WHITE PAPER

How to protect wind turbine rotor blades from leading edge erosion?

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Contents

Introduction

In this white paper you will learn:

- About the main drivers of leading edge erosion (LEE) and which problems come along with it.
- Which solutions exist to avoid LEE and what their distinctive characteristics are.
- How losses in annual energy production (AEP) resulting from erosion compare to a blade with a softshell leading edge protection (LEP) applied.

Leading edge erosion of rotor blades is a widespread damage observed on modern wind turbines. Repairs of eroded leading edges are often costly and time consuming. A forecast by the energy consultancy Wood Mackenzie shown in Figure 1 projects that, by the end of the decade, the money spent repairing leading edges will surpass one billion dollars per year. As rotor blades become longer and tip speeds are increasing, the problem of eroded blades is affecting more and more turbines. Material developers and turbine blade manufacturers are putting significant efforts in the development of new solutions to overcome the issue of LEE and thereby minimize the negative effects on power output and maintenance cost. Putting an end to LEE requires leading edge protection solutions that are capable of withstanding higher loads and endure the degrading effects of weathering. Combining these material capabilities with simulations that can be used for predictive maintenance will be one key enabler to lower the cost of wind energy.

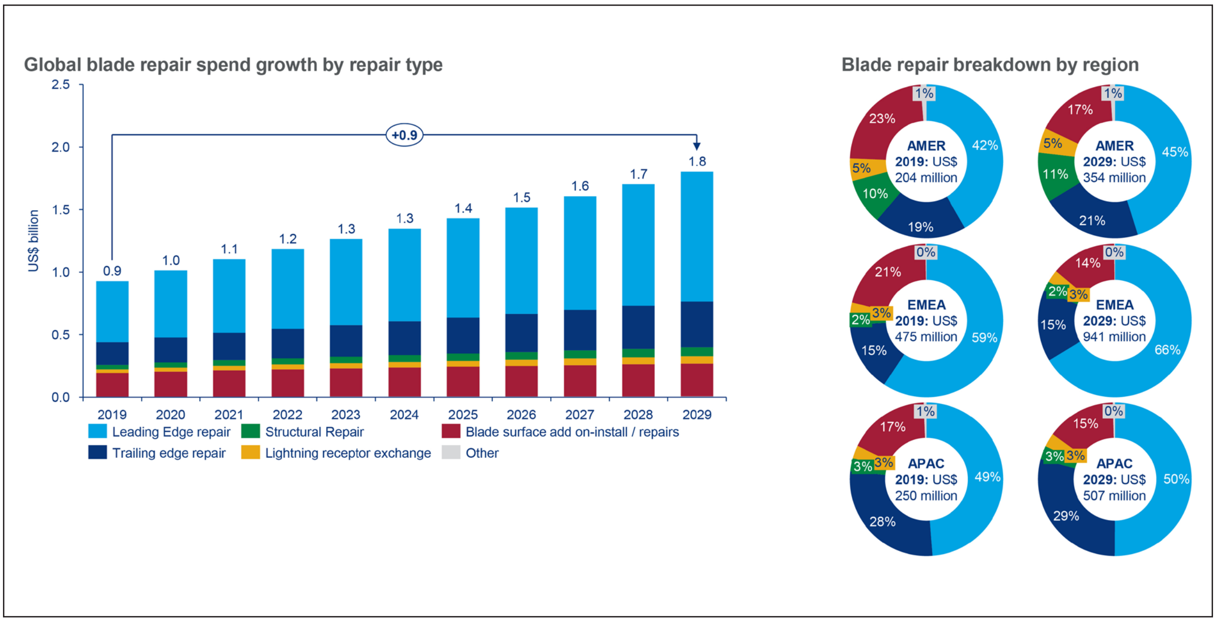


Figure 1 *depicts the forecasted global blade repair spend growth by Wood Mackenzie [1].*

Turbine design effect on erosion

As turbines grow in size and their tip speeds increase, the issue of leading edge erosion becomes more pronounced. Modern wind turbines are designed to harness maximum energy by utilizing longer blades and higher rotational velocities; however, this also heightens their exposure to environmental elements. The increased tip speed intensifies the impact forces as blades interact with rain, hail, and other particulates in the atmosphere. This amplified stress accelerates surface degradation, making the leading edges more vulnerable to damage.

Moreover, larger turbines often operate in harsher environments, such as offshore wind farms, where exposure to salt, high humidity, and extreme weather conditions compounds the erosion process. The combination of increased blade size and speed results in not only faster erosion rates but also more costly repairs and maintenance. These factors underscore the urgent need for enhanced leading edge protection solutions that can endure these heightened stress levels while maintaining blade efficiency and structural integrity.

