) and Global Wind Energy Council, (2024). Blades are one of the most important components of a wind turbine. Failures related to the blade system include: structural failure, rotor system, tip damage, edge damage, casing damage, hub damage, bearing wear, split tip, lightning strike, edge cracks, erosion, leading and trailing edge delamination, spalling, casing delamination, beam-to-casing joint crack, root clearance, uncontrolled surface roughness, unbalance, pitch mismatch, pin corrosion, element deformation, and fatigue of fibrous composite materials. Lopez and Kolios (2022), Katsaprakakis et al. (2021b) and Zhang and Tee (2019).

Díaz-Herrera, Sebastián, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo-Pensado, Juan Luis. [2025]. Remote dry ice blaster cleaning as a maintenance technique turbine blades in wind farms. *Journal of Technological Operations*. 9[22]1-16: e2922116 <https://doi.org/10.35429/JTO.2025.9.22.2.1.16>

The yaw system keeps the wind turbine aligned with the main wind direction as it changes under normal operating conditions. Wind speed generates load fluctuations on the blade surfaces depending on the angle of attack. Optimization of the wind turbine rotor torque is based on changes in yaw angle. If the yaw system is not synchronized between blades or has a suboptimal angle of attack, it will generate vibrations in the blades, tower, and nacelle. An imbalance in the blade system can even endanger the safety of the wind turbine, even to the point of destruction. Damage to composite wind turbine blades can be classified as: debonding of the skin/adhesive or main spar/adhesive layer, failure of the adhesive bond between the skins on the upwind and downwind leading or trailing edges, debonding of the sandwich panel face/core, delamination caused by tensile loading or buckling, and fiber failure in tension. Compression laminate failure, buckling-induced coating/adhesive peeling, gel coat cracking, and gel coat/coat peeling. Lopez and Kolios (2022) and Katsaprakakis et al. (2021b).

To identify critical failure events, methods are used to obtain sets of cuts. This is an algorithm to verify the reliability of the system or component through resolution of fault trees such as; the yaw system, logic gates, codes, yaw motor, drive alarm, meteorological unit, limit switch, among others. Chan and Mo (2017) and Ding et al. (2025).

The failure rate of wind turbines varies depending on the subsystem and varies between onshore and offshore systems, where severe environmental conditions such as storms, corrosion, leaks, salt spray, sandstorms, and high wind speeds significantly impact turbine reliability and availability. A previous assessment estimated that failure rates for electrical and electronic components and blade systems are seven times higher than for onshore turbines. However, for gearboxes and drivetrain systems, the approximate annual failure rate was estimated to be around four times higher than for onshore turbines. Therefore, planned maintenance periods should be less than 50 days. Aafif et al. (2022), Chan and Mo (2017), Chen et al. (2021), Dagdag and Kim (2024b), and Schouten et al. (2021).

Wind turbine blade inspection methods are divided into contact methods (magnetic, electromagnetic, eddy current, traditional ultrasonic, and liquid penetrant testing) and non-contact methods (visual inspection, ultrasonic, acoustic, mechanical vibration, electromagnetic, thermographic, radiographic, and shearographic techniques).

The failure frequencies in gearbox systems are shown in Figure 1. These are; control failure 0.25, sensor failure 0.19, hub failure 0.14, yaw system failure 0.12, converter failure 0.11, structural failure of the blades 0.07, brake failure 0.04, transformer failure 0.035, drive train failure 0.03 and bearing failure 0.028 Chen et al. (2021) and Gong and Chen (2024).

Box 1

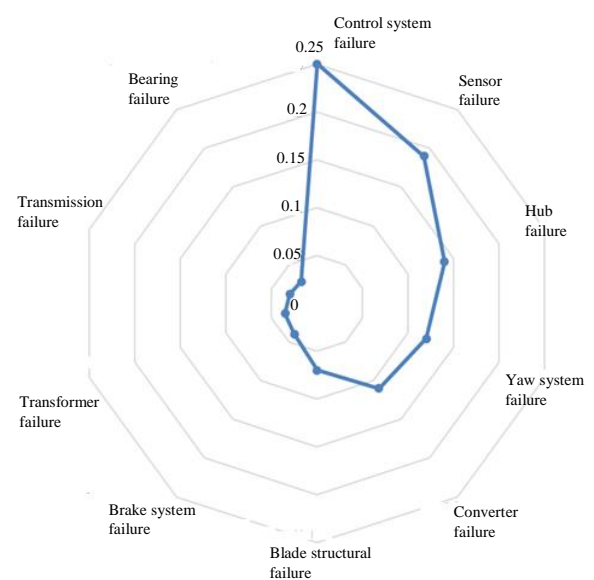
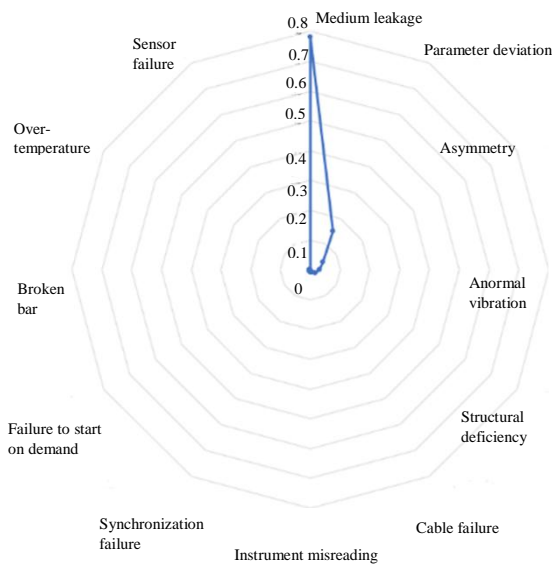


Figure 1

Failure frequency per year in gearbox systems.

