Blade Leading Edge Erosion Programme (BLEEP): Reducing the cost impacts of wind turbine blade erosion

Andy Kay, Innovation Manager

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One of the main issues facing the offshore wind industry is blade leading edge erosion (LEE), which can occur in a little as two years of operation and can affect the performance and structural integrity of wind turbines.

ORE Catapult's Blade Leading Edge Erosion Programme (BLEEP) is coordinating research to improve understanding on how to manage and prevent this issue to reduce the cost of energy impacts by facilitating collaboration between industry and the research community.

Summary of findings

- The potential impact of LEE severity on the power performance and revenue generating capabilities of wind turbines is not fully understood by the offshore wind industry..
- LEE is a very complex phenomenon; there is limited understanding on how blade Leading Edge Protection (LEP) systems degrade over time and therefore it is currently not possible to predict the design-lifetime of wind turbine blade LEP systems (protective coatings and materials).
- Tackling LEE offshore is challenging and expensive. Repair systems are difficult to apply by rope access and quality assurance is hard to enforce;
- All of these issues combined create uncertainty over the economic return of offshore wind farms.

Recommendations

- Promote collaboration between wind farm owner/operators, the supply chain and the research community to resolve the issue of blade LEE.
- Improve understanding on the 'cause and effect' of LEE to increase the durability of LEP systems and the economic return of operations and maintenance (O&M) interventions.
- Develop repeatable test and analysis methods, representative of the offshore operating environment, to validate the durability and design-lifetime of blade LEP and repair systems.
- Engage in developing innovative blade LE access, inspection, repair and condition monitoring solutions to optimise the performance and economic return of O&M interventions.

Leading edge erosion

Industry engagement undertaken by the Offshore Renewable Energy Catapult (ORE Catapult) has identified LEE as a substantial issue during the O&M phase of offshore wind farms. The problem is widespread across the European fleet of offshore wind farms and is also affecting onshore wind turbine installations.

LEE is known to occur when precipitation in the atmosphere and other airborne particulates impinge on wind turbine blades rotating at high velocities. The majority of these impacts are localised around the blade leading edge. The largest impact velocities are experienced at the outermost section of the blade, where the rotational speed is highest.

When the smoothness of a blade surface is degraded its aerodynamic performance is known to reduce; this restricts power and revenue generation. LEE increases surface roughness at the outer section of the blade, where the majority of lift, and hence power, is generated. Moreover, if severe enough, LEE can expose the blade materials to damaging levels of UV light exposure and moisture ingress, which can reduce structural integrity.

LEE is believed to be occurring at a faster rate offshore than onshore. Larger machines with higher blade tip velocities operating in harsher environments are believed to be the major cause. However, this is yet to be properly investigated.

Offshore wind farms coming out of warranty are facing substantial costs associated with the repair of LEE damage. Repairs can include coating and laminate repairs and LEP retrofits. Limited understanding of the design-lifetime of LEP systems and cost impacts of LEE make it difficult to optimise maintenance plans designed to minimise costs.

Given the high costs of installing offshore wind farm assets, owner/operators face growing pressures to reduce Operational Expenditure (OPEX) in order to achieve a sufficient return on investment.

Industry feedback from owner/operators, turbine manufacturers (OEMs) and the wider supply chain identified the following areas that require further investigation:

- Cost impact: It is necessary to quantify the impact of LEE severity on wind turbine power performance to improve the cost modelling and planning of wind farm installations and O&M interventions.

- Physics of failure: increased understanding on the science behind LEE failure mechanics and their impacts on blade coating and material properties is required to improve the resistance of LEP systems to erosion.

- Testing: LEE test and analysis methods that produce repeatable and realistic simulations of the offshore operating environment are required to accurately predict the design lifetime of LEP systems.

- O&M Innovation: new and innovative blade access, inspection and repair systems are needed to improve the quality and reduce the costs of LEE O&M.

Individual company research is ongoing to address the issues of LEE. For example, turbine OEMs are investing in new LEP system developments to prevent LEE at the blade production stage.

Coordination of this research on an industry wide scale is required to reduce the risk and maximise the efficacy of these measures. The following expands on the industry feedback to identify where focussed research is required.

Cost impact

LEE can increase the Levelised Cost of Energy (LCOE) by limiting energy production (through reduced turbine power performance) and increasing OPEX (through costly maintenance interventions).

