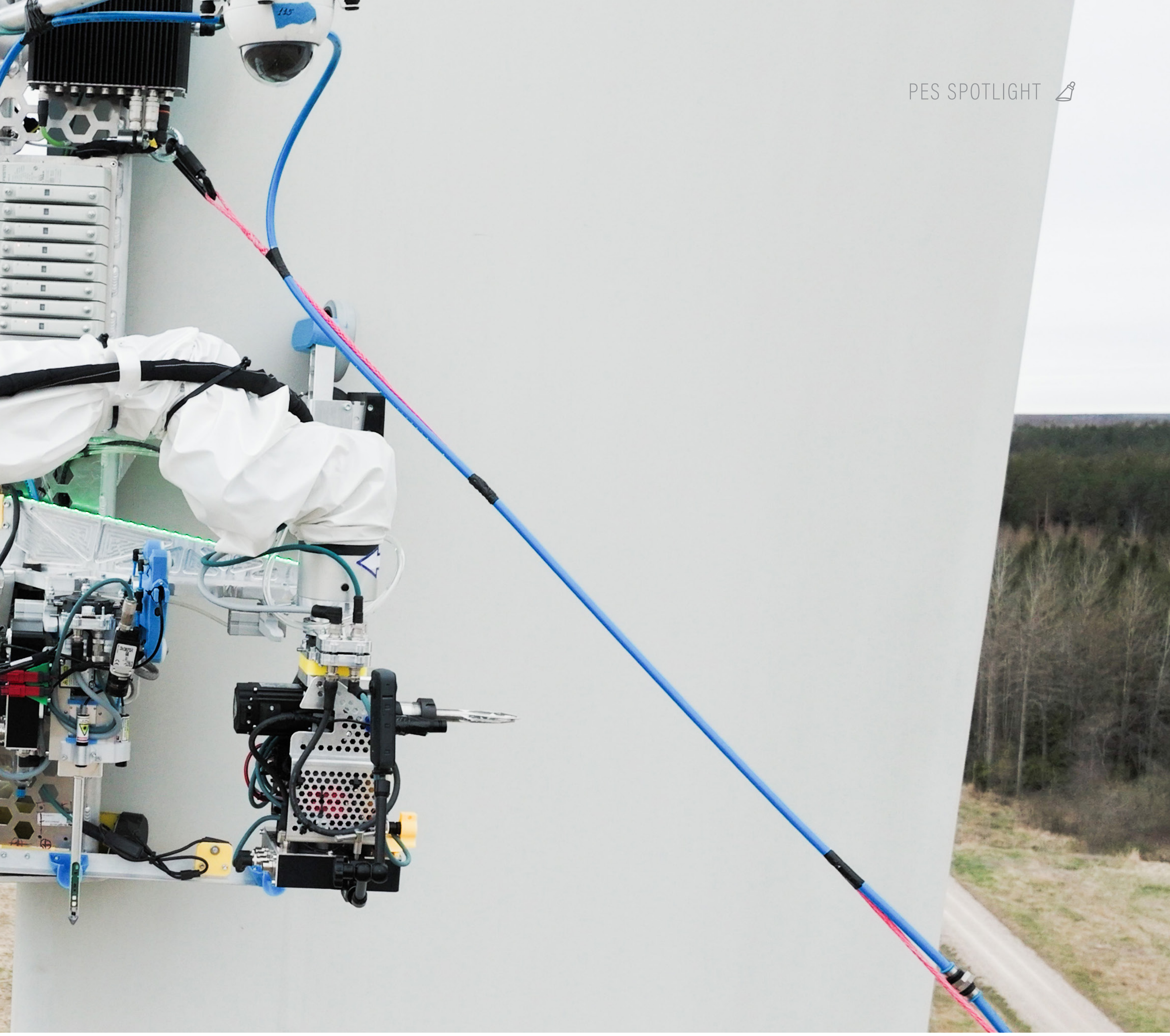
Can robotic repair change the economics of severe leading-edge erosion?

Blade damage at the most advanced stages has long pushed operators towards slower structural intervention or full replacement. New work on UV-curable materials, fibre-reinforced repair systems and robotic process control could give asset owners a repair option between the two, but only if laboratory progress translates into repeatable field performance.