Source: Own Elaboration

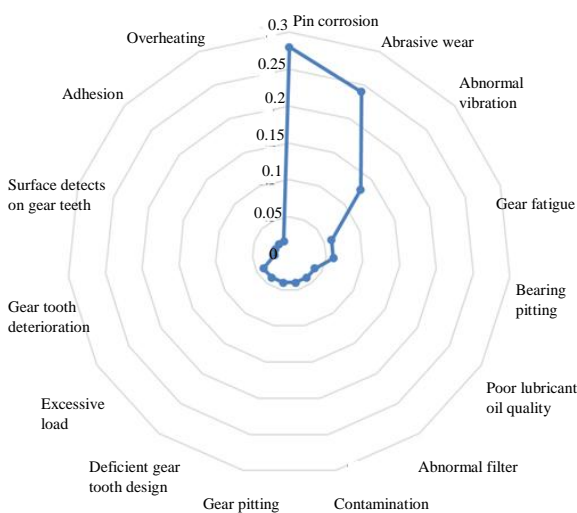
The fault frequencies in generator systems are shown in Figure 2. These are; media leakage 0.78, parameter deviation 0.15, asymmetry 0.05, abnormal vibration 0.03, structural deficiency 0.02, cable failure 0.01, instrument misreading 0.008, synchronization failure 0.006, failure to start on demand 0.004, broken bar 0.003, temperature over limit 0.002 and sensor failure 0.001 Chen et al. (2021) and Gong and Chen (2024).

Box 2**Figure 2**

Frequency of failures per year in generator systems

Source: Own Elaboration

The frequency of failures in other wind turbine systems. You can see in Figure 3. These are; pin corrosion 0.28, abrasive wear 0.24, abnormal vibration 0.13, gear fatigue 0.06, bearing pitting 0.06, poor lubricating oil quality 0.04, abnormal filter 0.04, dirt 0.04, gear pitting 0.04, poor gear tooth design 0.04, excessive pressure 0.04, gear tooth deterioration 0.02, tooth surface defects 0.02, sticking 0.019, and overheating 0.018. [Ding et al. \(2025\)](#) and [Schouten et al. \(2021\)](#).

Box 3**Figure 3**

Failure frequency per year of other wind turbine systems.

Source: Own Elaboration

Materials and manufacturing of wind turbine blades

The materials and manufacturing processes used in wind turbine blades must meet low density, high strength, stability, elasticity, and rigidity requirements to ensure optimal aerodynamic performance in the face of lightning strikes, humidity, temperature, and salt and sand storms. Therefore, they are manufactured with glass or carbon fiber reinforcement in a polymer matrix (epoxy or polyester); Covestro and Arkema Elium infusible polyurethane thermoplastic resins for longer blades; sandwich core materials (polyvinyl chloride, polyethylene terephthalate, styrene-acrylonitrile, or balsa wood); bonded joints, cladding (polyurethane), and lightning rods. Material combinations are chosen considering the cost of the vacuum-assisted resin transfer molding manufacturing process and resin infusion technologies.

The geometric nonlinearity of an infusion-manufactured wind turbine blade can cause crack damage that increases with local buckling, the Brazier effect, and large deformations under complex loads in service. The fibers used in blades can be: carbon fibers have greater stiffness and lower density than glass fibers; E-glass fibers; alkali-free, made from calcium alumina borosilicate; S-glass fibers; made from magnesium aluminosilicates; R-glass fibers; made from calcium aluminosilicates. On the other hand, aramid fibers (aromatic polyamide) but with serious disadvantages low compressive strength, low adhesion to polymeric resins; they absorb moisture; they degrade due to ultraviolet radiation. Basalt fibers; 30% stronger, 15-20% stiffer and 8-10% lighter than E-glass; and lastly, and with greater disadvantages, natural fibers; sisal, flax, hemp etc., which are hydrophilic and have poor adhesion to both thermoplastic and thermosetting polymers. [Lopez and Kolios \(2022\)](#).

Wind turbine blade maintenance

Wind turbine blade maintenance ensures their efficiency, safety, and longevity. Regular inspections detect cracks, erosion, lightning damage, and structural integrity. Maintaining aerodynamic performance requires high-tech access and logistics methods with real-time monitoring, such as drones and database transfer via artificial intelligence.

On the other hand, traditional methods such as ropes (ideal for rapid mobilization for small repairs) and gondolas (carrying more tools and materials for multi-hour jobs), with the associated insecurity, and jack-up or service vessels (onboard workshops for blade changes or heavy repairs offshore). However, traditional maintenance techniques continue to thrive due to maneuvering limitations, maintenance methods that high technologies cannot currently cover. [Aafif et al. \(2022\)](#), [Adedeji et al. \(2022\)](#), [Bošnjaković et al. \(2025b\)](#), [Danesh et al. \(2025\)](#), [Kong et al. \(2022\)](#) and [Yan et al. \(2023\)](#).

Wind turbine maintenance programs begin at the beginning of their useful life in an initial phase of 0-5 years; manufacturing defects are identified, a performance baseline is established, adhesion checks of the leading and trailing edge protection and verification of surface quality are carried out. In the intermediate phase of their useful life, corresponding to 5-20 years, uptime is maximized and wear is addressed.

Finally, in the final stage of their useful life of 20-25 years, conservation maintenance is carried out to allow safe and profitable operation with a view to a decommissioning program aligned with circular economy objectives. [Aafif et al. \(2022\)](#), [Adedeji et al. \(2022\)](#), [Begun and Schlickewei \(2024\)](#), [El-Naggar et al. \(2023\)](#) and [Zavvar et al. \(2025\)](#).

Proactive maintenance in wind turbine blades is an advanced asset management strategy focused on preventing failures before they occur based on identifying and eliminating root causes using historical data and predicts acting when data indicates it, which reduces downtime, improves safety, optimizes costs and prolongs the turbine lifespan. Visual and thermographic drone scans to detect surface erosion, delamination or underground voids, practical checks for leading edge notches, tip rounding, blade balancing, cleaning and recoating to restore the airfoil, patching or composite infusion for surface cracks/delamination, reapplication of erosion resistant coatings are proactive maintenance activities in wind turbine blades. [Lopez and Kolios \(2022\)](#), [El-Naggar et al. \(2023\)](#), [Kaewbumrung et al. \(2024\)](#), [Schouten et al. \(2021\)](#) and [Zavvar et al. \(2025\)](#).