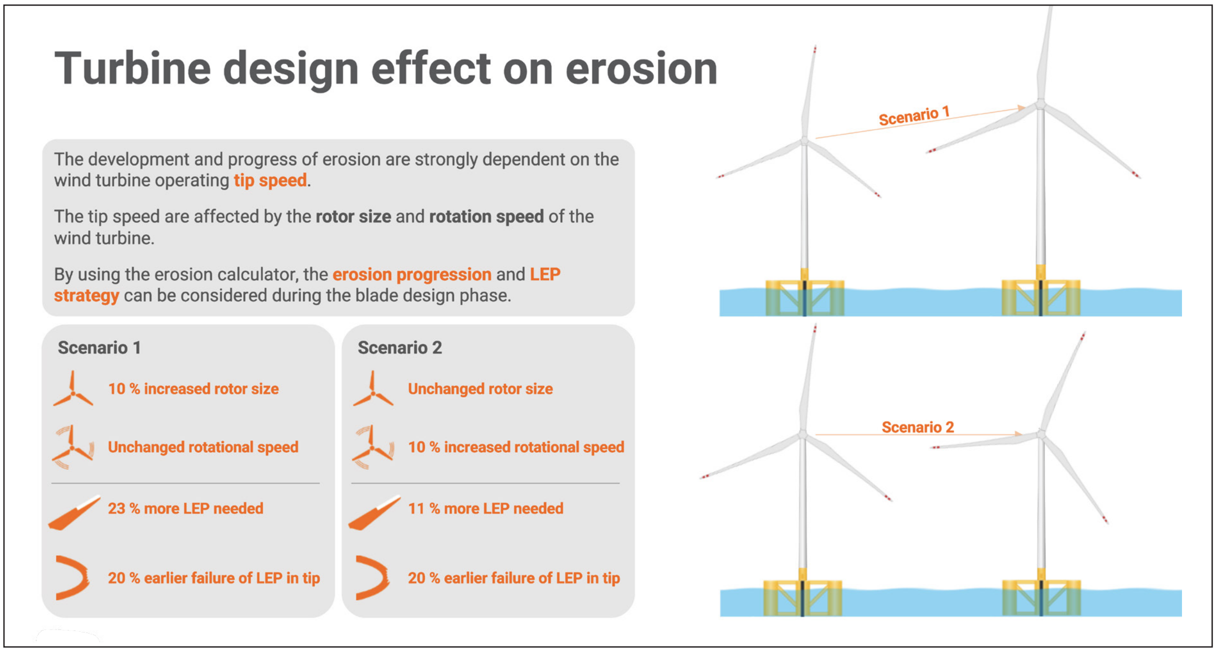


Figure 1a *shows how change in rotor size or tip speed increases the need for leading edge protection.*

Another significant environmental factor contributing to leading edge erosion is annual rainfall. The frequency, intensity, and distribution of precipitation play a critical role in determining the rate at which erosion occurs on wind turbine blades. Regions with high annual rainfall expose blades to increased droplet impacts, exacerbating wear and tear over time. Even light rain, distributed consistently throughout the year, can lead to cumulative damage on unprotected blades. This highlights the importance of considering local climate conditions when designing and selecting leading edge protection systems to ensure durability and optimal performance across varying environmental challenges.

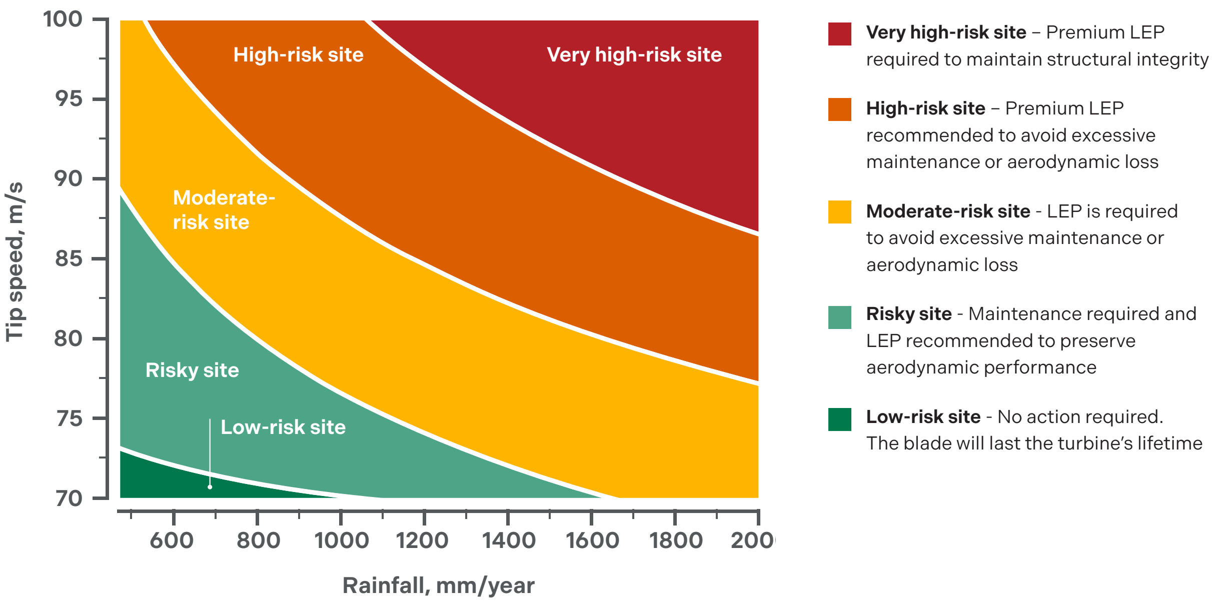


Figure 1b *shows how the relation between rainfall and tip speed calls for different qualities of leading edge protection.*

What is leading edge erosion and what problems come along with it?