Severe leading-edge erosion has become one of the most difficult decisions in blade maintenance.

Once damage moves beyond surface protection and into the laminate, operators are no longer choosing between simple repair methods. They are weighing downtime, weather risk, repair consistency, remaining blade life and the cost of replacement.

That is why replacement has gained ground in some severe erosion cases. Not because Category 4 and 5 damage can never be repaired, but because the repair process is harder to specify, harder to schedule and harder to execute consistently at height.

Lower and moderate stages of leading-edge erosion are now relatively well understood. Up to Category 3, the typical repair sequence is familiar: prepare the damaged area, restore the blade profile with filler, apply leading-edge protection and return the turbine to service.

Robotic systems have helped compress parts of that workflow by improving repeatability in surface preparation, application and inspection.

Category 4 and 5 damage is a different proposition.

At these levels, erosion has typically moved through the coating and filler and into the structural laminate. The geometry of the leading edge is compromised. The work is no longer a surface-protection job; it becomes a structural repair carried out on a suspended blade, often inside narrow weather windows.

DNV-RP-0171 is relevant here because it sets out how rotor blade erosion protection systems should be tested under controlled rain erosion conditions. It is not a repair-category rulebook, but it underlines a wider industry point: once erosion performance is being compared, process control, test conditions and repeatability matter.

For a wind farm with several blades in this state, the economics become difficult. Conventional severe-erosion repair takes longer than Category 3 work, depends more heavily on weather and can vary with the technician, the substrate condition and the cure environment.

A repair that can be completed quickly at Category 3 may stretch across several days when deeper laminate exposure, extended filler cure times and multiple coating passes are involved. The practical question is whether the market can bring the same level of control to severe erosion that it is beginning to see in lower-category robotic work.

That question is now the focus of active development among robotic repair specialists, materials suppliers and research groups. Aerones is one of the companies pursuing that integration route.

The Latvia-based company is working on two connected workstreams: UV-curable leading-edge protection materials and milled glass fibre reinforcement within the coating matrix.

The aim is to produce a single robotic repair system capable of addressing Category 4 and

5 damage with greater speed, repeatability and process control than conventional severe-erosion repair.

Aerones is not claiming that Category 4 and 5 robotic repairs have already been solved at scale. The significance of the work is the attempt to combine materials testing, robotic application, controlled curing and quality assurance in one repair workflow.

Why Category 4 and 5 are different

The technical jump between Category 3 and Category 4 is larger than the numerical scale suggests.

At Category 3, the protection layer has worn through in localised areas and the filler may show surface damage, but the structural laminate is usually not the main repair challenge. A robotic system can restore the profile and reapply protection in a planned sequence.

Category 4 erosion involves deeper gouging and substrate exposure, often across metres of blade length. Category 5 moves the problem further into structural repair territory, where the leading-edge shape, laminate condition and remaining useful life of the blade, all become part of the decision.

Aerones has modelled this escalation using a 3 MW reference turbine in a high-rainfall environment, with year-four damage affecting 7.3 metres of blade per turbine and year-five damage reaching 9.1 metres. The company's model estimates repair costs rising from roughly $16,200 to $32,400 over that period, with annual energy production losses increasing from around 258 MWh to 390 MWh.

Those figures are vendor-supplied and should be treated as illustrative rather than independently verified market benchmarks. Their value is in showing the direction of travel: once erosion is allowed to progress, both repair complexity and lost production rise sharply.

The operational problem is not just material loss. Category 4 and 5 work can require deeper preparation, controlled build-up of repair material, longer cure periods, more inspection stages and tighter judgement about whether the blade is still a repair candidate. At that point, repair and replacement start to compete directly in the asset owner's maintenance plan.

UV-curable coatings: reducing dead time in the repair sequence

Conventional leading-edge protection systems cure through chemical crosslinking influenced by ambient temperature and humidity. Two-component epoxies and polyurethanes can take hours, and in some cases longer, to reach the mechanical properties required for the next process step.

For a robotic repair system, cure time is not a minor detail. The blade remains in position, the robot cannot move to the next stage of the sequence and the weather window continues to close.