SCADA-integrated wind turbine blade monitoring detects vibration, acoustic/leak sensors, detachments, and cracks early on. Complete routine inspections are performed every 6 to 12 months using drones, depending on the requirements of the database indicators. Maximizing aerodynamic performance directly impacts energy efficiency, as small areas of erosion on the leading and trailing edges reduce production by 1% to 3%. Failure prevention will prevent unplanned shutdowns or catastrophic blade losses.

Drone imaging has revolutionized wind turbine blade inspections. High-resolution visual cameras capture ultra-sharp images (up to 40 MP) of blade surfaces to detect cracks, erosion, lightning, and delamination. Drones also feature infrared (thermal) imaging technologies, which can remotely detect defects in blade coatings and substrates, as well as moisture penetration and bond failures, in the absence of light. LiDAR (Light Detection and Ranging): 3D models of blade geometry to identify deformations. Multispectral imaging: Useful for detecting material degradation or coating wear that is imperceptible to the naked eye. [Lopez and Kolios \(2022\)](#) and [LiDAR Technology, n.d.-b, \(2025\)](#).

Cleaning methods for wind turbine blades

Manual cleaning-washing and repair method; technicians rappel from a suspended rope or an elevated gondola platform, taking advantage of favorable weather conditions. Cleaning is carried out using low-pressure water spray, soft brushes, and mild biodegradable detergents to remove sand, salt, and biological debris adhering to the blade. Techniques include sanding, painting, finish marking, repairing or replacing the erosion shield, filling composite cracks and curing resin, dynamic balancing, efficient water management at remote sites, and completing repair logs. Visually and manually inspecting blades may overlook details or make errors due to fatigue and spatial identification of the fault. [Zhang and Tee \(2019\)](#) and [Zhang W. et al. \(2025\)](#).

Robotic scrubber and drone cleaning method: Self-propelled robots or multi-rotor drones equipped with rotating brushes or ultrasonic transducers can inspect and clean blades autonomously.

By integrating cameras and humidity sensors, they record coverage maps in real time, ensuring thorough blade treatment with minimal human supervision. However, this technique has limitations in cleaning performance due to the variables that influence adhesion removal and the final finish obtained, making it dependent on the manual method. Gong and Chen (2024). Laser ablation cleaning method; is an emerging, non-contact, innovative, and environmentally friendly technique that uses optimized pulsed lasers to vaporize contaminants (bird droppings, oxidation layers) generating a plasma column that emits light, which can be analyzed by breakdown spectroscopy to identify the chemical composition of the dirt without damaging the composite substrate. Laser systems can simultaneously analyze the material composition, providing operators with immediate information on cuticle depth and cleaning effectiveness. This method integrates robotics and drones for remote and automated cleaning, but is still under development, however, it promises to reduce downtime and improve turbine efficiency by up to 40% with faster, safer, and more sustainable maintenance. Adedeji et al. (2022), Begun and Schlickewei (2024), Kaewbumrung et al. (2024) and Zavvar et al. (2025).

Cleaning method: hydrophobic coatings; the application of non-stick films instead of routine low-surface-energy washes facilitates water film cleaning and reduces fouling adhesion by more than 50%. When combined with occasional light cleaning, these coatings extend cleaning intervals while maintaining the blade's aerodynamic efficiency.

Mixed cleaning methods: By combining traditional rope-access washing with robotics, coatings, and even lasers, modern wind farms can keep blades operating at peak aerodynamic performance with less risk, less water consumption, and fewer man hours.

Recommendations: Always follow a documented cleaning-inspection cycle to detect damage early; collect cleaning efficiency data in a maintenance management system to optimize cleaning programs and reduce costs. Use environmentally certified detergents and closed-loop water systems to minimize ecological impact, especially in sensitive landscapes. Abderrahmane et al. (2022) and Dagdag and Kim (2024b).

Remote trajectory capture is Artificial Intelligence.

Drone flight patterns and data capture follow preprogrammed flight paths around each blade (non-destructive, non-contact testing), using GPS and obstacle avoidance sensors to maintain a constant distance and angle. This coverage achieves a 360° sweep by orbiting the turbine and capturing images from multiple elevations and angles. They use AI-based flight control to automatically focus on areas of interest, such as leading edges or known stress zones. Image processing and data analysis are uploaded to cloud platforms where AI algorithms detect anomalies and classify damage types by wear pattern. Results are often visualized in interactive 3D models or digital twins, allowing engineers to analyze defects in greater detail and plan repairs. Standardized flight paths of 30 minutes or less allow blade inspections to be performed while the turbines are still in operation. This ensures a full sweep of consistent data for digital twin analysis. Leon-Medina et al. (2025), Li et al. (2022), Liu et al. (2023), Shah et al. (2024), Yan et al. (2023) and Zeitler et al. (2023).

Optimizing drone route recording using Artificial Intelligence.

Automated route planning is performed using a genetic algorithm that optimizes the shortest and most efficient route to maximize coverage and minimize battery life using dynamic reinforcement learning. Real-time route adaptation and the use of sensors (LiDAR, cameras, GPS) feed AI models with continuous data, enabling instant obstacle detection and avoidance. Drones adjust their trajectories on the fly in response to weather changes, moving objects, or unexpected no-fly zones. Optimal flight sequences reduce inspection times and labor costs. Energy-monitoring algorithms plan energy-efficient trajectories by optimizing swarm coordination to synchronize multiple drones, sharing position data to maintain formations and avoid collisions. Past data and route management optimize machine learning. Vision-based simultaneous localization and mapping in GPS-deprived environments represents one of the maintenance trends for wind turbine blades. El-Naggar et al. (2023), Gong and Chen (2024), Kaewbumrung et al. (2024), Kong et al. (2022) and LiDAR Technology, s. f.

