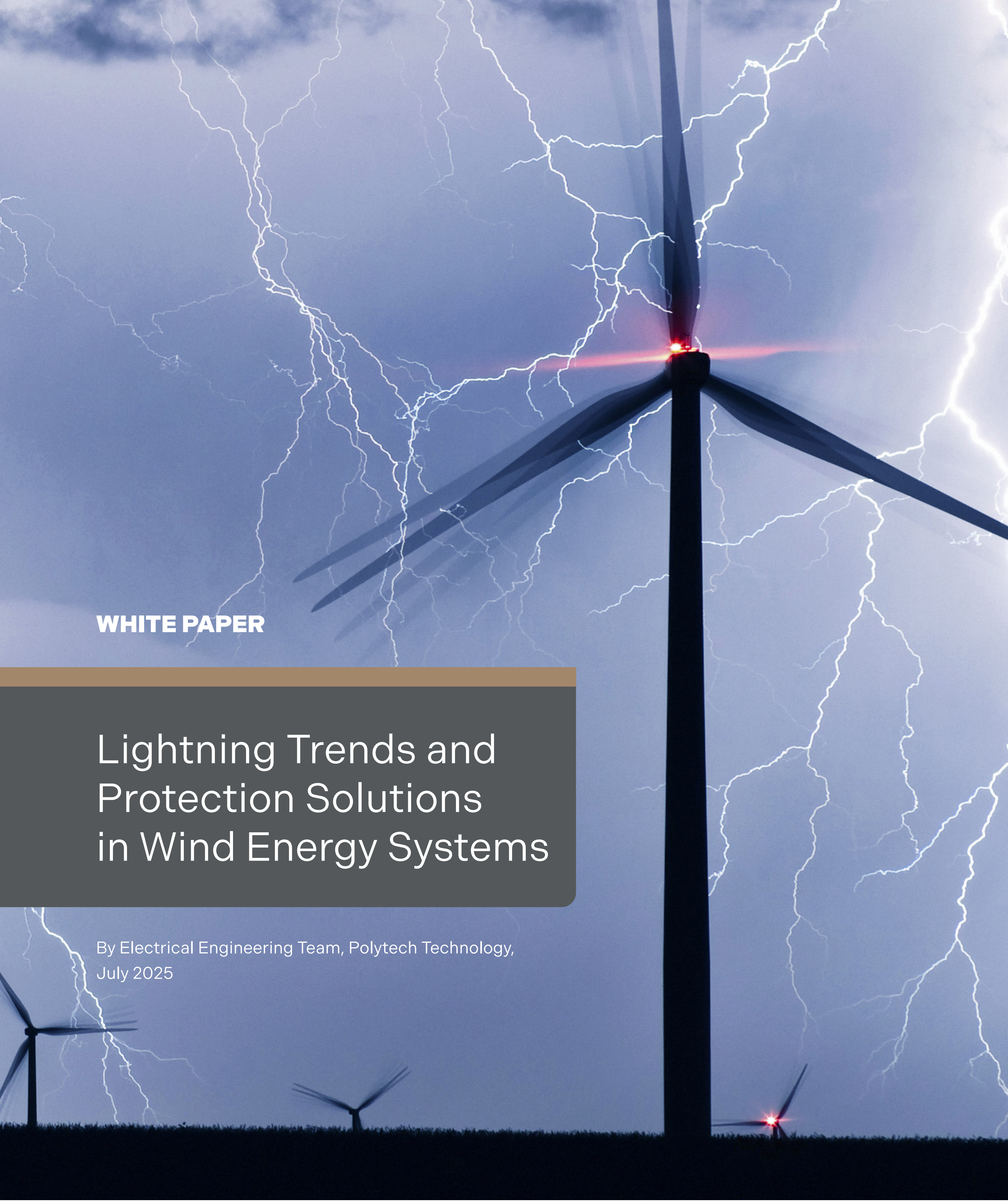

WHITE PAPER

Lightning Trends and Protection Solutions in Wind Energy Systems

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Executive Summary

This report captures the accumulated and consolidated expertise of Polytech's lightning team from the past 20 years and provides an up-to-date overview of lightning protection for wind turbines.

Our insights, gathered through published academic research, leading industry studies, ongoing innovation, and active participation in international standardization efforts, are intended as a practical foundation for OEMs, operators, and asset owners.

