Closing the quality gap: the science of robotic blade leading-edge repair

How systematic materials research, rain erosion testing and a new generation of robotic systems are reshaping the economics of leading-edge protection in wind turbine maintenance.

The leading edge of a wind turbine blade is among the most punishing environments in renewable energy. At tip speeds routinely exceeding 80 to 100 metres per second, each blade endures relentless high-energy impacts from raindrops, hailstones and airborne particulates over its entire operating life.

The resulting erosion is not merely cosmetic: it degrades the blade's carefully engineered aerodynamic profile, triggers turbulent airflow, increases drag and steadily erodes annual energy production by as much as 1 to 5% depending on the severity of damage.

Over the lifespan of a modern wind farm, that figure translates into millions of dollars in lost revenue.

The wind industry has long recognised leading-edge erosion as a critical operations and maintenance challenge. Yet for many years, the response was largely reactive: inspect blades when convenient, send rope access technicians up the tower when damage became severe, apply filler and coating by hand and hope the result lasted long enough to justify the cost and downtime.

The limitations of this approach are well documented: variable quality, restricted weather windows, high idle time and repair cycles that can stretch to nine or more working days per turbine.

Aerones, a global independent service provider, was founded on the belief that this situation was fundamentally unacceptable and fixable. Since its establishment in 2019, the company has pursued a systematic programme of technology development that spans robotic hardware, materials science, laboratory testing and AI powered software.

The result is a suite of leading-edge repair capabilities that is redefining what quality, speed and consistency mean in blade maintenance.

The scale of the problem

Before examining Aerones' solutions, it is worth dwelling on the scale of the challenge facing the industry. The wind sector is growing at an extraordinary pace, and with it the maintenance burden.

Industry data indicates that an additional 628,000 workers will be needed in the wind power sector over the next five years, which is an estimate that has increased by 20% in just one year.

Even setting aside the question of whether that workforce can be recruited and trained in time, the economics of deploying hundreds of rope access technicians for leading-edge repair work are increasingly difficult to justify.

Take a 3 MW turbine on the Gulf Coast of Texas, where annual rainfall can reach 1,600mm and blade tips rotate at close to 80 m/s, conditions that put leading edges under near constant hydrometeor bombardment.

In year one, erosion is typically negligible. By year two, Category 2 erosion, minor surface degradation, may be present, with a repair cost of approximately $5,400 per turbine and an annual energy production (AEP) loss of around 65 MWh.

By year four, Category 4 erosion, deep gouging with substrate exposure, can affect 7.3 metres of blade per turbine, carrying an estimated repair cost of $16,200 and an AEP loss of roughly 258 MWh per year. By year five, Category 5 erosion across 9.1 metres pushes costs to $32,400 and AEP losses to approximately 390 MWh annually.

Data from the one wind site with almost 200 wind turbines further illustrates the compounding effect: Category 4 erosion accumulates at roughly nine metres per turbine per year at that location, adding approximately $18,000 in maintenance and repair costs annually per turbine. For a fleet of more than 170 turbines, that equates to around $3.1 million every year in avoidable costs that could be substantially reduced through timely, high-quality preventive maintenance.

The aerodynamic mechanism behind these losses is well understood. Erosion creates surface roughness at the leading edge that increases both frictional drag, caused by tangential forces acting on the blade surface, and form drag, which results from pressure differences around a blunter aerodynamic profile.

A smooth, correctly profiled leading edge generates minimal friction and keeps airflow attached to the blade surface efficiently. As erosion progresses, both drag components increase and lift diminishes. A timely reaction to blade surface damage is important to prevent fast blade degradation, a principle that underpins the entire Aerones maintenance philosophy.

From concept to global operations

Aerones was founded in 2019 with the invention of a winch-based robotic arm platform specifically designed for wind turbine service work. The core insight was that the hazards, inefficiencies, and quality inconsistencies of manual high altitude maintenance could be addressed through purpose-built robotics, not general purpose industrial drones or robots adapted for the task, but systems engineered from the ground up for the unique demands of turbine blade work.