It is important to quantify the potential LCOE impact of LEE to improve the cost modelling of offshore wind farms. The economic return of a wind farm will be hindered by any performance degradation of the wind turbines, including LEE. Blade O&M interventions to inspect and repair LEE are expensive offshore. Understanding when lost production costs outweigh repair costs is crucial to optimise the frequency and economics of such O&M interventions.

O&M costs for LEE are well understood. However, the relationship between LEE severity and power performance loss has not been suitably quantified. Several wind tunnel studies have shed some light on the potential impacts but tests on full scale operational turbines are required to support accurate wind farm cost models.

The impact of LEE severity on turbine power performance is difficult to measure and quantify. There are many other parameters that can cause a turbine's power output to deviate from its mean value, including variations in atmospheric conditions and wind direction alignment errors. Carefully planned and executed measurement campaigns are required to isolate the impact of LEE on power performance.

This information, combined with an understanding of the sensitivity of LEE to various operational (such as turbine age) and contextual (localised rain densities and velocities) parameters, is necessary to optimise the scheduling and scoping of blade O&M interventions.

Developing this insight requires an assessment of performance and site data from multiple wind turbine technologies, installed in various operating environments, both onshore and offshore. This is dependent on collaboration and data sharing between wind farm owner/operators.

Physics of failure
LEE on wind turbine blades is a complex phenomenon which can be influenced by many factors, including:

- rain droplets (size, shape and blade impact velocity vector);
- hail particles (size, density and blade impact velocity vector);
- air particulate content (sand, soot, salt etc);
- blade aerodynamic profile and tip speed;
- blade coating properties (hardness, elasticity, fatigue resistance, adhesion defects);
- blade base materials (structure, properties, damping behaviour, defects);
- coating and material weathering (UV exposure and moisture ingress).

The significance of these factors on LEE will depend on the turbine technology, the operation of the turbine and the environment at the wind farm location. Moreover, the interdependency of these factors must be considered. For example, degradation of the material properties due to combinations of UV light exposure and moisture ingress can, over time, reduce the resistance of blade coatings and base materials to rain droplet impacts.

The complex nature of LEE is not fully understood and warrants further investigation. This is necessary to improve the resistance of coatings and materials to both erosion and weathering degradation. Fully understanding wind turbine operating environments (onshore and offshore) and their contribution to LEE will help to make testing more representative and accurate and will de-risk LEP systems. Furthermore, understanding the combined effect of weathering and erosion on LEP degradation is vital to improve LEP performance.

Testing
Highly accelerated laboratory-based testing is performed on coatings and materials to evaluate their resistance to LEE. Test results should provide a level of assurance on the durability and design-lifetime of a LEP system.

Testing is typically performed by rotating coated blade samples through a simulated rain field for a period typically between a few minutes up to 30 hours. The test is accelerated through the speed of the rotating arms and intensity of the rain field. Samples can be pre-weathered in advance of erosion testing through combinations of UV, temperature and humidity exposure in a weathering chamber.

There are growing concerns within the wind industry that erosion test methods are not an accurate or reliable reflection of real life, which is leading to uncertainty on the performance of LEP systems. Accelerated lifetime testing of coatings generally follow the guidelines set out in the ASTM G73 industry standard. Originally developed for Aerospace applications, the tests are not fit for purpose for evaluating blade materials and coatings in wind turbine operating environments. As a result, it is currently not possible to relate the accelerated test performance of a coating/material to its expected design-lifetime in operation.

The repeatability of current test facilities is also a major concern. As such, it is difficult to perform meaningful comparisons of the erosion resistance of different coatings and materials, both in the same rig and in different test rigs. This has been attributed to the complex nature of the test rig environment, the individuality of the various rig designs and the lack of a comparative test method. For example, characterisation of water droplet sizes and impact conditions on test samples is a major challenge. These are known to vary using existing test rig designs.

Improved and then standardised erosion test methods are required for accurate qualitative and quantitative assessments of LEP systems. Combined with innovation in blade coating and material technology, these test methods are necessary to design better LEP coatings.

O&M Innovation

Offshore, LEE is currently monitored through visual blade inspections using rope access technicians or remote methods, such as cameras and telescopes. The classification of observed damage can vary, depending on the organisation performing the inspection or the client. There is no standard criteria for classifying erosion damage. This level of standardisation is necessary to facilitate the consistent mapping of LEE across the sector and the development of tools to support cost/benefit-balanced action plans for repairs.

Other than monitoring the power output of the turbine, there are currently no techniques in use that can remotely detect LEE. Offshore maintenance is generally more expensive than onshore. In the offshore environment variable weather conditions can prevent personnel from accessing sites and working on turbine blades.