The growing size and complexity of today's wind turbines, especially in offshore and remote settings, amplifies the need for tailored, site-specific lightning strategies. By addressing how lightning interacts with turbine structures, clarifying optimal protection system designs, and translating real-world monitoring data into actionable intelligence, this report offers guidance towards greater operational reliability and cost efficiency.

All recommendations are aligned with current industry standards, and our experience underpins the case for comprehensive, blade-level lightning monitoring in accordance with the latest regulatory expectations.

Introduction

Lightning continues to drive significant operational risk for wind turbines if you do not have an efficient lightning protection design and system.

Spoiler alert: At Polytech we develop and produce designs with a documented LPS efficiency exceeding 99.5% compared to the standard criteria of 98% defined by IEC 62305-1:2024 and IEC 61400-24: 2019.

As turbines continue to grow in scale and value, the imperative for effective protection becomes both a business and technical priority. Polytech's lightning specialists have long been at the heart of the industry's progress. Our team's accumulated knowledge, informed by rigorous research, real-time data analysis, and direct involvement in policy and standardization groups, has contributed to meaningful advances in how the industry addresses lightning threats. This report combines findings from publications, field studies, and committee work, with the objective of guiding wind industry stakeholders towards data-driven, cost-effective, and future-proofed lightning risk management.

Lightning Attachment to Wind Turbines

An in-depth understanding of lightning attachment is essential for protecting blades and nacelles against both direct and secondary effects. Decades of inspections and empirical data have confirmed that most lightning events target the outer, most exposed sections of wind turbine blades.

The below risk exposure assessment for a blade design shows where lightning strikes on the blade. To achieve 99% protection, a LIBI (Lightning Interception Blade Implant) is installed in the blade tip plus several sets of side receptors covering the first 9-10 meters of a blade.

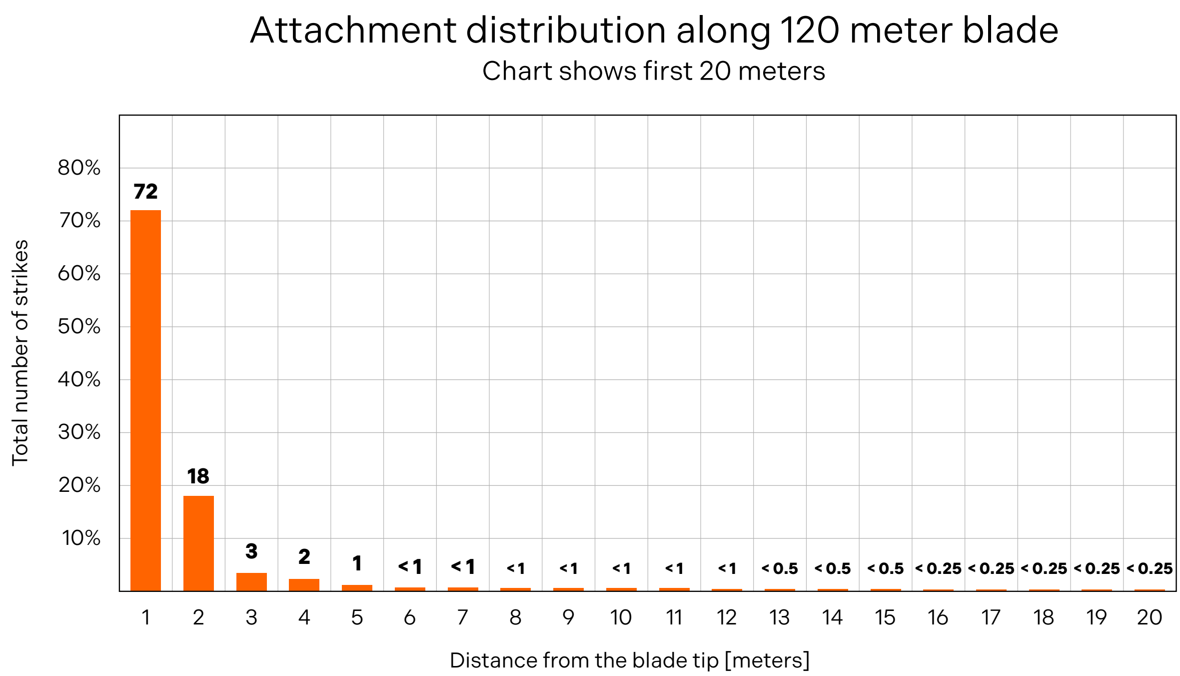


Figure 1: *Lightning distribution across the length of a wind turbine blade. 90% af lightning strikes happen within the first couple of meters. Attachment from 8 to 20 m is possible, but very unlikely.*

Occasional strikes attachments to blade inboard sections are observed, though these remain rare. The correct design of intermediate discrete receptors and expanded metal foil above conductive structural components like spar caps or heating systems minimizes the risk of structural damage to the blade.