The company's growth trajectory has been remarkable. In 2020, amid the disruption of the global pandemic, Aerones launched international services and began expanding into the US and EU markets alongside Australia. The fleet grew significantly in 2021, driven by iterative improvements to the robotic hardware.

By 2022, with over 50 engineers on the team, turnover doubled as major investment flowed in to accelerate technology development. In 2023, operations reached Australia and revenue tripled, with the workforce exceeding 250 people, including 140 field technicians. The year 2024 was designated a 'Year of Innovation', with the introduction of the world's first modular leading-edge repair system and Internal Surveillance camera.

By 2025, the company had serviced 7,920 turbines in that year alone, up from 3,712 in 2023 and 1,619 in 2021. It now operates across 35 countries on four continents, serving more than 130 clients and with a cumulative fleet total surpassing 20,000 turbines serviced.

As of early 2026, Aerones employs more than 600 people, including 50 plus hardware engineers, 50 plus software engineers, a 25 strong AI and data team, 60 plus manufacturing engineers, more than 10 robot testing engineers, and over 100 field teams comprising 300 plus technicians. The company holds nine patents and continues to expand.

Following a $62 million investment round in 2025, it has made substantial commitments to both its robotics hardware and its software platform, including AI powered inspection analysis and a customer-facing platform that enables predictive maintenance at scale.

The overarching vision is to be the most compelling wind turbine maintenance company in the world, driving the industry from reactive to genuinely preventive maintenance.

The LER system: engineering for quality and speed

At the heart of Aerones' blade repair capability is the Leading-Edge Repair (LER) product

range, a modular suite of robotic toolheads that collectively cover every stage of the repair process.

The system is anchored by the toolbase robot, a blade-holding unit that secures the wind turbine generator (WTG) blade in a stationary position while the various robotic attachments carry out their work. This is a critical design choice: by immobilising the blade, the system eliminates the dynamic instability that makes precise manual application in high winds so difficult.

A modular repair ecosystem

The repair sequence begins with surface preparation. The designated robotic tool handles surface activation, washing and drying, sanding, removing contamination and creating the surface profile needed for good coating adhesion.

Where 3M erosion protection tape has been previously applied, the optional tape removal unit strips it cleanly before the repair work begins. The next tool then sands the surface to the precise roughness specification required for the subsequent coating steps, preparing it for painting.

Filler application is carried out by the Spatula Application tool, which restores the edge profile by applying filler material, either a standard two-component epoxy or polyurethane filler, or a pullable LEP system, to a consistent geometry.

Once the filler is cured, the grinder returns for a second sanding pass to remove surface imperfections and achieve the required smoothness, followed by cleaning to remove residual dust. Finally, the robot applies the leading-edge protection coating using a sprayable system to deposit a uniform, controlled-thickness layer across the full repair zone.

The full seven step process: tape removal, sanding, cleaning, promoter application, filler, sanding and cleaning again, then LEP coating, can be completed by the Aerones robotic system in approximately 20 hours of active work at the turbine, equivalent to two regular working days at 10 hours each.

This compares to 54 hours, or five or more days, for cherry pickers, 74 hours, or seven or more days, for suspended platforms, and 93 hours, or nine or more days, for rope-access technicians completing an equivalent Category 3, 15 metre leading-edge erosion repair on a single turbine.

The scalability argument

Beyond per-turbine efficiency, the scalability advantage of robotic repair becomes decisive at fleet level. Aerones presents a compelling comparison: to complete 1,500 blade repairs in a single season, an operator can deploy either 10 robot sets with up to 40 operators or 200 rope-access technicians.

The rope-access option requires almost no capital investment and can be mobilised at short notice if capacity is available in the market, but at the cost of significant training time, highly variable quality, no long-term performance guarantee, and elevated safety risk. The robotic option delivers factory-level, repeatable quality on every blade, with quality assured by sensors and the robot system rather than depending on individual technician skill.

It operates effectively up to 12 m/s wind speed with only 14% expected idle time, compared to 35% idle time for rope access technicians capped at 8 m/s. It is fast and scalable, capable of completing 500 WTG repairs per year with a fleet of 10 robots.