Artificial intelligence algorithms are programmed to recognize, categorize by type and severity the patterns in thermal images, detecting anomalies such as delamination, moisture ingress and tribological faults, eliminating the need to manually review thousands of images reducing human error and fatigue prioritizing repairs based on risk and urgency under trend analysis and repeatable digital twin integration across turbine batches making it ideal for wind farms with global repeatability. Artificial Intelligence and Machine Learning faces obstacles and challenges such as false positives, data capture assurance, standardization, compatibility between models, "long tail" cases lack of credibility based on the explainable, data privacy, continuous updating and budget injection top state of the art at all times. [Albatayneh et al. \(2025\)](#), [Bošnjaković et al. \(2025\)](#), [Ding et al. \(2025\)](#), [Kong et al. \(2022\)](#), [Li et al. \(2022\)](#), [Shah et al. \(2024\)](#), [Sheehan et al. \(2025\)](#) and [Zhang W. et al. \(2025\)](#).

Remote cleaning analysis and comparison with digital twins

Wind turbine blades accumulate dust, pollen, salt, sand, insects, bird droppings, and soot, especially near deserts, farms, or offshore areas. This buildup hardens the leading and trailing edges, altering the blade's aerodynamic profile. This increases drag, reduces lift, and reduces annual energy production by 2% to 6%, resulting in thousands of dollars in lost revenue per turbine per year.

Uncontrolled surface roughness causes turbulent flow and unstable aerodynamic loads, accelerating blade and powertrain fatigue. The debris becomes a source of corrosion from ice or salt, eroding the composite surface and shortening blade life. Non-destructive testing methods (ultrasound, thermography) require clean surfaces to detect cracks or adhesion defects. A clean blade guarantees accurate condition monitoring. Meanwhile, smart coatings integrate de-icing technologies or hydrophobic surfaces that repel water and prevent ice from adhering. Especially those reinforced with nanoparticles such as graphene, these coatings resist this erosion, preserving lift and reducing drag. The coatings are designed to last longer and self-heal from minor damage, improving aerodynamic performance by maintaining a smooth and clean surface. [Zhang and Tee \(2019\)](#) and [Zhang W. et al. \(2025\)](#).

AI algorithms process real-time data from sensors embedded in or near the blades, measuring vibration, stress, temperature, and acoustic signals. These patterns indirectly help detect anomalies such as cracks, delamination, or ice buildup before they become critical due to changing sensor signal patterns. AI models are run directly on-site using edge computing devices, Artificial Neural Networks (pattern recognition and anomaly detection), Convolutional Neural Networks (for analyzing images and acoustic spectrograms), Fuzzy Logic Systems (uncertainty removal), Genetic Algorithms (natural selection that optimizes inspection programs), and statistical methods, such as Decision Trees (reference modeling and trend analysis), reducing the need to send large amounts of data to the cloud.

This enables faster diagnostics and lower latency in remote wind farms. By learning from historical performance and failure data, AI can monitor, learn, protect, and predict when a blade is likely to need cleaning, repair, or replacement, minimizing downtime and maximizing energy consumption. [Liu et al. \(2023\)](#), [Zavvar et al. \(2025\)](#), and [Zeitler et al. \(2023\)](#).

Proposal for cryogenic cleaning of blades using the dry ice blasting method

Dry ice cryogenic blasting is a cleaning equipment method that offers a powerful and environmentally friendly alternative to laser, sand, soda, and various traditional abrasive methods. Dry ice blasting uses solid CO₂ pellets at -70°C. Upon impact with the surface to be cleaned and pressure changes, they sublimate, removing contaminants without damaging underlying surfaces or leaving secondary residue. [Admin \(2025b\)](#) and [Dagdag and Kim \(2024\)](#).

The pellet size (0.3–3.0 mm) ensures application-specific cleaning performance. Sure, Flow Feed: Vibration agitation and ramrod flow ensure continuous pellet feeding. The insulated hopper or tank maintains pellets at maximum cleaning temperature. Smart Interface: Programmable and monitor real-time performance metrics for consistent results. Non-abrasive and non-conductive: Safe for delicate parts, electrical equipment, and finished surfaces. - Zero secondary waste: CO₂ pellets are vaporized, eliminating media disposal costs.

Clean-in-place: No disassembly or drying required, less downtime and fewer man-hours. Environmentally friendly: Recycled CO₂ helps companies meet their sustainability goals and promotes a circular economy. Factory air supply or compressor (110V/220V). Hose and nozzle: Variety of diameters and shapes to tailor ice and air flow. Dry ice supply: On-site pelletizer or external supply. It is a production system that goes beyond cleaning on-site dry ice production machines that convert recycled CO₂ into pellets, ensuring consistent ice quality and reducing logistics costs. This comprehensive approach integrates shot peening and manufacturing to maximize uptime and sustainability. [Admin \(2025b\)](#).

Custom nozzle designs optimize reach and pattern for complex geometries. Industry-specific applications include mold cleaning for plastics, rubber, and foams, automotive, electrical equipment maintenance, food, energy, nuclear decontamination, aerospace production, surface pretreatment, lead paint removal, restoration, and countless other applications where cleaning must not leave behind additional residue or change the state of matter. [Aafif et al. \(2022\)](#), [\(International Organization for Standardization, 2017\)](#) and [Manikowski et al. \(2025\)](#).

ISO 21072-1:2019, in its general requirements for cryogenic cleaning equipment, covers performance, safety interlocks and materials compatibility cryogenic equipment. Doc. EIGA 170/21 design, operation, maintenance. [Abderrahmane et al. \(2022\)](#), [Albatayneh et al. \(2025\)](#), [\(Cold Jet, 2025\)](#), [\(International Organization for Standardization, 2004\)](#) and [Cold Jet Dry Ice Production, n.d., \(2025\)](#).

Dry ice cryogenic cleaning has a higher initial cost than traditional methods but is much lower than laser ablation cleaning. However, it often pays for itself in the long run thanks to reduced labor, downtime, and cleaning costs.

The initial cost of cryogenic cleaning equipment in the global market ranges between \$15,000 and \$50,000 USD. The operating costs of cryogenic cleaning using CO₂ pellets depend on several factors specific to the industrial process and the resulting product.

Both laser and cryogenic cleaning techniques share the costs of autonomous drones and digital twin technologies. Maintenance and surface wear: Cryogenic cleaning is gentler, reduces long-term maintenance costs, and is environmentally friendly with no chemicals, water runoff, or any type of abrasive to dispose of. Cryogenic cleaning meets all the specifications in industries where uptime and precision are crucial. [Abderrahmane et al. \(2022\)](#), [McMorland et al. \(2022\)](#), and [Gonzalo et al. \(2022\)](#).