The trend toward taller turbines also increases the prominence of upward lightning, especially in winter-prone and complex terrains. Our data, paired with advanced mapping of local wind and meteorological patterns, indicates a clear link between certain site conditions and elevated attachment rates—including first-row turbines on the windward edge of a farm.

Protection System Design Principles

Besides identifying and defining effective lightning attachment points, the second fundamental goal of lightning protection is secure, verified current transfer across all parts of the wind turbine. Polytech's approach is rooted in the latest edition of IEC 61400-24:2019, which recognizes the need for efficient air termination points AND verified lightning protection coordination to mitigate the risk of discharges between conductive components within the blade.

Blade tip, receptor systems, down conductors, bonds, and earthing arrangements should all be tested under realistic high-current and high-voltage conditions, where electromagnetic simulation is used to determine test levels and thereby ensuring real-world efficacy. Current standards now require type-certified, laboratory-tested LPS hardware, with both first and subsequent stroke conditions explicitly considered (see IEC 61400-24:2019).

Nacelle and tower electronics benefit from a zoning concept (Lightning Protection Zones – LPZ), adjusted to varying electromagnetic energy levels and integrating best-practice EMC measures from the earliest design stage. Polytech has observed that numerically aided design, validated against field and test data, leads to more robust and economical LPS deployment.

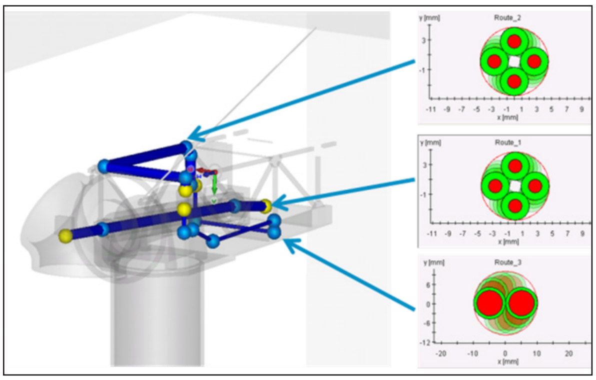


Figure 2: *Induced voltage and currents in wind turbine nacelle installations, determined in time domain along different cable routings.*

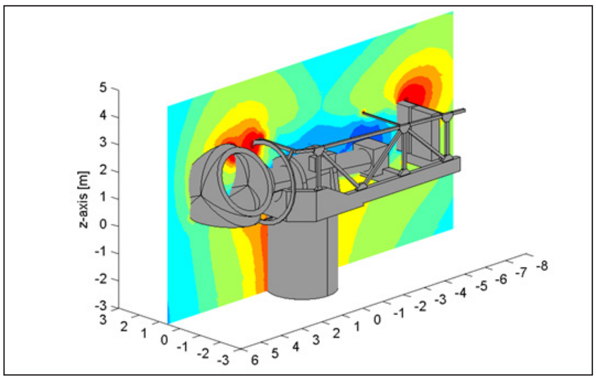


Figure 3: *Magnetic field distribution within a nacelle structure used to assess the shielding requirements of control panels.*

Site-Specific Risk Assessment

Contemporary risk assessment must go beyond generic national isokeraunic maps. Our studies and current state-of-the-art underline how microclimatic factors, prevailing thunderstorm paths, and specific topographical features all play direct roles in the spatial distribution of strike rates across a wind farm. At certain sites, wind direction at the time of storm approach consistently correlates with the pattern of strikes, confirming that turbines on windward frontiers or situated on ridges experience greater exposure. This approach builds on the approach of IEC61400-24:2019 and adds another layer of information for our customers.