During operation, the leading edge is exposed to wear and tear, which results in blade material surface deterioration and increased surface roughness and thus reduced annual energy production (AEP). This leading edge surface erosion increases dramatically with increased rotor speed. Additionally, certain wind turbine environmental conditions, such as annual rainfall and droplet distribution can cause leading edge erosion if the blade is unprotected.

When liquid droplets impinge upon the solid blade surface, the stress created by the droplets may cause pits or cracks on the surface eventually leading to loss of material. This damage, called "erosion" or "rain erosion", will significantly weaken the material integrity, and over time the blades will suffer from losses in AEP and ultimately risk a complete blade failure. There are principally two ways that a droplet can cause damages to the material upon impact. The initial impact of the droplet causes an increase in pressure acting across the liquid-solid interface contact area, which results in a force that is normal to the solid surface. This force generates stress waves traveling along the surface and inside the material, eventually leading to cracks in the material. After the initial impact, the water droplet breaks up and the liquid escapes laterally and forms what is known as a water jet. During the incubation period where no mass loss is observed, the consequences of the water jet are negligible. However, when the first crack has appeared on the material surface, the water jet will play a significantly larger role in progressing the erosion further. The water jet will interact with small cracks and surface imperfections and tear off smaller pieces of material. This will enhance crack growth with significant crack propagation.

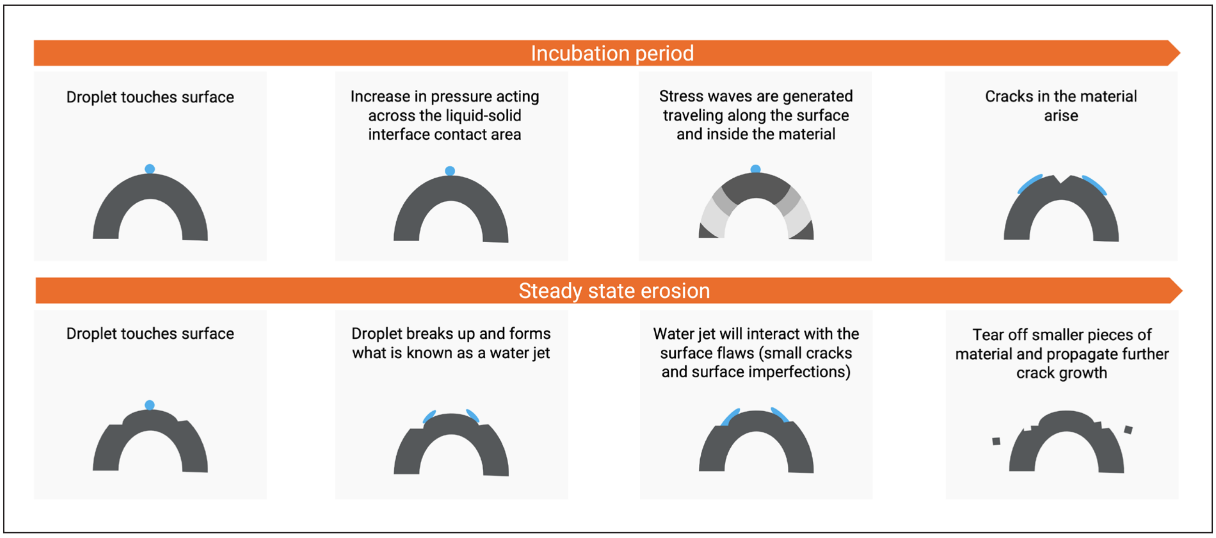


Figure 2 *How rain causes progressive LEE on the blade surface.*

Experimental studies have shown that the weight loss of the materials that are subjected to repeated droplet impingement varies as a function of the number of impacts [2]. During the so-called "incubation period", the weight loss is negligible. The length of the incubation period can be considered as a key material property that is used to describe the erosion resistance. After the incubation period, the rate of mass loss is constant. This period is called "steady state erosion region". In this region, mass loss increases as a function of the number of impacts. It is within this region that we observe disturbance of the aerodynamic flow around the blade that leads to losses in AEP. After the steady state erosion region, the mass loss becomes more complex. This stage is referred to as the "final erosion region". In this region, we will often see that the material used as leading edge protection will suffer from breakthrough to the substrate, and thereby expose the underlying layers for further erosion. These underlying layers typically consist of conventional coatings, fillers, and glass fiber reinforced plastics - all of which have a significantly lower erosion resistance when compared to modern leading edge protective materials. Once breakthrough has occurred, it will further accelerate the erosion of the leading edge and thereby jeopardize the structural integrity of the blade. Figure 3 schematically depicts the erosion progression as described here.