A numerical analysis of supersonic flow through dry ice blasting nozzles is based on comparative studies of nozzle designs, particle transport efficiency, and cryogenic cleaning (an effective method for industrial soil removal that treats contaminated surfaces). The dry ice blasting method operates through three main phenomena: thermal effects (cooling), kinetic energy abrasion, and sublimation.

The final force impacting the surface to be cleaned is the sum of three components: the force of the compressed air, the force exerted by the solid CO₂ particles due to their velocity, and the sublimation force resulting from a sudden phase change accompanied by rapid volume expansion. Critical factors in this cleaning mechanism are the system components that influence these parameters: nozzle design and angle of attack adaptable to the geometries of the surface to be cleaned, the effect of dry ice particle size on surface finish behavior, and cleaning mixture parameters.

A simulation of dry ice particle flow in two-phase supersonic flow with particle collisions and mass consumption in the environment, and its behavior in a supersonic nozzle. The observed pressure and velocity profiles (Mach number 1 being supersonic) are typical of a two-phase convergent-divergent nozzle. Particle transport efficiency depends on the nozzle geometry, inlet pressure, and particle size. Nozzle efficiencies exceed 85%, with a maximum efficiency of 91.1% at an inlet pressure of 4 bar. The lowest efficiencies (highest losses) were observed for particles with a diameter of 250 μm. The cleaning zone was defined as a region 15–30 cm from the nozzle exit. Particle velocities range from 50 to 150 m/s, depending on the distance, particle diameter, and nozzle geometry. [Admin \(2025b\)](#) and [Todorović \(2025b\)](#).

There are several methods used for the removal of industrial contamination. These methods are divided into physical, chemical, and physicochemical. In this study, dry ice cleaning is an abrasive physical method for removing industrial dirt. A dry ice cleaning system consists of an air compressor, a gas dryer, a dry ice pellet feeder, and a blasting nozzle.

Procedure: Air is compressed and dried, then mixed with dry ice pellets in a mixer. The pellets are fragmented into smaller particles, and the mixture flows through the nozzle, where a pressure change accelerates the solid-gas mixture to high speed and directs it toward the contaminated surface. The cleaning mechanism is based on three main steps: surface subcooling, contamination fracturing due to a decrease in temperature, and dry ice sublimation, with rapid volume expansion, which causes crack propagation of the contaminant and subsequent removal of dirt.

Finally, residual particles are carried out of the cleaning zone by the gas flow. The maximum air pressure does not exceed 16 bar, while the dry ice mass flow rate remains below 200 kg/h. Supersonic two-phase flow nozzles. A dedicated cryogenic cleaning nozzle length optimization in the context of noise generation is presented in Noise Reduction Optimization Admin (2025b), Manikowski et al. (2025) and Todorović (2025b) the properties of dry ice pellets depend on their manufacturing process and their lifetime (interaction with air). See Figure 4.

Box 4

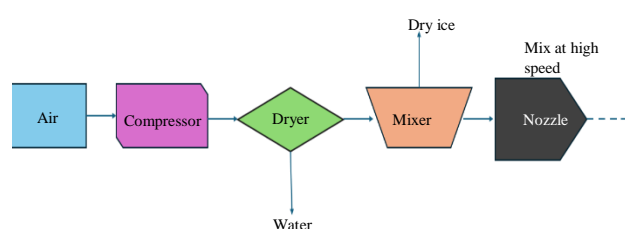


Figure 4

Flow diagram of cryogenic cleaning with dry ice blasting.

Source: Own Elaboration

The safety of dry ice cleaning technology for wind turbine blades using autonomous technologies can be observed in Figure 5. This is a decontamination method with controlled surface erosion, without secondary residues, without phase change of contaminants, and without massive damage to the part morphology.

This method is safe, and the material removal rate can be considered almost zero under method optimization conditions, considering that it influences a controlled surface roughness pattern and that it depends on factors such as; mixture percentages, dry ice particle size, mixing fluid velocity in the nozzle, angle of attack, and application distance, but it does not affect the microstructure of the materials and controls the roughness pattern uniformly. Manikowski et al. (2025).

Box 5

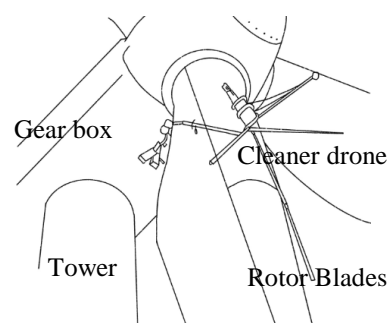


Figure 5

Cryogenic dry ice cleaning of wind turbine blades with autonomous technologies.

Source: Own Elaboration

Previous studies have shown that there are two basic types of contamination: loose contaminants, which usually attach to the surface by weak Van der Waals forces, and fixed contaminants, in the layer of surfaces with adhesion by encrustation to the material. Traditional cleaning methods, shot blasting, cleaning with chemical solvents generate secondary contaminated waste that requires additional decontamination. Radioactive decontamination at the Fukushima nuclear power plant, unmanned vehicles use cryogenic cleaning to remove hazardous chemicals.

The international standards that standardize cryogenic cleaning with dry ice in the aerospace and nuclear industries, where this cleaning method is most developed, are: ASTM D5608; standard practices for decontamination of field equipment used at low level radioactive waste sites (ASTM International, 2019), ASTM E2721; evaluation of effectiveness of decontamination procedures for surfaces (ASTM International, 2016), ISO 17873, nuclear facilities criteria for the design and operation of ventilation systems, ISO 16647; Radiation protection monitoring and clearance of materials from nuclear facilities,

China Energy (NB/T20142-2012) Guide for Chemical Decontamination of Primary Loop System and Components of PWR Nuclear Power Plants Admin (2025b) and (International Organization for Standardization, 2017).