UV-curable LEP materials change the sequence. Instead of waiting for ambient cure, the material can be applied, checked and cured on demand using an onboard UV source. In a controlled robotic workflow, this creates a possible path to faster layer build-up and more predictable cycle times.

The concept is straightforward; the formulation challenge is not.

A UV-curable material for wind blade repair has to spray cleanly through the robot, wet the prepared substrate, cure at the right depth and speed, retain erosion resistance and remain compatible with the blade materials underneath. Viscosity, cure kinetics, adhesion chemistry and environmental durability all have to be tuned together.

Aerones says it is developing this capability with a UV-curable material manufacturer as a dedicated materials programme, rather than simply adapting an off-the-shelf coating. Early rain erosion testing is reported by the company as promising, but comparative third-party data and field results will still be needed before the industry can judge durability at scale.

Glass fibre reinforcement: adding structural function

Speed alone will not solve severe erosion.

The deeper challenge is restoring a damaged leading edge so that the repair is not just a protective skin over a weakened area. For Category 4 and 5 blades, the repair material has to contribute to shape recovery, adhesion and mechanical performance.

Aerones' second line of development focuses on milled glass fibres within the LEP matrix. The intention is to improve the mechanical performance of the cured repair system and strengthen the bond between the reinforced material and the underlying laminate.

This is where the work becomes more than coating selection. A fibre-reinforced system has to remain stable during spraying, avoid clogging or separation, and limit air entrainment during application. Voids, poor wet-out or uneven fibre distribution would reduce both adhesion and erosion resistance.

Aerones is working through these issues in its Riga materials laboratory, where full-size blade stands are used for prototype application and repeat testing. That matters because the path to field use depends not only on whether the material performs in a coupon test, but also on whether it can be applied consistently by the robot on a real blade geometry.

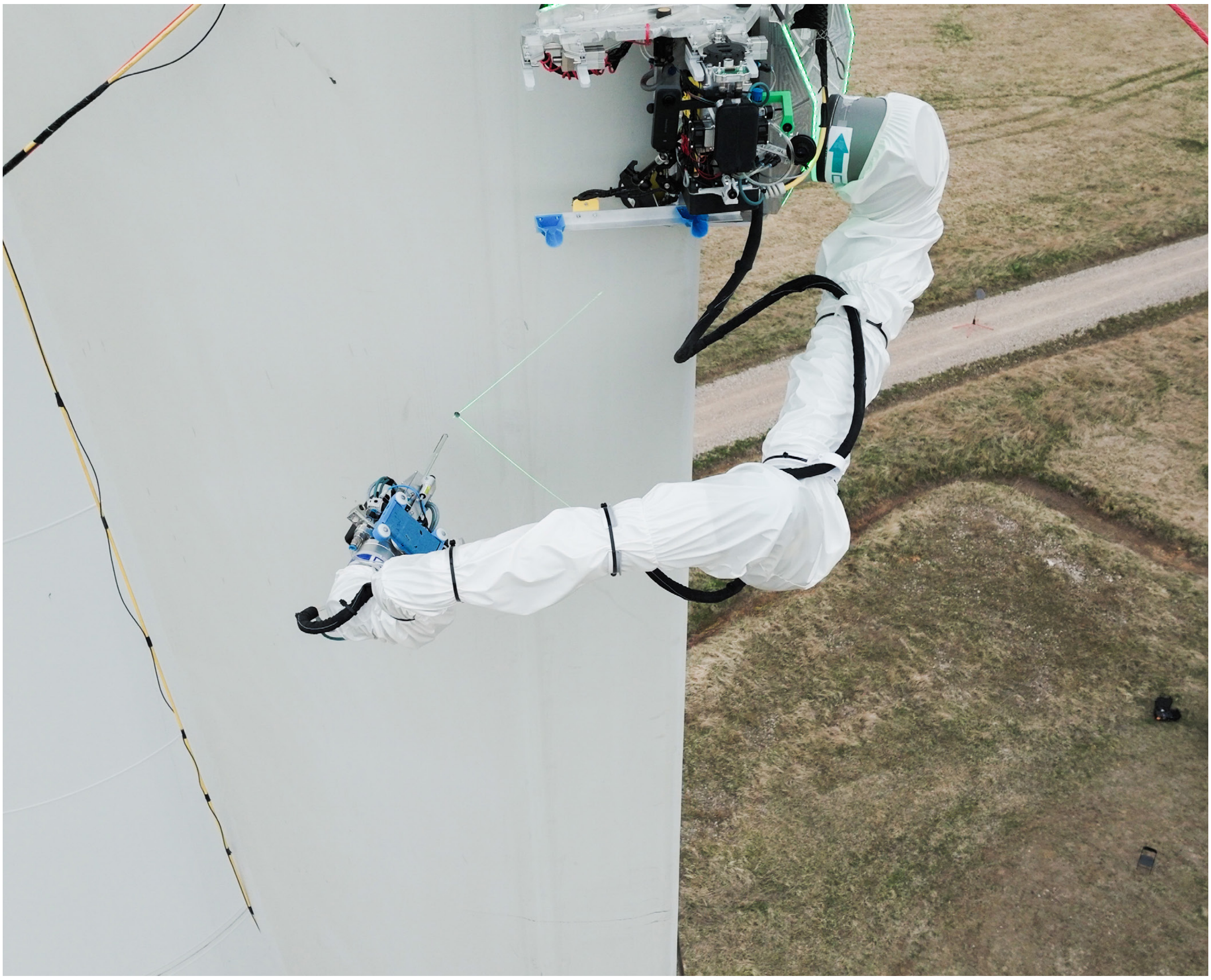
Fibre-reinforced repair materials are not unique to Aerones. Research at DTU Wind Energy and the University of Strathclyde has examined rain erosion mechanisms, leading-edge degradation and test methods for evaluating protection systems, while several material suppliers have developed reinforced fillers or protection systems for wind blade repair.