In October 2025, with 13 robot sets deployed in the field, the company completed 296 blade repairs in a single month, which it describes as a potential world record for robotic leading-edge repair throughput.

Weekly throughput in the peak period reached 27.3 WTGs per week with 13 sets, a figure reflecting both the improved speed of the latest-generation robots and the process optimisations accumulated through hundreds of hours of field experience.

The laboratory: where materials science meets robotics

Robotic precision in application is only as valuable as the materials being applied. Recognising this, Aerones has made a significant investment in its own materials laboratory, a dedicated research and testing facility at its manufacturing plant in Riga, Latvia.

This is not a conventional quality assurance lab. It is a full-scale research capability that allows the business to evaluate, validate and optimize LEP materials under controlled conditions before committing them to field deployment.

The laboratory is equipped for three broad categories of testing. The first is adhesion and surface science: pull-off adhesion testing using a PosiTest AT-A instrument with specialised dollies, conducted in accordance with ISO 4624 and ASTM D4541 standards; and surface free energy evaluation using Kruss technology to map the wettability of blade substrate surfaces, to evaluate the efficiency of different surface preparation methods and to verify which preparation method provides the best compatibility with the LEP coating, also complying with ISO 19403.

The second category is environmental and load stress analysis, covering material behaviour under extreme temperature and humidity cycles, and integrated robotic load testing to simulate real-world mechanical fatigue in controlled environments. The third is microscopic material analysis, using high-resolution microscopy to conduct in-depth structural examination for defect detection and surface characterisation, with data driven insights used to verify curing quality and coating uniformity.

Critically, the testing methodology mirrors real-world conditions as closely as possible. A specialised fixture (JIG) developed by Aerones mounts the rain erosion test (RET) substrates on a suspended real blade, fixing them in the exact orientation and at the exact surface profile they would occupy on an operating turbine.

Material application is performed using the same robotic system and methodology employed in field service, meaning that any performance differences attributable to the application process, rather than the material itself, are minimised.

The facility currently houses four full-size turbine blade stands, equipped with real blades, enabling continuous daily testing of LEP material and application processes, robot operator training and rapid iteration on robot development.

In 2024, more than 500 tests were conducted. In 2025, that figure exceeded 1,000 and the company plans to continue at that pace or above in 2026. This sustained testing programme produces a data set of extraordinary richness, one that supports genuinely evidence based decisions on material selection, application parameters and repair process design.

Rain erosion testing: the industry standard under the microscope

The Rain Erosion Test (RET) has become the de facto standard for evaluating the durability of leading-edge protection materials. It works by subjecting coated test specimens to high-velocity water droplet impacts under controlled conditions, simulating the erosion exposure that a blade tip would experience over years of operation, compressed into hours or days of laboratory testing.

Aerones conducts its RET work in collaboration with the AeroNordic laboratory in Horsens, Denmark, an independent testing and engineering company specialising in composite materials for wind turbine applications.

All testing is conducted in accordance with the DNV-GL-RP-0171 standard, which provides clear and internationally recognised guidelines for the evaluation of erosion protection systems on rotor blades. Adherence to this standard ensures that results are reliable, reproducible and directly comparable with data from other laboratories and material suppliers.

Test conditions and parameters

The RET protocol employed by Aerones and AeroNordic runs at a maximum impact velocity of 130 m/s, a deliberately severe condition that accelerates damage compared to typical field exposure.

To put this in context: the blade tip speed of a Vestas V136-3.45 turbine is approximately 85

Aerones is not the only company working on this problem, but it is currently the best-resourced, most data-rich and most systematically innovative.

m/s, while a Vestas V164-8.0 runs at 90–100 m/s. The test speed of 130 m/s is the standard accelerated life test condition specified by DNV/IEC, designed to compress years of field erosion into manageable test durations.

The rotor speed in the test apparatus is set to 1,039 rpm to achieve the 130 m/s condition. Water flow is maintained at a constant 65 litres per hour, with a mean droplet diameter of 2.418 mm (standard deviation 0.366 mm) and rain intensity of 31.34 mm/hour.

Water temperature, pressure, conductivity and chamber temperature are all continuously monitored to ensure stable and reproducible conditions throughout each test. All specimens are cured for a minimum of seven days before testing to ensure complete material hardening.