Cryogenic cleaning has shown that dry ice decontamination parameters such as pressure, angle and blast time can have a significant impact on the decontamination effect without damage to the substrate, but changing the above parameters can lead to its use as a cleaning medium for maintenance, as it can even cause damage to the material by using it as a removal medium in preparation of new deposition films on composite materials such as graphene, carbon and glass fibres inherent to the substrate in wind turbine blades. Dagdag and Kim (2024b).

The cryogenic dry ice cleaning method is an excellent cleaning method with controlled regulation of material removal that can be used as a means of surface cleaning of contaminants in the form of surface conservation with manufacturer specifications or roughness regulation for surfaces including those with a mirror finish, whose roughness oscillates around $2 \mu\text{Ra}$, up to being used as a means of removing very high rates of material for repair systems, where it can replace manufacturing processes such as shot blasting, grinding, sanding, etc. that depending on the particle size of the dry ice, the angle of attack of the nozzle, the impact speed of the mixture on the surface to be treated, the distance from the nozzle to the surface and the exposure time of the process, it can be used for the required industrial purposes. Dagdag and Kim (2024b) and (International Organization for Standardization, 2004). You can observe Figure 6.

Box 6

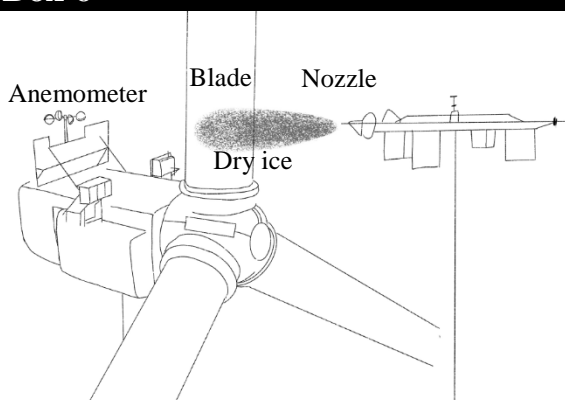


Figure 6

Cryogenic cleaning of blades with parameter control through digital twins.

Source: Own Elaboration

During maintenance tasks, the maximum level of decontamination is sought and damage to components must be minimized to allow their reuse. Previous studies of the cryogenic dry ice cleaning method identified that in cleaning processes without substrate attack on metals and non-metals, the material removal rate was determined to be in the range of $[0.5 \text{ to } 24] \text{ g/m}^2$. However, very little research has been conducted on polymeric materials and composite materials. Abderrahmane et al. (2022), Admin (2025b), McMorland et al. (2022) and Gonzalo et al. (2022).

To evaluate the erosion damage caused by dry ice blasting on surfaces, a commercial dry ice blasting machine assisted by an air compressor (flow pressure of 0.1–0.9 MPa and volume of 100 L) and a rectangular nozzle (exit dimensions of 25 mm × 5 mm) connected to it by a flexible hose were used as an experimental platform. The dry ice blasting machine receives compressed air from the compressor, which propels the dry ice pellets at high speed through the hose and out of the nozzle, impacting the sample surface. The wear marks, as a function of area and depth, are dependent on process variables such as angle of attack, pressure, dry ice flow, distance, and positioning time in the same area (feed). You can see them in Figure 7.

Box 7

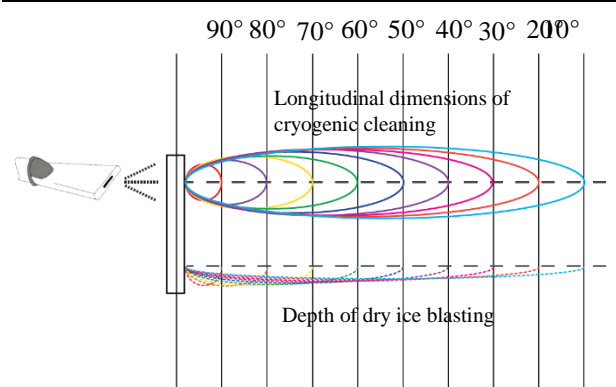


Figure 7

Cryogenic cleaning wear marks.

Source: Own Elaboration

Materials with high coefficients of thermal expansion, such as brass, can experience greater thermal stress during rapid cooling, causing microcracks or surface corrosion. Conversely, materials with lower coefficients of thermal expansion tend to exhibit greater stability and less damage under the same conditions.

At cryogenic temperatures (below -150°C), carbon fiber is known to have a low or even negative coefficient of thermal expansion in that range, making it ideal for aerospace structures, cryostats, and space telescope components.

On the other hand, composite materials like epoxies can withstand cryogenic shocks of 5–10 min without cracking, carbon-epoxy residual stresses up to 30–50 MPa making them feasible for dry ice cryogenic blasting, maximum CO_2 rate and short shot peening time are recommended with 5 bar pressure and 80 kg/h CO_2 rate, similar residual stresses as low as 0.9 MPa are obtained. Admin (2025b), (Cold Jet, 2025b), Cold Jet Dry Ice Production, n.d., (2025) and Rama et al. (2023).

Exposing a fully cured epoxy to cryogenic temperatures does not cause chemical degradation; -150°C to absolute zero. Common data sheets indicate -55°C remains unchanged at -273°C . What does change is the stiffness: upon cooling, the elastic modulus increases and the material becomes more brittle, which reduces stress on the bonded parts during cooling.

Commercially available cryogenic-grade epoxies EPO-TEK series: 301-2/301-2FL, T7110, EJ2189 are particularly characterized by high shear strength and low thermal stress under cryogenic conditions. Certified adhesives in tensile and shear tests at $\sim 77\text{ K}$, CTD Cryobond 621, Masterbond EP29LPSP and 3M Scotchweld 2216 showed no failures. (Cold Jet, 2025b), Ding et al. (2025) and Rama et al. (2023).

Wind turbine blades are designed to withstand frigid winds. Typical blade composites (polymers reinforced with glass or carbon fiber) are perfectly resistant down to approximately -30°C to -50°C . Beyond that, in truly "cryogenic" territory (below -150°C), most standard epoxies and polyesters become glassy and very brittle.

In practice, wind farms in Arctic or high-altitude environments mitigate icing and extreme cold with: blade heating systems (electric or hot air), surface coatings that resist ice buildup, and material adjustments that reduce the ductile-to-brittle transition.