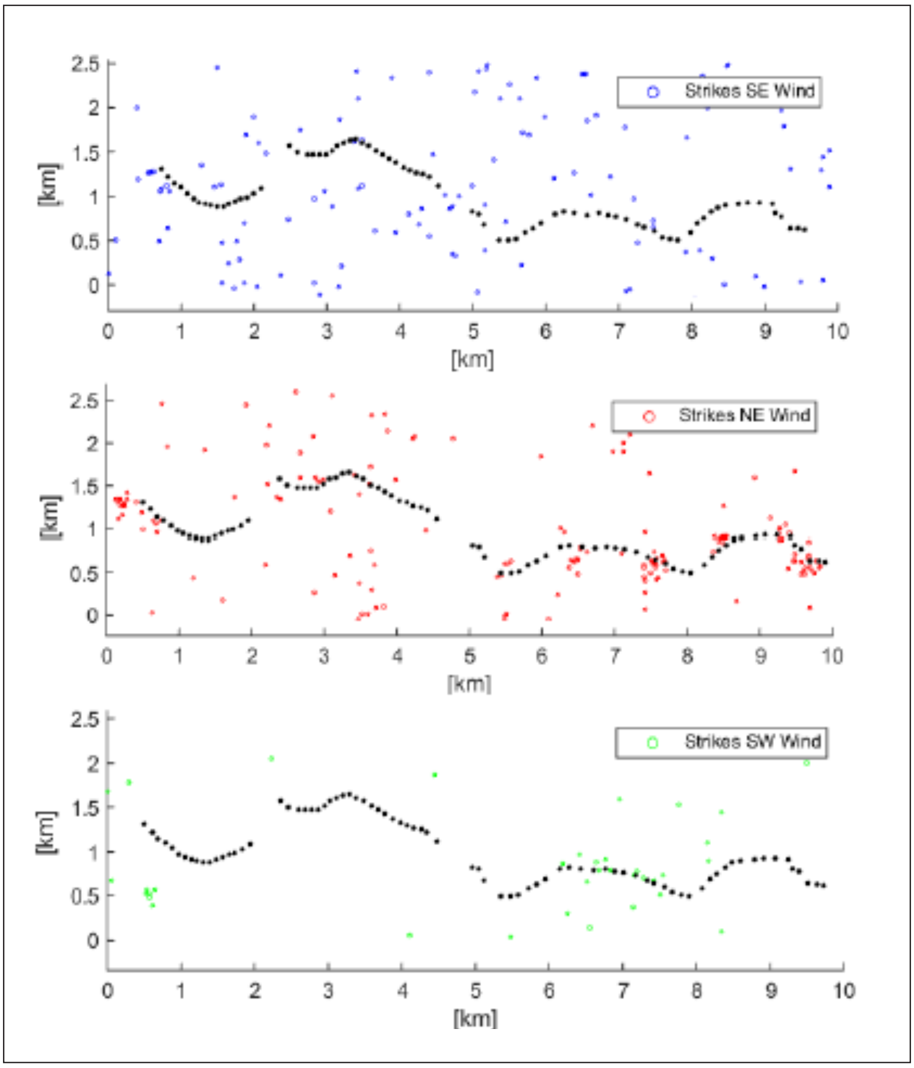
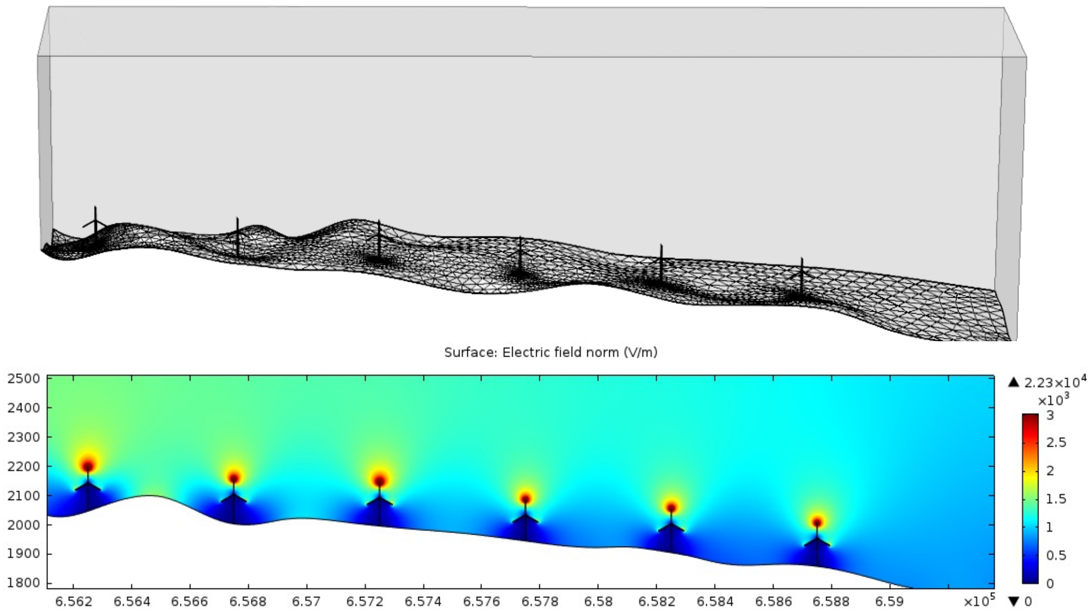