The key performance metrics are time to erosion onset, the point at which visible surface damage first appears and time to breakthrough, when the protective coating is penetrated and the underlying substrate is exposed. Samples are inspected at 20-minute intervals. Three specimens are tested for each material and application configuration, providing statistical robustness to the results.

Layer thickness verification

Before each batch of test specimens is submitted for RET, Aerones conducts a rigorous acceptance testing programme. Application parameters are first optimised in preliminary trials using 25 mm wide paper tapes placed on the sample blade.

The resulting coating layer thickness is then measured using a Leica Ivesta 3 high-resolution stereo microscope, which captures cross-sectional micrographs of the coating at multiple positions across the specimen.

For one of the materials tested at 21°C and 61% relative humidity, the measured dry layer thickness was consistent across positions: 110 micrometres at the left position, and 120 micrometres at both the leading edge and right positions. This tight thickness control, achieved by the robotic spray system, is itself a significant quality advantage over manual roller application, which introduces variable micro-texture, roller marks and uneven curing that increase frictional drag and reduce aerodynamic efficiency.

Rain erosion test results: one material sets a new benchmark

The comparative RET data published by Aerones involves three materials. Material names and manufacturers are anonymized in this article as: Material A sprayable coating in both single-layer and two-layer configurations; the Material B tape; and the Material C. The results are unambiguous.

The Material C, a widely used pullable polyurethane tape, showed a breakthrough at approximately 28 hours at 130 m/s, the lowest performance in the comparison. The Material B tape demonstrated an average breakthrough time of approximately 38 hours and 5 minutes across three specimens (individual results of 945 minutes, 2,310 minutes, and 3,600 minutes), with a peeling effect observed once water penetrated the coating through the pierced area.

The single-layer Material A application, with a leading-edge dry film thickness of 120 micrometres, achieved an average breakthrough time of 55 hours and 20 minutes (3,320 minutes) across three specimens.

Notably, one of the three samples withstood the full 91-hour test duration without any damage, suggesting that the true mean performance may be modestly underestimated by simple arithmetic averaging. Single-layer Material A thus outperforms Material B by approximately 45%and Material C by almost 100%.

For the two-layer Material A system, two of the three specimens showed no damage whatsoever after the full 200-hour test duration at 130 m/s, and the test was ultimately stopped, not because the material failed, but because it had already exceeded every other material tested and the budget for extended testing had been reached.

The first specimen showed a breakthrough at 2,100 minutes (35 hours), while specimens 2 and 3 remained intact at test termination after 200 hours. The average for the two-layer system is therefore recorded as '200+ hours', more than four times the performance of the single-layer application.

The conclusion is clear: Material A, as applied by the Aerones robotic system, provides the highest rain erosion resistance among all materials tested, and the two-layer configuration in particular represents a step-change improvement over conventional LEP tape systems.

Adhesion testing: the foundation of coating integrity

Rain erosion resistance is the most visible performance metric for an LEP system, but adhesion to the blade substrate is equally fundamental. A coating that resists erosion brilliantly but delaminates from the blade under thermal cycling or mechanical stress provides no long-term protection.