High toughness and thermal shock resistance: they maintain their bond without cracking even under rapid temperature drops, application methods: vacuum impregnation techniques and microwave curing, case studies: cryogenic bonds in liquid hydrogen tanks and satellite sensors, nano-reinforcements (graphene, nanodiamond) to improve conductivity and resistance to thermal shock. Admin (2025b) and (Cold Jet, 2025b), Gong and Chen (2024).

Methodology

Develop give the meaning of the variables in linear writing and important is the comparison of the used criteria.

Results

The results shall be by section of the article.

Conclusions

Cryogenic dry ice cleaning represents an advanced technology that meets all the requirements for decontamination and preparation of substrates for new film deposition on wind turbine blades, increasing the efficiency of wind energy utilization. This technique fulfills the objective set forth in this research, which was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. Cryogenic cleaning, supported by technologies such as digital twins and autonomous systems, makes it the most promising methodology on the market for cleaning wind turbine blades with minimal invasiveness.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Díaz-Herrera, Sebastián: Participated in developing the research concept, collecting information, and drafting several sections of the article, drawing on his professional expertise.

Article

Cruz-Gómez, Marco Antonio: Assisted in reviewing the manuscript and offered overall improvement recommendations, supported by his professional background.

Mejía-Pérez, José Alfredo: Took part in revising and drafting multiple sections of the article, contributing with his professional knowledge.

Castillo-Pensado, Juan Luis: Collaborated in the review and preparation of several sections, informed by his professional experience.

Availability of data and materials

This work is a review of existing literature, relying solely on previously published sources. No original datasets were produced as part of this study.

Funding

This work was self-funded by the authors.

Acknowledgements

To the Benemérita Universidad Autónoma de Puebla; Engineering Faculty for the support in the use of its infrastructure., To the Tribology and Transport Group, BUAP, for their support in the analysis and development of the work, and 189 Disaster Prevention, Sustainable Development and Tribology Academic body, BUAP.

Abbreviations

3D	Three-dimensional
AI	Artificial Intelligence
ASTM	American Society for Testing and Materials
cm	centimeters
CO ₂	Carbon dioxide
EIGA	European Industrial Gases Association
GPS	Global Positioning System
GW	Gigawatts
ISO	International Organization for Standardization
K	Kelvin
Kg/h	Kilograms per hour
L	Liter
LiDAR	Light Detection and Ranging
MP	Megapixels
MPa	Megapascal

SCADA	Supervisory Control And Data Acquisition
USD	United States dollar
UV radiation	Ultraviolet radiation
V	Volts
g/m ²	Grams per square meter
m/s	Meters per second
mm	Millimeters
µm	Micrometers
µRa	Average roughness value (Ra) measured in micrometers (µm)
°	Degrees
°C	Degrees Celsius

References

Antecedents

Albatayneh, A., AbuAlRous, R., Kay, M., Abdallah, R., Juaidi, A., García-Cruz, A., & Manzano-Agugliaro, F. (2025). [Wind farm capacity factor forecasting: An Australian case study](#). *Energy Nexus*, 18, 100422.

Danesh, A., Yazdanmehr, S., & Kumble, P. (2025). [Visual impact assessment of wind farms using open-source software: A free method for creating accurate and realistic visualizations](#). *Energy Reports*, 13, 3013–3023.

Manikowski, P. L., Craven, M. J., & Walker, D. J. (2025). [Many-objective optimisation of offshore wind farms](#). *Applied Soft Computing*, 173, 112879.

Sheehan, H., Poole, D., Silva Filho, T., Bossanyi, E., & Landberg, L. (2025). [Investigations into deep Reinforcement Learning for wind farm set-point optimisation](#). *Expert Systems with Applications*, 282, 127627.

Basics

Aafif, Y., Chelbi, A., Mifdal, L., Dellagi, S., & Majdouline, I. (2022). [Optimal preventive maintenance strategies for a wind turbine gearbox](#). *Energy Reports*, 8, 803–814.

Abderrahmane, F., Bouslikhane, S., Hajej, Z., Dellagi, S., & Trabelsi, W. (2022). [An improved integrated maintenance/spare parts management for wind turbine systems with adopting switching concept](#). *Energy Reports*, 8, 936–955.