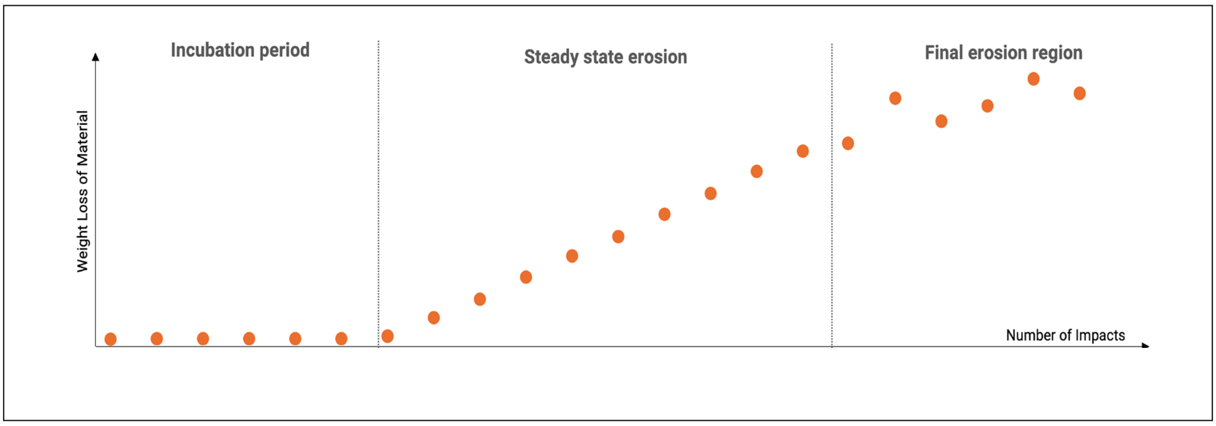


Figure 3 *A principal sketch of the erosion progression for a specific material exposed to N number of impacts at a specific impact speed [2].*

There are four basic ways by which erosion can be minimized or completely avoided [2]:

1. Running the turbine blade at lower speed,
2. Diverting the droplets from the surface before they hit the blade surface,
3. Breaking up droplets before they impinge upon the blade surface,
4. Using materials which can withstand the forces created by impacting droplets.

The first method will make the turbine less efficient and thus increase the cost of energy. Methods 2 and 3 are not feasible from a practical point of view considering a wind turbine and its operating environment. This leaves method 4, using materials for minimizing and preventing the damage from occurring, as the most obvious and practical approach.

To select and design materials that withstand the repeated droplet impingements, the material characteristics must be fully understood. Typically, empirical studies using whirling arm rain erosion tester are the preferred choice within the wind turbine industry to study the behavior of materials subjected to impingement of liquid droplets. Researchers and material developers subject the materials to relatively high speeds (i.e., 160 m/s) during testing and characterization. Having said that, lately testing is also being conducted at the actual operating speed of the wind turbine blade and thus improving the correlation between test conditions and real-life exposure. This means that one of the key factors for creating erosion on the leading edge of the blade surface can be understood and characterized without having to extrapolate outside the test regime.

The wind turbine manufacturers, operators, and material developers have on two occasions joined forces to create recommended practices on how to conduct rain erosion tests and which data to acquire during testing. These principles of rain erosion testing and data acquisition are published by DNV GL as "DNVGL-RP-0171 Testing of rotor blade erosion protection systems" [3]. Furthermore, a second joint industry project was established with the purpose of developing a methodology to evaluate erosion protection systems and provide input on how to perform calculations of the expected durability using results from rain erosion testing. This methodology functions as a guide for operators, wind turbine blade manufactures, and material developers to establish the needed data to evaluate the durability of erosion protection systems. The document is published by DNV GL as "DNVGL-RP-0573 Evaluation of erosion and delamination for leading edge protection systems of rotor blades" [4]. These two recommended practices are being used as the foundation for evaluating existing erosion protection systems and provide guidance for new erosion protection systems in development.

Which solutions are being used to avoid leading edge erosion?

There are different mitigation strategies used by the wind turbine blade manufacturers to avoid leading edge erosion. Typically, these solutions have been inspired by other industries that also face the challenge of erosion. Products such as liquid applied paint, either epoxy or polyurethane, and protective tapes based on thermoplastic polyurethanes have been transferred from the aviation and helicopter industry to be used on wind turbine blades. Newer products, such as shells that are installed on the finished blade made from semi-rigid thermoplastics or softer polyurethanes, have appeared on the market within the last five years. Figure 4 provides an overview of the different solutions and their distinct features.

