



WHOLISTIC AND INTEGRATED DIGITAL TOOLS FOR EXTENDED LIFETIME AND PROFITABILITY OF OFFSHORE WIND FARMS

Key Results

FINAL
NEWSLETTER

September 2026



WHOLISTIC AND INTEGRATED DIGITAL TOOLS FOR EXTENDED LIFETIME AND PROFITABILITY OF OFFSHORE WIND FARMS

5
countries

5.8M€
budget

12
partners

36
months

WILLOW ID

Acronym / WILLOW

Program / The European Union's Research and Innovation Program HORIZON-CL5-2022-D3-03-04 Integrated wind farm control

Duration / October 2023 – September 2026

Main objective / WILLOW project aims to achieve an integrated system that provides an open-source, data-driven health aware curtailment strategy to the wind farm operators. This integrated wind farm control system in offshore environments will look for a trade-off between the power production and the lifetime consumption.

Partner countries / Belgium, Germany, The Netherlands, Norway and Spain.

HIGHLIGHTS

12th June 2026

Final event & final AB meeting held in the *WindEurope Technology Workshop* in Rotterdam



EDITORIAL

Dear WILLOWers,

Welcome to the final edition of the WILLOW Newsletter. As the project comes to an end, we are pleased to share the main results achieved throughout this journey and reflect on the work carried out by the consortium over the past three years.

Throughout the project, our newsletters have highlighted key milestones. In **Newsletter 1**, we introduced the WILLOW project, its objectives and early activities. **Newsletter 2** and **Newsletter 3** shared insights from discussions with the Advisory Board, whose feedback helped shape the project's development.

In this issue, we look back at WILLOW's main achievements and outcomes. We hope that the knowledge generated through the project will continue to support future developments and collaborations.

We hope you enjoy reading this newsletter and, as always, we welcome any feedback or reflections you would like to share with us. Stay connected through our website and LinkedIn page (@WILLOW Project EU), where we will continue sharing the latest project news and results.

The consortium



Funded by
the European Union

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WILLOW Results at a Glance

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IoT Cybersecurity Strategy for Wind Farm Monitoring Systems





Introduction: Securing IoT-based Wind Farm Monitoring

The integration of IoT monitoring systems in wind farms significantly enhances operational efficiency and predictive maintenance capabilities. However, increased connectivity, integration with Industrial Control Systems (ICS), and reliance on distributed architectures introduce new cybersecurity risks. Using the WILLOW's cybersecurity strategy as reference, this document presents key insights adapted specifically for IoT monitoring infrastructures, focusing on secure architectures, regulatory alignment, and advanced protection mechanisms.

I. Cybersecurity risks in wind farm IoT environments

The expansion of Distributed Renewable Energy Systems (DERS) increases the attack surface derived from an increment of interconnected sensors, SCADA systems, and cloud platforms managing data and information derived from relevant and sensitive processes. Relevant attack vectors target supply chain compromises, operational asset control or malfunctioning, IoT data integrity manipulation, and propagation through malware. For these reasons, the incorporation of frontier cybersecurity measures is extremely relevant for DERS and other critical systems.

II. Regulatory alignment

A robust cybersecurity strategy must align with evolving regulatory frameworks such as NIS2, the Cyber Resilience Act (CRA), and national directives. On the one hand, standards such as ISO/IEC 62443, NIST SP 800-82, and NIST SP 800-213 provide structured approaches for securing ICS and IoT environments. These frameworks emphasize risk management, secure product design, supply chain security, and continuous monitoring. Therefore, from a technical point of view, the WILLOW's cybersecurity strategy implements the technological baseline for covering NIS2 and CRA requirements, including:

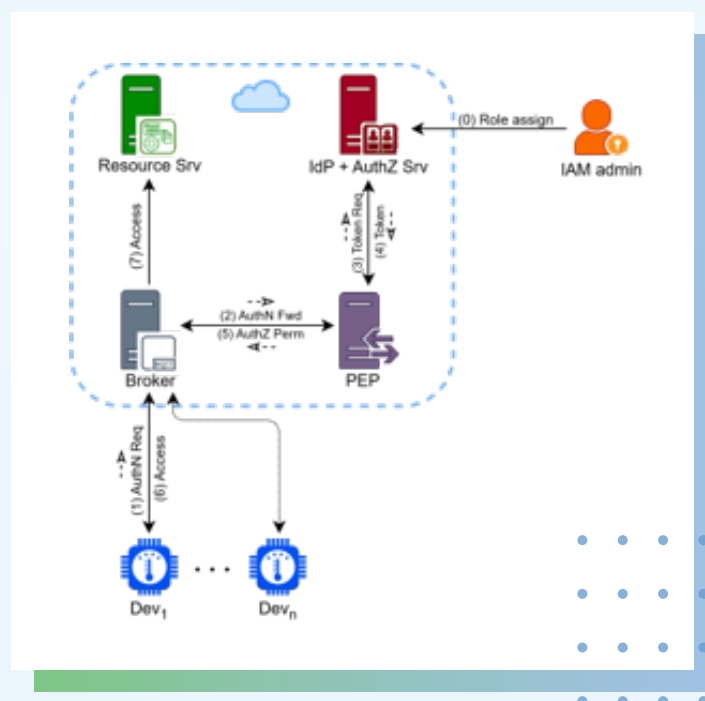
- Native authentication and access control mechanisms for IoT nodes, equipment, and human actors for the production and consumption of monitoring data.
- Security by design, by integrating encrypted and authenticated component-to-component communication as default.
- Security in the supply chain by leveraging secure continuous delivery and integration of IoT node firmware.
- High visibility and incident response derived from anomaly detection techniques.
- Network security by enforcing the isolation of administration, control, and monitoring planes via segmentation techniques.