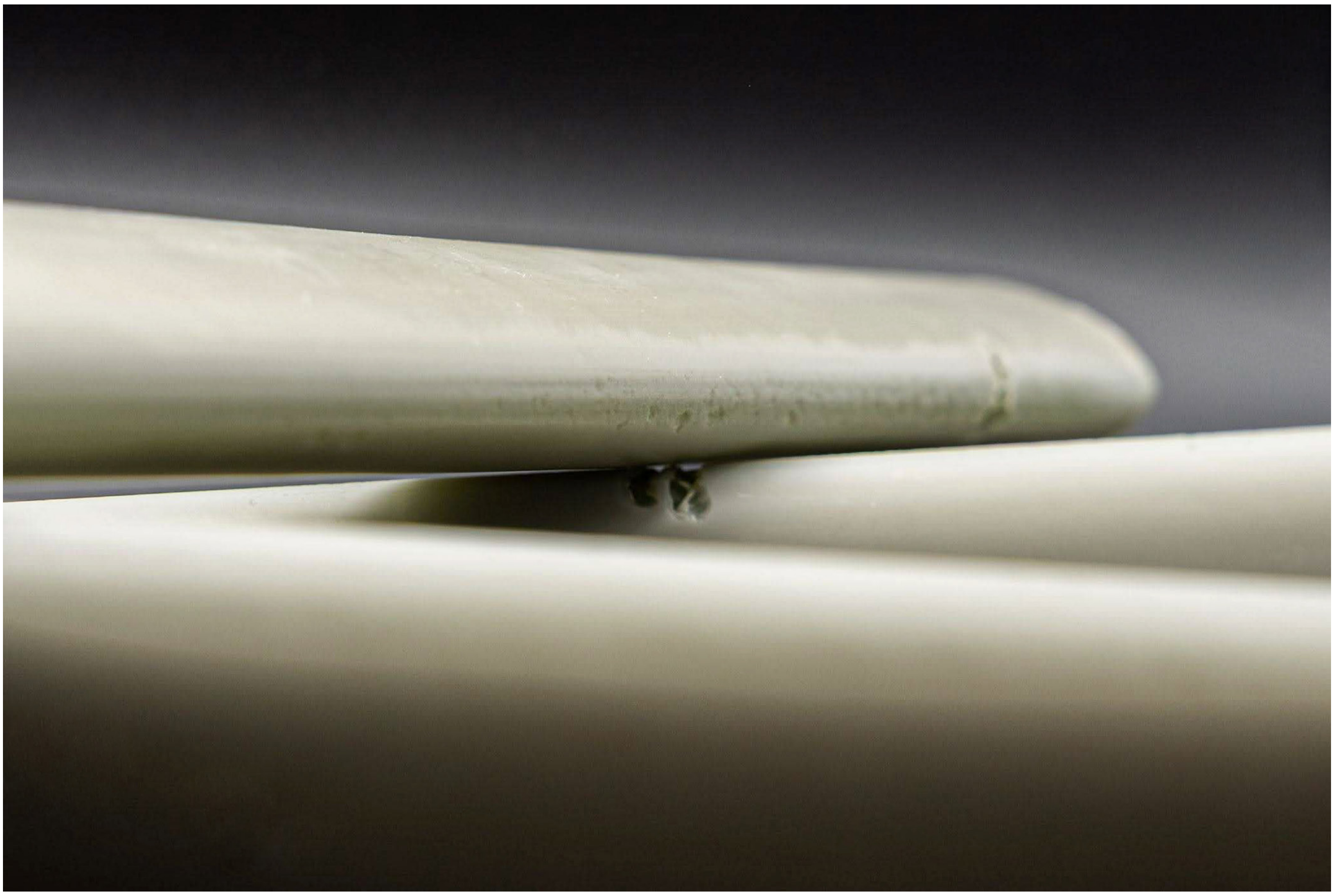
Aerones therefore conducts systematic pull-off adhesion testing on Material A coatings applied to both epoxy and polyester blade substrates, under the same application conditions used for RET sample preparation.

The results reveal important differences between substrate types. On epoxy surfaces, Material A shows inherently strong adhesion without any filler intermediate coat, the 'Raw' configuration achieves average adhesion of 8.42 MPa (range 8.2 to 8.7 MPa), confirming excellent intrinsic compatibility between the coating and the substrate.

The addition of SikaForce 800 Blue filler raises average adhesion to 8.62 MPa, while Akzo Nobel Relest Wind Putty Contour achieves 8.48 MPa. All three epoxy configurations are rated as excellent.

On polyester substrates, the picture is more nuanced. Without filler, Material A adhesion to polyester averages only 5.06 MPa, acceptable, but the lowest result across all tests. It should also be noted that the adhesive break observed in tests conducted on polyester surfaces between the LEP coating and the fiberglass substrate indicates that the weakest link in the entire system is the interfacial bond, rather than the cohesive strength of the material itself.