	ELLE®	ELLE® Onshore	Most used Protective Tape	Most used Paint
Average Performance Index	100%	55%	20%	5%
Application Temperature	+5 to +35°C	+10 to +38°C	+10 to +30°C	+15 to +35°C
Application Humidity	≤80% RH	≤100% RH	≤80% RH	≤100% RH
Application Time	20%	10%	20%	100%
	Very high-risk site – High-risk site	Moderate-risk site	Risky site	Low-risk site

Figure 4 *A comparison of different LEP systems. Based on 20 years remaining lifetime for a central European WTG of the 3MW class with medium rain exposure, 1 exchange/repair for best-in-class tape and coating, 5 exchanges/repairs for most used tape and coating.*

Protective Tapes

Protective tapes have a long history in the wind industry and have for years represented the standard solution for blade leading-edge protection. Traditionally, these tapes are relatively thin (less than 0.5 mm) and attached to blades using acrylic-based pressure-sensitive adhesives—typically made from extruded thermoplastic polyurethane. Over time, material advancements have led to the adoption of polyether-based thermoplastic polyurethanes, notably improving resilience to hydrolysis. When installed correctly, protective tapes offer better erosion resistance than conventional liquid coatings and can be applied both in blade manufacturing facilities and as part of up-tower repairs on operational turbines.

Despite these advantages, the inherent trade-offs of conventional tapes are well known. Limited material thickness means that the interval between the first appearance of cracks and full-thickness erosion can be short. Moreover, partially detached tapes may remain on the blade surface, generating excessive noise, increasing aerodynamic drag, and ultimately resulting in measurable Annual Energy Production (AEP) loss.

In response, Polytech developed ELLE® Onshore: a next-generation leading-edge protection system drawing upon advanced soft-shell technology. Introduced in 2024, ELLE® Onshore features an increased thickness of approximately 1.0 mm with precision-chamfered edges—delivering the durability and heightened erosion resistance associated with rigid shells, while retaining the ease and flexibility of installation of protective tapes. The result is a solution engineered to extend asset life, minimize downtime, and safeguard AEP—all with the installation efficiency today's wind industry demands.

Shells

In recent years, another approach has entered the market for leading edge protection. The premanufactured shells that are specifically made to fit the turbine blades provide a readily available alternative to the other established routes of erosion protection. The manufacturing of the shells in a dedicated production environment using specialized equipment ensures high quality material production by completely avoiding mixing errors at site, low film thickness and mm size imperfections that can all lead to pre-mature erosion on the leading edge. The thick and compliant material is designed to withstand repeated impingement of rain droplets and other airborne particles. Additionally, the thickness of the softshell ensures that any smaller cracks in the material do not lead to breakthrough failure. It therefore provides the blade with protection and minimizes the aerodynamic disturbances when compared to thinner alternatives.

Basic aerodynamics and the impact from LEE and LEP on aerodynamical performance

The impact of leading edge erosion on the AEP has been subject to research and testing for several years [5]. These studies have mainly focused on the impact on the overall aerodynamical performance of the blade since this is directly related to the performance of the turbine. In general, there are two basic aerodynamical parameters that are essential for this performance: lift and drag. The lift is causing the required torque on the rotor to produce electricity, whereas the drag (also known as "air resistance") is causing a force on the blade in the downstream direction of the wind. These two forces are dependent on different parameters, such as airfoil shape, relative thickness of the airfoil, angle of attack, Reynolds number, and surface roughness, which is highly related to erosion and contamination.

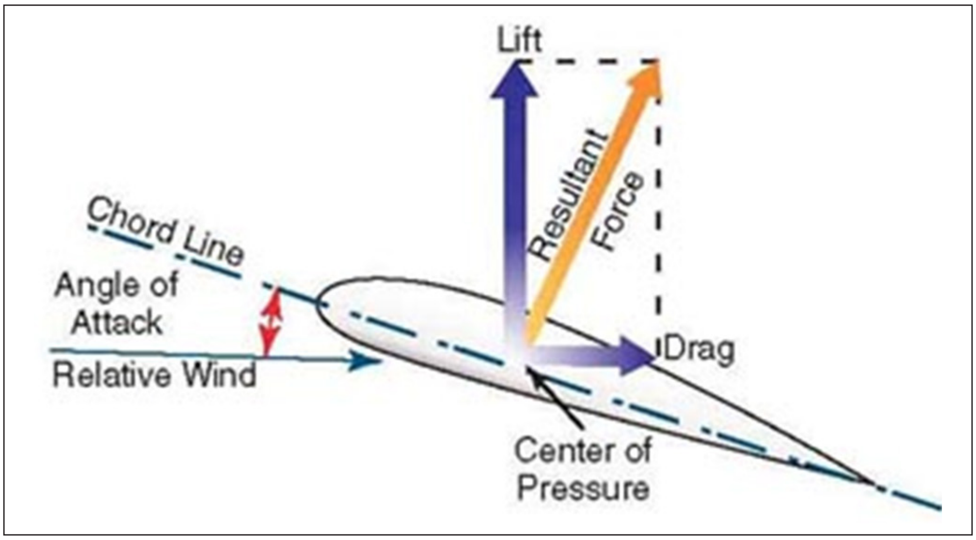


Figure 5 *A schematic sketch of lift and drag on an airfoil.*

Two non-dimensional parameters related to the forces are C_L and C_D, which are the lift and drag coefficients, respectively. It is the relationship between the two parameters that is essential for the performance of the turbine, as the lift has a positive impact and the drag has a negative impact on the power production. This means that a high lift over drag coefficient, C_L/C_D, is desired. This can be found from looking at the simplified expression for the viscous loss in the local power coefficient [6].

$$PowerLoss_{local,viscous,simplified} = \frac{3}{2}\frac{\lambda_{loc}}{\frac{C_L}{C_D}}$$

The power loss decreases as the lift over drag relation increases. The difference between viscous and inviscid flow and the relation to the power coefficient, together with the influence from the axial induction factor and the loss at the tip, are intentionally left out for the more interested readers to pursue themselves.