Dedicated access systems are required to enable more time per year to safely inspect and repair LEE. Inspection innovations which reduce the dependency on rope access technicians could help to improve safety and increase weather windows to inspect for damage. New, cost effective condition monitoring systems which detect LEE remotely could enable predictive approaches to LEE maintenance, which could help to reduce O&M costs and lost generation during inspection.

Using rope access technicians to repair LEE offshore is a substantial challenge. Application of paint based LEP systems requires stable atmospheric conditions. Limits on temperature and relative humidity can prevent coatings curing properly, which reduces their durability against LEE. In particular regions, such as the North Sea, relative humidity levels are high for extended periods of the year which reduces weather windows for performing repairs. Technology innovations which increase maintenance weather windows and improve the quality and consistency of repairs are required to reduce costs and increase blade reliability.

ORE Catapult has identified a number of areas that require immediate attention to advance the industry in tackling LEE. These issues cannot be resolved simply by one stakeholder group alone. Wind farm owner/operators, OEMs, research institutes and the wider supply chain can all benefit from increased understanding on the factors which cause LEE and their impact on wind farm profitability. This can be used to improve test methods and solutions for LEP systems, as well as O&M strategies which maximise revenues from sites where LEE has occurred.

Due to the complexity of LEE and the large amount of research and testing required, a large collaborative research program is required with the involvement of all of the key research and industry stakeholders.

BLEEP

ORE Catapult has developed and launched the Blade Leading Edge Erosion Programme (BLEEP); a collaboration between industry and the research community to reduce the cost of energy impact of LEE.

Through consultation with industry, BLEEP has been structured to develop new knowledge and innovations in areas that can benefit the whole the industry. The programme is split into four projects as shown in Figure 1. A steering group of industry participants was convened to clarify the focus and objectives of BLEEP.