The addition of an appropriate filler dramatically improves adhesion: SikaForce 800 Blue raises the average to 5.66 MPa with a top result of 7.8 MPa, and Akzo Nobel Relest Wind Putty Contour achieves an average of 6.94 MPa with a top result of 8.0 MPa. The optimal filler thus increases adhesion on polyester by approximately 37%, bringing it to a level comparable with unfilled epoxy performance.



Overall, adhesion on epoxy surfaces (8.42–9.04 MPa average across configurations) is approximately 30 to 70% higher than on polyester (5.06–6.94 MPa). The practical implication is important: repair specifications should always identify whether the blade substrate is epoxy or polyester and filler selection should be made accordingly.

The adhesion results also validate Aerones' laboratory methodology. While developing the surface preparation robot, the company conducted hundreds of adhesion tests on materials exceeding 10 MPa on some epoxy substrates, far higher values than are achievable with manually rolled-on materials.

Gloss measurement confirms the quality of robotic surface preparation: the robot consistently achieves surface gloss values well below 5 GU (gloss units), exceeding best practice specifications and confirming the level of surface matting required for optimal coating adhesion.

The surface finish advantage

One dimension of robotic LEP application that deserves particular attention is surface finish quality. When leading-edge protection materials are applied by hand, using a roller, brush or squeegee, the resulting surface inevitably carries micro-texture: a pattern of small peaks and valleys caused by variable application pressure, roller marks and uneven curing. Under microscopic examination, the difference between a hand-rolled and a robotically sprayed LEP surface is dramatic.

Manual roller application produces a distinctly textured surface with visible waviness and irregular micro-relief, analogous to running a paint roller across a wall at high speed. The Aerones robotic spray system, by contrast, produces a surface characterised by exceptional uniformity and smoothness, with consistent coating thickness across the full width of the application zone.

This is not simply an aesthetic difference. Surface irregularities at the leading edge directly increase frictional drag, reduce aerodynamic efficiency, introduce additional blade vibration, and can elevate acoustic noise from the turbine.

The practical consequence for operators is measurably better energy yield, the data indicates a gloss measurement well below 5 GU is consistently achieved, confirming the ultrasmooth finish and a more predictable, repeatable outcome on every blade. When rain erosion resistance is combined with aerodynamic surface quality, the robotic application advantage compounds.

Innovation in focus: next-generation repairs and UV-curable materials

The current Aerones LER system already represents a significant advance over conventional repair methods. But the company is not standing still. Two innovation streams are particularly noteworthy: the development of Category 4 and 5 repair capability, and research into UV-curable LEP materials.

Category 4 repairs with UV LEP

Category 4 and 5 blade erosion represents the most complex repair challenge in the industry. At these damage levels, which can involve penetration to the glass-fibre laminate and structural compromise of the leading-edge geometry, conventional repair processes are extremely time consuming, weather dependent, and difficult to execute consistently at altitude.

Aerones is developing robotic capability specifically for this market, in collaboration with a UV-curable material manufacturer.

The core advantage of UV-curable systems for robotic applications is rapid on-demand curing: rather than relying on ambient temperature and humidity to drive chemical crosslinking over hours or days, UV-curable materials cure on exposure to ultraviolet light in seconds to minutes.

This presents the possibility of a fully robotic, closed-loop repair process in which material is applied, layer thickness is verified, and curing is triggered on-board the robot, eliminating cure-time waiting periods that currently constrain throughput.

As the wind industry scales to meet global renewable energy targets, the companies that can maintain the largest fleets to the highest quality at the lowest cost will define the economics of wind power.

Rain erosion test results for the custom UV-curable material are reported as demonstrating high durability and superior resistance to environmental impact, with high potential for integration into Aerones' production and repair workflows.

The collaboration with the material manufacturer allows the formulation to be tailored specifically to the mechanical demands of robotic sprayable LEP application, including optimising viscosity, cure kinetics and adhesion to the blade surface.

Glass fibre reinforcement

A parallel research thread involves the incorporation of milled glass fibres into the LEP material matrix to increase structural integrity. Laboratory prototype development is underway, with early results suggesting improved mechanical bonding. The primary technical challenges at this stage relate to base material compatibility, selecting a resin system with appropriate fibre compatibility and flow properties for robotic spray application, and controlling the de-airing process to eliminate bubble formation during application, which would otherwise create void defects in the cured coating.