Figure 4. *Lightning detection data in the wind plant in 2010-2014 recorded for predominant wind from SE (top), wind from NE (middle) and wind from SW (bottom).*



Figures 5 & 6: *Polytech 3D site specific risk assessment: Turbines on top of the hill are exposed to higher electric fields compare to turbines in the valley.*

Elevated terrain increases strike frequency, but so do abrupt elevation transitions and proximity to contours that amplify local electric fields. Data-driven, site-specific risk mapping — drawing on actual strike logs and detailed meteorological overlays — enables more accurate engineering and financial risk appraisal.

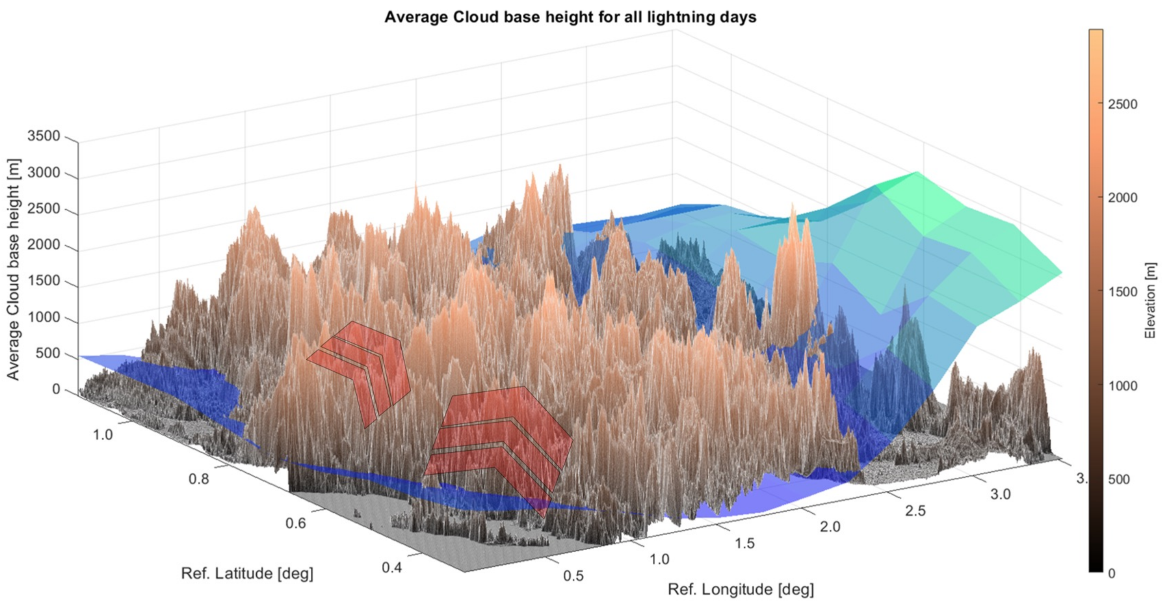


Figure 7: *Average cloud base height extrapolated over 3D terrain for Site 3. Wind direction represented as red arrows.*

Scan QR or click to get a free site assessment!

Condition Monitoring and Predictive Maintenance

Industry best practice now recognizes the value of detailed, near real-time lightning event data—not just for accident response, but as a core input to predictive asset management and OPEX optimization.