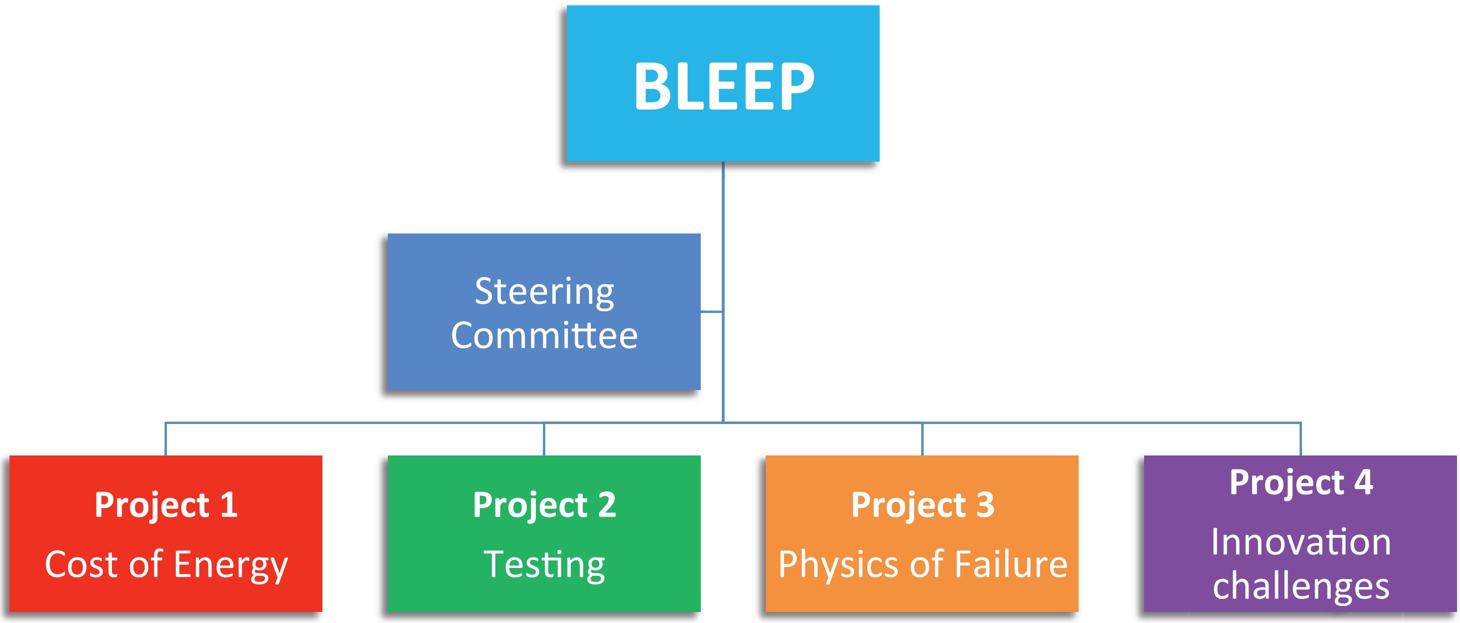

FIGURE 1: STRUCTURE OF BLEEP

Project 1 is determining the correlation between LEE severity and wind turbine power performance loss. A primary objective is to convene industry to establish a standard criteria for ranking LEE severity, based on visual inspections. A dedicated measurement campaign on an offshore wind turbine with eroded blades has been completed to establish the improvement in performance following repair. The campaign concluded that an uplift in AEP of between 1.5 to 2% is possible following the repair of moderate blade erosion.

The campaign was designed to isolate the impact of LEE on power performance from other performance affecting parameters to increase the accuracy and reliability of the results. Combined with further analysis on performance and environmental data from turbines installed at multiple locations, the results will be used to inform cost modelling and O&M planning at offshore wind farms.

Project 2 aims to develop new test facilities at ORE Catapult that enable the accurate and repeatable assessment of LEP systems and their erosion resistance. Pilot studies, including testing and numerical modelling, have been completed to determine the requirements for test rig designs, operation and functionality. The aim is to utilise the facility to develop and optimise the much needed test methods for wind turbine blade LEP systems. Future research using the rig will focus on how to characterise and simulate test environments representative of wind turbine operating environments, with a focus on offshore. The learning outcomes can support development of standardised test methods and guidelines. Longer term the rig can act as an open access facility for the development and validation of new and innovative LEP systems.

Project 3 will coordinate and deliver collaborative research across Europe to determine the fundamental science behind LEE. A number of research areas have been developed to investigate the factors affecting the degradation of coatings through LEE on wind turbine blades. One area where work has begun is the characterisation, through field measurements and computational modelling, of the offshore environment, in terms of the parameters associated with LEE, such as typical rain droplet size distributions and UV levels. The outputs of this research will inform the development of representative test methods, industry coatings research, and analysis, measurement and inspection technologies. It will also be used to develop guidance for testing which can be implemented into the ongoing standardisation work. Collaboration has been established with a number of European research institutes, industry partners and universities, and methods of funding this research are being pursued.

Project 4 is developing innovation challenge statements based on inspection, monitoring, repair and new coatings technologies for LEE on offshore wind turbines. These will be developed in collaboration with industry to ensure innovation in this area meets the requirements of end users. The challenges are focusing on technologies and techniques which can improve the quality and reduce the time and costs of blade O&M interventions. ORE Catapult is promoting the challenge statements to SMEs, universities and other businesses who may have viable solutions, including those from other established industries such as aerospace and oil and gas. Support will be provided to assist the development and commercialisation of solutions which meet the criteria, including supporting bids for funding and providing access to dedicated technical expertise and test and demonstration assets. Engagement with industry throughout this process is needed to accelerate the exploitation of high potential solutions which can realise cost reduction for the offshore wind sector.

Support for BLEEP to date has been strong, with industry and the research community backing the programme. ORE Catapult has maintained from the outset that collaboration and knowledge sharing across the industry is required to resolve the issue of LEE. To accelerate the delivery of BLEEP, a joint industry project (JIP) proposal focussing on Project 1 has been developed and presented to wind farm operators. A unified group of key industry stakeholders can drive consensus on topics such as erosion damage classification and O&M optimisation.

Appendices

Author profile

Andy is Innovation Manager at ORE Catapult and is a chartered engineer with masters degrees in both Aeronautical Engineering and Renewable Energy Systems.

At ORE Catapult, Andy is primarily focussed on developing new research and technology innovation projects in the area of offshore wind farm operations and maintenance.

Andy researched and developed the concept for BLEEP, leading discussions with industry and academia to ensure the program addressed the right topics. Recently, the main focus of his work has been establishing a Joint Industry Project (JIP) to support the delivery of some aspects of BLEEP.

ORE Catapult
Inovo
121 George Street
Glasgow, G1 1RD
T +44 (0)333 004 1400

National Renewable Energy Centre
Offshore House, Albert Street, Blyth
Northumberland, NE24 1LZ
T +44 (0)1670 359 555
Email: info@ore.catapult.org.uk Web: www.ore.catapult.org.uk