The parameter λ_{loc} in the expression above is called the local speed ratio. In general, the speed ratio is given at the tip as

$$\lambda = \frac{v_{tip}}{v_{wind}}$$

That means a turbine with a tip speed of 80 m/s at a wind speed of 10 m/s will have a speed ratio of 8. By introducing the speed at any radial position on the rotor, given by the radius from the center of the rotor, we can obtain the local speed ratio,

$$\lambda_{loc} = \frac{\omega \cdot r}{v_{wind}}$$

where *w* is the angular velocity and *r* is the radius. As derived from the equation, the local speed ratio is increasing as we move closer to the tip. This illustrates that a high lift over drag relation on the outer part of the blade is much more important than on the inner part. This is directly relatable to LEE as it is also in the outer region where most erosion appears and is therefore the most important part to protect.

The viscous power loss introduced earlier is highly related to the phenomena occurring in the vicinity of the airfoil. All around the airfoil, there is a boundary layer where the flow profile is different from the freestream flow away from the profile. This boundary layer is very sensitive to any disturbances that might appear (e.g., imperfections on the surface as erosion, contamination, etc.). The flow profile is described by the Reynolds number, whereby a low Reynolds numbers indicates a more laminar flow and high number a more turbulent flow. The Reynolds number is dependent on wind speed and some other parameters that we - in this case - assume to be constant for the sake of simplicity. An increase in wind speed will result in an increase of the Reynolds number.

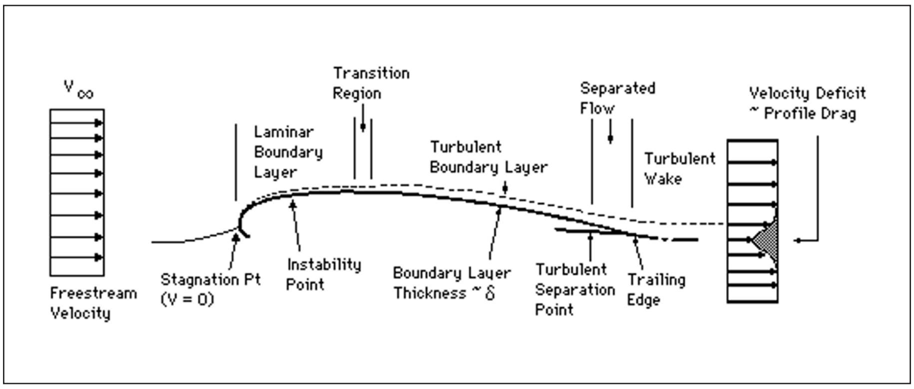


Figure 6 *The laminar flow in boundary layer at different zones of the airfoil.*

Figure 6 illustrates the laminar flow over the airfoil. Near the leading edge, the flow in the boundary layer can be described as laminar. As we move along the surface in the chordwise direction, a transition zone appears, where the flow changes to be dominated by turbulences. It is of great importance where this transition zone appears, as the more laminar flow we have in the boundary layer the better. The position of this transition zone is affected by erosion, contamination, or other elements that can disturb the laminar flow near the leading edge. Figure 7 shows a picture taken in a wind tunnel with a thermographic camera. It illustrates how erosion can affect the flow and thereby shift the transition zone. The yellow line indicates the original transition zone, and the dark grey areas arising from the leading edge up to the yellow line show the desired laminar flow. The test demonstrates that erosion disturbs and can even eliminate the laminar flow.