The strategic vision here is clear: combine the UV-cure speed advantage with glass-fibre reinforcement to produce a LEP system capable of addressing Category 4 and 5 damage with factory-level quality and robotic speed.

In Aerones' framing, this is 'not just a new material; it is a new, scalable repair ecosystem', one in which the full repair process, from surface preparation through filler and LEP coating, can be executed robotically to a consistent standard in any weather window that the blade holding system can accommodate.

The optimal maintenance strategy

Taken together, Aerones' capabilities of robotic inspection, leading-edge repair, AI-powered data analysis and a growing library of validated material performance data enable a fundamentally different approach to wind turbine asset management.

The company's model is explicitly preventive: rather than waiting for blades to reach Category 4 or 5 erosion before intervening, operators using the Aerones platform can identify Category 1-2 damage early and address it with a lower-cost, faster repair process before the degradation cascade accelerates.

The maintenance cost and energy production comparison between the current industry approach and the Aerones preventive maintenance model is striking. Under Aerones' preventive model, targeted early interventions keep AEP close to 100% across the blade lifespan, with more frequent but lower-cost and faster repairs, ultimately delivering better economics over the full turbine life.

The digital infrastructure supporting this approach is integral to its effectiveness. Aerones' customer platform, accessible through the Visual Inspection Studio software, aggregates inspection data from drone surveys and internal crawler robots, applies AI-powered computer vision to detect and classify anomalies, and makes the results available to asset managers in near real-time.

Human specialists verify AI findings to ensure accuracy, the company reports a near-100% anomaly detection rate using this hybrid approach, and the platform enables side-by-side comparison of current and historical inspection data for trend analysis. By merging this data intelligence with physical repair capability, Aerones is creating what it describes as digital twins of wind turbine assets, enabling operators to predict degradation, optimize maintenance schedules and reduce unplanned downtime.

Conclusion: the new standard in blade maintenance

Leading-edge erosion will remain one of the defining maintenance challenges for the wind industry for decades to come. As turbines grow larger, tip speeds increase, and blade replacement costs climb, the economic and technical arguments for proactive, high-quality repair programmes become ever more compelling. The question is no longer whether to invest in better repair processes, but which processes and materials deliver the best combination of quality, speed and durability.

The evidence assembled by Aerones, from hundreds of thousands of adhesion tests and more than 1,000 laboratory application tests in 2025 alone, through to the definitive RET comparison conducted with AeroNordic, makes a persuasive case.

Robotic application of Material A in a two-layer configuration outperforms the best competing LEP tape systems by a factor of more than four in standardised rain erosion testing. Adhesion data confirms that, with appropriate filler selection, this performance extends to both epoxy and polyester blade substrates. The surface finish quality advantage of robotic spray application contributes a further aerodynamic benefit that manual methods cannot replicate.

For wind farm operators, the practical implications are clear. The days of sending 200 rope-access technicians up turbines to complete a seasonal repair campaign, with all the quality variability, safety risk, weather dependence and idle time that entails, are numbered. Robotic leading-edge repair delivers factory-level quality at turbine height, at scale, with a documented performance advantage that compounds over the blade lifespan.

Aerones is not the only company working on this problem, but it is currently the best-resourced, most data-rich and most systematically innovative. Its combination of hardware capability, materials, science, rigour and AI-powered software intelligence positions it well to define what wind turbine maintenance looks like in the coming decade.

As the wind industry scales to meet global renewable energy targets, the companies that can maintain the largest fleets to the highest quality at the lowest cost will define the economics of wind power. Aerones is building to be that company.

aerones.com

About the company

Aerones is the global leader in robotic wind turbine asset maintenance, with operations across 35 countries on four continents.

Founded in 2019 and headquartered in Riga, Latvia and with regional Headquarters in Denton, Texas, the company provides robotic inspection, cleaning, and leading-edge repair services backed by AI-powered data analytics.

Aerones employs more than 600 people and has serviced over 20,000 wind turbines.