Polytech's long-standing emphasis is for blade-specific monitoring: each blade requires independent Class 1 sensors and data capture to ensure a complete understanding of accumulated strikes, severities, and exposure patterns. This granular approach both meets the intent of the latest IEC 61400-24:2019 guidance and unambiguously closes gaps in older, turbine-level monitoring strategies.

Advanced systems such as Polytech's Lightning Key Data System (LKDS) enable near real-time characterization of every relevant event, enabling automated risk segmentation, targeted inspection scheduling, and data-driven maintenance. From a specific onshore site, it is seen how savings in terms of reduced repair costs and reduced down time improve the business case of operating a modern wind farm. Quantitatively, the case demonstrates how the annual OPEX savings due to predictive maintenance amount to 1.8 EUR/MWh or 2000 EUR/MW installed capacity. Adding to this, the annual energy yield gain is another 1.0 EUR/MWh or 1500 EUR/MW, improving the overall business case by 3500 EUR/MW annually.

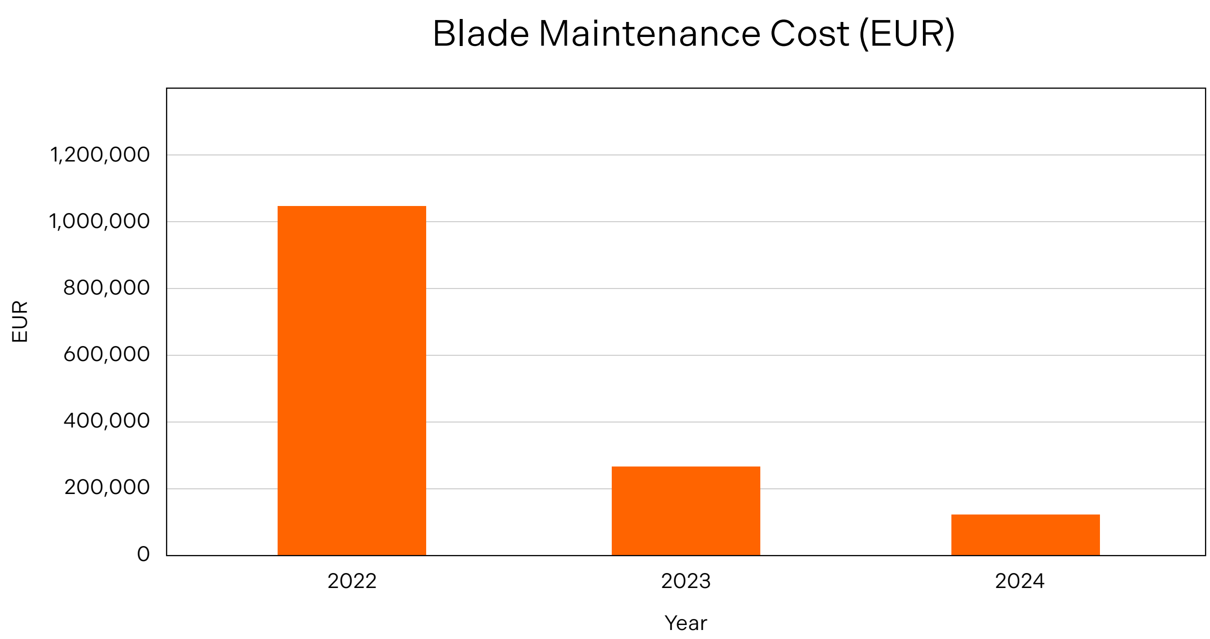


Figure 8: *Evolution of maintenance costs by utilizing lightning measurement systems for driving turbine maintenance.*

Industry Collaboration and Standards Development

Polytech remains committed to progress not only through in-house technical development, but also by fostering open industry dialogue and serving on international standards boards and technology committees. Regular input into IEC TC88 (MT24) and research consortia ensure that emerging field knowledge is translated into robust, future-ready guidelines.

Widespread data-sharing has accelerated improvements in modelling accuracy and testing protocols. As standards continue to evolve to reflect real-world findings, Polytech maintains close alignment between our product designs, monitoring solutions, and regulatory expectations—advocating the case for asset transparency, continuous improvement, and industry-wide learning.