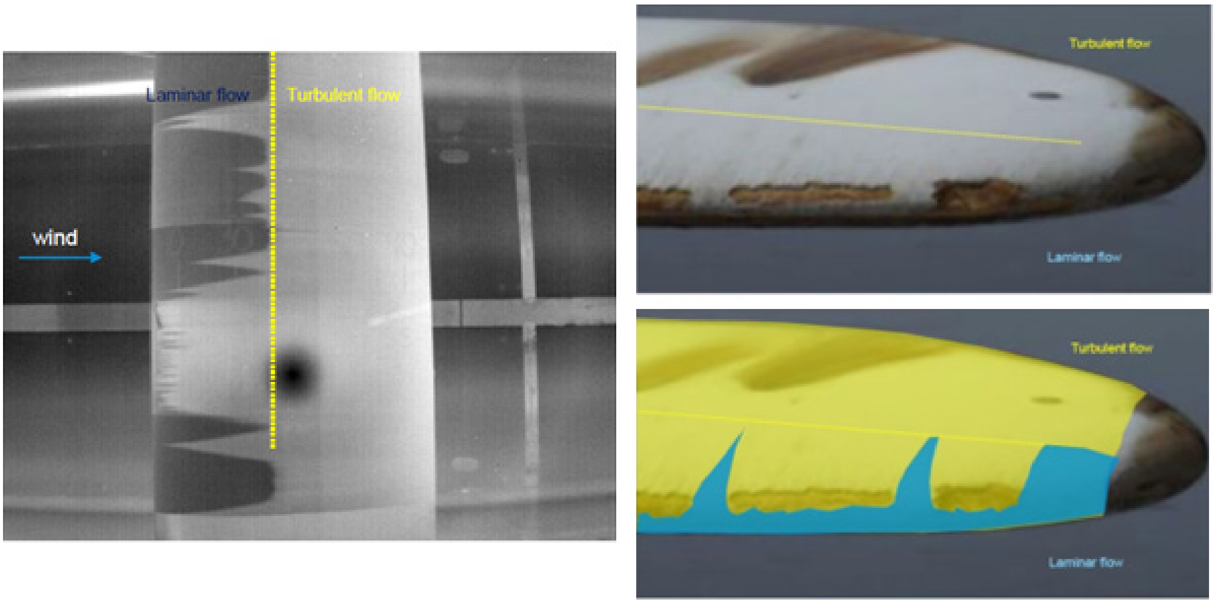


Figure 7 *Shift of the transition zone from laminar to turbulent flow due to erosion within a wind tunnel setup (left) as well as for a heavily eroded blade (left).*

Study on potential AEP loss

To investigate how AEP can be affected by different erosion stages, a wind tunnel test was conducted in the Poul La Cour Tunnel at the Technical University of Denmark (DTU) in 2020. The test was conducted in a collaboration between a wind turbine manufacturer, DTU and Polytech. The wind tunnel setup at DTU can be seen in Figure 8.

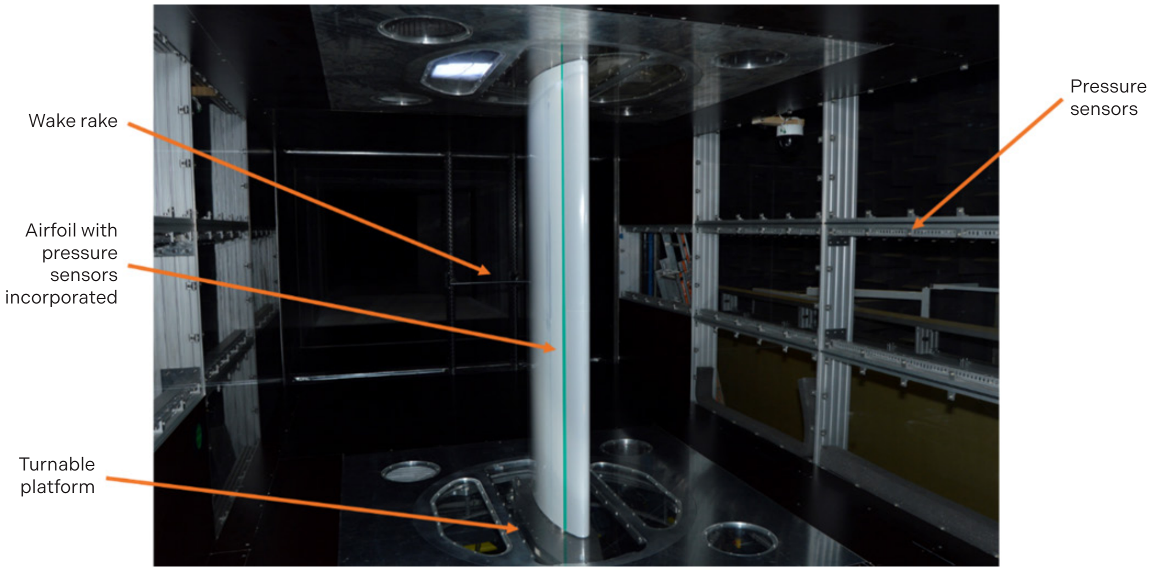


Figure 8 *The wind tunnel test setup at the Technical University of Denmark (DTU)*

Within this test setup, the following features were tested (among others):

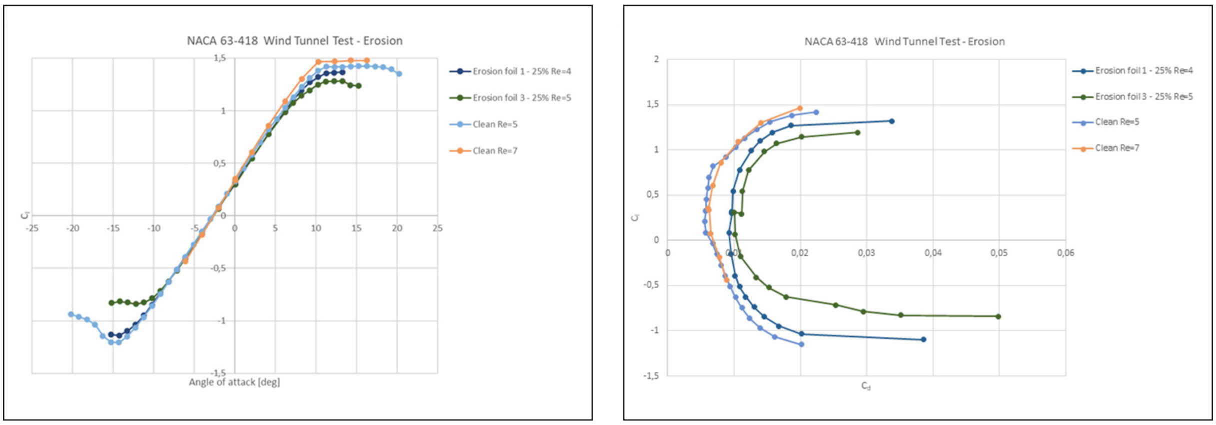
- Light erosion (stage 1) – 300 μm indentation
- Severe erosion (stage 3) – 600 μm indentation
- Clean blade