- Adedeji, P. A., Olatunji, O. O., Madushele, N., Akinlabi, S. A., & Adeyemo, J. A. (2022). Cluster-based wind turbine maintenance prioritization for a utility-scale wind farm. *Procedia Computer Science*, 200, 1726–1735.
- Akgül, E. F. (2024). Navigating decarbonization: Examining shipping companies' fleet modernization strategies worldwide. *Dokuz Eylül Üniversitesi Denizcilik Fakültesi Dergisi*, 16(1), 1–21.
- ASTM International. (2019). *Standard practice for thermographic inspection of insulation installations in envelope assemblies and materials (ASTM D5608-19)*.
- ASTM International. (2016). *Standard guide for fire prevention for photovoltaic panels (ASTM E2721-16)*.
- Begun, V., & Schlickewei, U. (2024). Cost-optimized probabilistic maintenance for condition monitoring of wind turbines with rare failures. *Energy Reports*, 12, 4864–4882.
- Chan, D., & Mo, J. (2017). Life cycle reliability and maintenance analyses of wind turbines. *Energy Procedia*, 110, 328–333
- Chen, L., Su, H., & Huangfu, L. (2022). Preventive maintenance model analysis on wind-turbine gearbox under stochastic disturbance. *Energy Reports*, 8, 224–231.
- Contreras Lopez, J., & Kolios, A. (2022). Risk-based maintenance strategy selection for wind turbine composite blades. *Energy Reports*, 8, 5541–5561.
- Ding, Y., Zhu, F., Li, H., Parlikad, A. K., & Xie, M. (2025). A failure knowledge graph learning framework for offshore wind turbines with incomplete knowledge. *Renewable and Sustainable Energy Reviews*, 215, 115561.
- El-Naggar, M., Sayed, A., Elshahed, M., & EL-Shimy, M. (2023). Optimal maintenance strategy of wind turbine subassemblies to improve the overall availability. *Ain Shams Engineering Journal*, 14, 102177.
- Gong, L., & Chen, Y. (2024). Machine Learning-enhanced IoT and Wireless Sensor Networks for predictive analysis and maintenance in wind turbine systems. *International Journal of Intelligent Networks*, 5(1), 133–144.
- International Organization for Standardization. (2017). *Nuclear facilities — Criteria for the design and operation of confinement systems for nuclear facilities other than reactors (ISO 16647:2017)*.
- International Organization for Standardization. (2004). *Nuclear facilities — Criteria for the design and operation of ventilation systems for nuclear installations other than nuclear reactors (ISO 17873:2004)*.
- Jamshidi, A., Jamshidi, F., Ait-Kadi, D., & Ramudhin, A. (2019). Applied Risk Analysis Approaches for Maintenance of Offshore Wind Turbines; A Literature Review. *IFAC PapersOnLine*, 52(13), 1075–1078
- Kaewbumrung, M., Plengsa-Ard, C., Pansang, S., & Palasai, W. (2024). Preventive maintenance of horizontal wind turbines via computational fluid dynamics-driven wall shear stress evaluation. *Results in Engineering*, 22, 102383.
- Kang, J., Sun, L., & Guedes Soares, C. (2018). Fault Tree Analysis of floating offshore wind turbines. *Renewable Energy*, xxx, 1–13.
- Kong, K., Dyer, K., Payne, C., Hamerton, I., & Weaver, P. M. (2023). Progress and Trends in Damage Detection Methods, Maintenance, and Data-driven Monitoring of Wind Turbine Blades – A Review. *Renewable Energy Focus*, 44, 390–412.
- Leon-Medina, J. X., Tibaduiza, D. A., Parés, N., & Pozo, F. (2025). Digital twin technology in wind turbine components: A review. *Intelligent Systems with Applications*, 26, 200535.
- Li, H., Huang, C.-G., & Guedes Soares, C. (2022). A real-time inspection and opportunistic maintenance strategies for floating offshore wind turbines. *Ocean Engineering*, 256, 111433.
- Liu, S., Ren, S., & Jiang, H. (2023). Predictive maintenance of wind turbines based on digital twin technology. *Energy Reports*, 9, 1344–1352.

McMorland, J., Collu, M., McMillan, D., & Carroll, J. (2022). [Operation and maintenance for floating wind turbines: A review](#). *Renewable and Sustainable Energy Reviews*, 163, 112499.

Peinado Gonzalo, A., Benmessaoud, T., Entezami, M., & García Márquez, F. P. (2022). [Optimal maintenance management of offshore wind turbines by minimizing the costs](#). *Sustainable Energy Technologies and Assessments*, 52, 102230.

Rama, V. S. B., Hur, S.-H., & Yang, J.-M. (2023). [Predictive Maintenance and Anomaly Detection of Wind Turbines Based on Bladed Simulator Models](#). *IFAC PapersOnLine*, 56(2), 4633–4638

Saleh, A., Chiachío, M., Fernández Salas, J., & Kolios, A. (2023). [Self-adaptive optimized maintenance of offshore wind turbines by intelligent Petri nets](#). *Reliability Engineering & System Safety*, 231, 109013.

Schouten, T. N., Dekker, R., Hekimoğlu, M., & Eruguz, A. S. (2022). [Maintenance optimization for a single wind turbine component under time-varying costs](#). *European Journal of Operational Research*, 300, 979–991.

Shah, S. S., Daoliang, T., & Kumar, S. C. (2024). [RUL forecasting for wind turbine predictive maintenance based on deep learning](#). *Heliyon*, 10, e39268.

Yan, R., Dunnett, S., & Jackson, L. (2023). [Impact of condition monitoring on the maintenance and economic viability of offshore wind turbines](#). *Reliability Engineering & System Safety*, 238, 109475.

Zavvar, E., Rosa-Santos, P., Taveira-Pinto, F., & Ghafoori, E. (2025). [Lifetime extension of offshore support structures of wind turbines: A review](#). *Renewable and Sustainable Energy Reviews*, 217, 115788.

Zeitler, W., Quandt, M., Stern, H., & Freitag, M. (2023). [Web based maintenance work support by neural networks – Detection and wear estimation of components in wind energy turbines](#). *Procedia CIRP*, 118, 1126–1131.

Zhang, C., & Tee, K. F. (2019). [Application of gamma process and maintenance cost for fatigue damage of wind turbine blade](#). *Energy Procedia*, 158, 3729–3734.

Zhang, W., Vatn, J., & Rasheed, A. (2025). [A differential evolution-based approach for short-term predictive maintenance optimization of an offshore wind turbine](#). *Ocean Engineering*, 335, 121507.

Supports

Admin, C. (2025, 21 mayo). [Dry Ice Blasting & Cleaning Australia | Cold Jet Australia](#). Welcome To ColdJet Australia.

Bošnjaković, M., Martinović, M., & Đokić, K. (2025). [Application of Artificial Intelligence in Wind Power Systems](#). *Applied Sciences*, 15(5), 2443.

Cold Jet. (2025, 21 mayo). [Equipos de Limpieza con Hielo Seco - Sistemas de Producción de Hielo Seco | Cold Jet](#).

Dagdag, O., & Kim, H. (2024). [Cryogenic Impact on Carbon Fiber-Reinforced Epoxy Composites for Hydrogen Storage Vessels](#). *Journal Of Composites Science*, 8(11), 459.

Global Wind Energy Council. (2024, April 16). [Wind industry installs record capacity in 2024 despite policy instability](#). GWEC.

Katsaprakakis, D. A., Papadakis, N., & Ntintakis, I. (2021). [A Comprehensive Analysis of Wind Turbine Blade Damage](#). *Energies*, 14(18), 5974.

Production, C. J. D. I. (s. f.). [Producción de hielo seco y peletizadores de Cold Jet](#).

Tecnología LiDAR. (s. f.).

Todorović, I. (2025, 3 junio). [GWEC: Record wind power capacity was installed globally in 2024](#). *Balkan Green Energy News*.