The differentiator in this case is the proposed integration: reinforced material, robotic spray application, controlled UV cure and process verification as one repair method.

The integration challenge

The opportunity is not UV curing on its own or fibre reinforcement on its own. It is the combination.

A robotic system that can prepare the surface, apply a reinforced repair material,



verify thickness, cure the layer on demand and log the process could give severe-erosion repair a level of repeatability the market has not had before.

That is also where the engineering risk sits.

Each element is at a different stage of maturity. UV curing, fibre reinforcement, robotic application and automated quality control all have their own variables. Bringing them together on a suspended blade, under field conditions, is likely to expose issues that laboratory testing cannot fully predict.

The phrase 'AI-guided process control' is often used loosely in this part of the market, so it needs definition. In this context, the useful functions would be practical rather than cosmetic: vision-based surface recognition, spray-path control, layer-thickness verification, cure confirmation, defect detection and a digital QA record for the completed repair.

Those functions would not replace engineering judgement. They would make the repair easier to specify, repeat and audit.

For asset owners, that distinction matters. A repair method does not need to be fully autonomous to be valuable. It needs to reduce the number of variables that currently make severe erosion work slow, weather-sensitive and inconsistent.

Why it matters for fleet planning

If Category 4 and 5 erosions can be addressed with more controlled robotic processes, the replacement case changes.

Blade replacement would remain necessary where structural condition, remaining life or economic risk make repair unattractive. But if severe erosion repair becomes faster, more repeatable and easier to validate, asset owners could have a wider set of options before committing to replacement.

That would affect maintenance reserves, campaign planning and lifetime-extension assumptions. It could also change the timing decision. Instead of waiting until enough turbines justify a heavy repair campaign, operators may be able to intervene earlier on individual blades if the repair process becomes more predictable.

For sites already approaching Category 4 or 5 damage, the decision remains difficult. The next generation of robotic, UV-cured, fibre-reinforced repair is not yet a fully proven commercial standard. Operators still have to weigh current repair capability, blade replacement cost, lost production, contractual structures and early-adopter risk.

For newer fleets, the more important point is strategic. It is no longer safe to assume that severe erosion repair will look the same in three to five years as it does today.

The hardest problem in blade erosion repair has not been solved. Any claim that it has should be treated carefully.

The direction of travel is clearer than the timeline. Severe erosion repair is moving away from largely manual intervention and towards controlled, materials-led robotic repair. If that transition holds, the next few years could reshape how operators think about blade replacement, lifetime extension and the economics of ageing fleets.

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