The erosion profiles shown in Figure 9 were specified and delivered by the wind turbine manufacturer.

Figure 9 *The 300 μm (top left) and 600 μm (top right) indentation were used within the wind tunnel test.*

In the wind tunnel the drag and lift coefficient were measured according to the angle of attack, this resulted in the lift and drag curves depicted in Figure 10.

Figure 10 *Showing drag vs. lift for different angles of attack.*



By evaluating the results from Figure 10 one can conclude that the erosion has an impact on both lift and drag.

A reference blade with the following specification was used to calculate the AEP impact:

- Blade length: 61.5m
- Max chord: 4.62m
- Tip speed at rated power: 80m/s
- Rated power at a wind speed of 13 m/s
- Rated power: 6MW

The AEP loss is calculated as a difference from the clean profile to the eroded one. The AEP loss in the following graphs is calculated for different spans of erosion and for wind class I, II and III.

Figure 11 *The AEP loss in percent for different levels of for different wind classes and spans covered.*

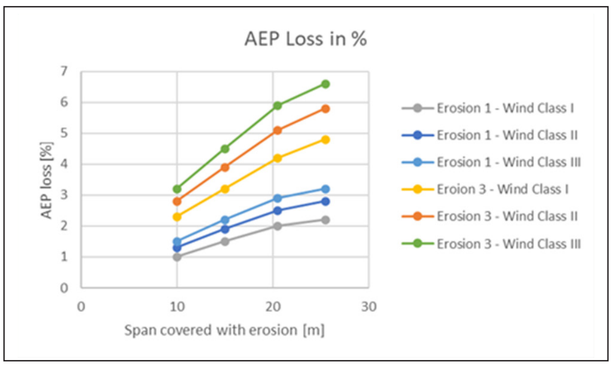


Figure 11 shows that the light erosion profile can cause an AEP loss from 1% up to 3.2% depending on span and wind class. Severe erosion can cause a loss from 2.3% up to 6.6%.

Measured AEP Losses with Different LEP Solutions

Measured data from both controlled testing and real-world operation have demonstrated that the choice of leading edge protection (LEP) has a significant influence on annual energy production (AEP) loss over a turbine's operational life . Comparative wind tunnel analyses reveal that pristine, clean blades finished at the factory with only standard paint or a thin gelcoat may initially offer minimal surface roughness; however, this approach provides only limited resistance to environmental wear.

No real life comparison to Polytech's knowledge has ever been made. And within a few months of exposure anyway, these surfaces typically begin to degrade, resulting in a rapid increase in surface roughness and, consequently, higher AEP losses that can reach or exceed 3% under moderate to severe site conditions.

In contrast, the application of modern LEP solutions—such as advanced protective tapes, shells, or softshells—has been shown to mitigate this loss. For example, best-in-class softshell systems have demonstrated the ability to limit AEP loss to only 0.4%–1.4% across a wide range of operating scenarios, thanks to their superior durability and erosion resistance. Conversely, tapes and thin coatings, while initially effective, often lead to greater energy losses over time due to their propensity for early damage, partial detachment, or breakthrough, especially under high rain or particulate exposure. At the end of the day, the critical metric for operators is not simply an initial cost or surface finish, but the sustained aerodynamic performance of the blade throughout its service interval. Long-lasting, durable LEP solutions minimize the need for frequent repairs and production stops, directly supporting lower life-cycle costs and higher energy yield compared to short-term, less robust alternatives.

Conclusion and Recommendation

This white paper has presented how LEE develops and propagates, which mitigation strategies exist, what their specific features are, and which recommended practices are available. Combining these with understanding the effects of LEE on aerodynamic performance and AEP, one can draw a holistic conclusion. Addressing LEE with a LEP product can not only reduce or eliminate costly repairs but can also give aerodynamic advantages compared to even slightly eroded blades. As a result, a LEP product can contribute to lowering the cost of wind energy.

We at Polytech think that a solution with a high erosion strength has the lowest lifetime cost and best potential for lowering LCOE for many sites and can be the enabler to ending leading edge erosion on modern wind turbines. Therefore, we decided to develop and constantly innovate our softshell solution, ELLE.

Any further questions?

If you have any further questions, please contact us at info@polytech.com.

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