Figure 9: *Picture from Initial Leader Attachment Test performed on a blade.*

Conclusion and Outlook

The future of lightning protection for wind turbines hinges on a deeper application of physics, advanced risk quantification, and disciplined engineering throughout the asset life cycle. A shift is already underway toward a more predictive, data-driven, and fully integrated approach—one that supports larger, more complex turbines in diverse and challenging environments.

Standards such as IEC 61400-24:2019 reflect an industry-wide consensus: every blade and turbine design should begin with a rigorous modeling of the lightning environment, followed by transparent documentation of how these environmental risks inform protection strategies and system verification. Beyond compliance, this shift is driving higher engineering standards, robust verification planning, and broader adoption of quality management frameworks like APQP4Wind.

Polytech's Design Approach

Risk exposure assessment

- For blades: Determine occurrency and severity of strikes attaching to the different blade zones, first step in any blade design process.
- For turbines: Magnitude of strikes attaching to hub, nacelle, weather instruments, etc.
- For wind farms: Which turbines are most exposed, where to begin retrofit campaign. For site owners and operatores.
- Site specific: Consider local lightning environment and expected operational costs. For site owners and operatores.

Air terminations

- Pre-tested and certified Lightning Interception Blade Implant (LIBI) for the tip.
- Side receptors to ensure reliable interception efficiency for the outer blade section.
- Surface Protection Layer (SPL) to protect for inboard attachment.
- Customized design upon request.

Down conductor

- Insulated down conductor for all fiberglass blades (GFRP).
- CFRP blades: Equipotentialise with main down conductor and control current entry into CFRP structure by SPL.
- Coordinate current and voltage distribution with additional conductive elements.

Design for manufacturing

- Optimize design for smooth manufacturing.
- Design blade LPS to ensure minimum impact on blade mould cycle time.

Prototyping

- 3D print and dryfit of parts in actual blade production.
- Full functional prototypes, to be installed in actual blade production for tailoring working instructions.
- Full functional prototypes for manufacturing samples for electrical and mechanical verification tests.

Verification plan

- High voltage and high current verification tests according to IEC 61400-24 Ed2.
- Mechanical tests to determine strength towards tensile load, shear, peel, etc.
- Weathering/Environmental testing to determine design susceptibility to water, sunlight, vibrations, chemicals, etc.

Polytech commitment

Effective lightning protection will increasingly be built on precise risk exposure assessment, using site-specific or portfolio-wide data to map the probability and severity of direct strikes. These analyses, supported by numerical modeling and field observations, underpin the correct placement of air terminations and down conductors, as well as insulation and bonding strategies adapted for increasingly advanced blade structures, including carbon composites and integrated sensor systems.

A core requirement emerging from both best practice and regulatory evolution is the need for accurate, blade-level lightning monitoring. Monitoring each blade individually enables a true cumulative profile of strike count and severity, facilitating sharper predictive maintenance, reducing risk of hidden damage, and ensuring compliance with evolving standards.

Future-focused solutions will require quality lightning data, combined with rigorous laboratory validation and scalable, design-for-manufacturing processes—all supported by an industry that is increasingly collaborative. Prototyping, accelerated lifetime testing, and clear communication between design, production, and operations teams will be critical to ensure that protection measures remain robust as turbines grow longer and sites become more exposed.

As the industry continues along this path, the alignment of engineering rigor, advanced monitoring, and comprehensive quality assurance will elevate both reliability and performance for wind power assets worldwide, positioning the sector for resilient, long-term growth.

Polytech References and Presentations

Lightning Measurement Systems (LMS) for Lowering Wind Farm Operational Costs / International Symposium on Lightning and Wind Turbines (ISLW2025) / 2025

Wind Turbine Blade LPS Design Process Revisited—Leveraging on the Latest Knowledge from Actual Lightning Measurements in Wind Turbines / Machines / 2023

Investigation of Weather Conditions Leading to Different Types of Lightning Strikes Measured in Wind Turbine Blades / International Conference on Lightning and Static Electricity, Madrid / 2022

An Insight on the IEC 61400-24 Ed2: Lightning Protection of Wind Turbines / International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil / 2019

Design and Verification Methods for Wind Turbines: Ensuring Safe Operation During Lightning Exposure / 4th International Symposium on Winter Lightning (ISWL), Søren F. Madsen, Polytech / 2017

Effect of Local Topography on Lightning Exposure of Wind Turbines / International Conference on Lightning and Static Electricity, Toulouse, France / 2015

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