III. IoT-centric cybersecurity strategy

One of the most prominent outcomes of the project in terms of cybersecurity is the development of an Identity and Access Management (IAM) solution that ensures secure authentication and authorization of devices using protocols such as OAuth2.0 and OpenID Connect. Secure communication relies on MQTT over TLS combined with controlled broker architectures and policy enforcement mechanisms.

- A Role-based Access Control (RBAC) model for industrial application scenarios has been developed for WILLOW.
- The core idea of this model is to establish an access control structure that is aligned with the organization of assets and responsibilities in industrial applications, maintaining a hierarchical relationship between the system entities.
- The hierarchical relationship between participants, equipment, and devices, allows for a straightforward definition of access policies for access to MQTT topics.



Additionally, the WILLOW's cybersecurity approach incorporates advanced security and privacy measures such as:

Data Protection and Privacy Homomorphic Encryption

- Enables privacy-preserving data processing by allowing computations on encrypted data. This approach mitigates risks associated with cloud environments while maintaining data confidentiality and enabling analytics.

Network Security and Segmentation

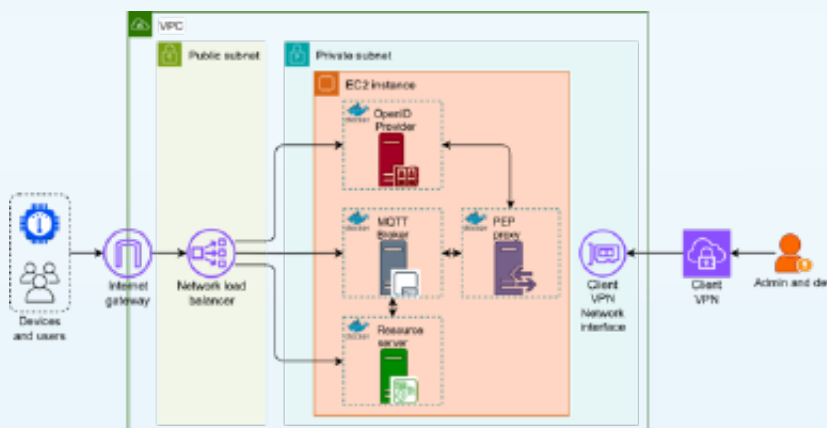
- The strategy defines segmentation at both cloud and container levels and provides isolation between system components. VPNs and secure channels restrict access to critical infrastructure, minimizing opportunities for lateral movement for attackers.

Secure Software Development Lifecycle Security

- This is integrated across the entire development lifecycle using CI/CD pipelines, automated testing, and vulnerability scanning. Hardware-level protections in IoT devices include secure boot, firmware validation, memory protection, and tamper detection.

Detection of Advanced Threats

- Intrusion Detection Systems (IDS) based on anomaly detection and machine learning to enable identification of zero-day threats. Monitoring MQTT traffic patterns allows proactive detection of abnormal behavior and automated response actions.



Conclusion

The integration of cybersecurity measures into IoT monitoring systems is essential for ensuring resilience in wind farm operations. A multilayered approach combining alignment with regulatory compliance, secure architectures for access control, confidentiality via encryption, and intelligent detection mechanisms provides a robust defense against evolving threats.



Innovations in Offshore Corrosion, Coating and Cathodic Protection Monitoring





Innovations in Offshore Corrosion, Coating and Cathodic Protection Monitoring

I. Monitoring Localized Pitting in Low Carbon Steel

Pulse-Echo Ultrasound (US) Monitoring: Key Outcomes



Optimized Transducer Selection

For effective monitoring, transducer frequency and diameter are critical.

Simulation Insights

Using the **k-Wave MATLAB toolbox**, researchers successfully replicated real-world pulse reflections. Simulations suggest that most real-world pits behave like conical geometries, causing scattered reflections that distort the ultrasound wavefront.

Advanced Signal Distortions

Unlike simple flat reflections, curved pit walls scatter energy and convert some longitudinal waves into shear waves. Diffraction often causes overlapping echoes, making the second echo the most prominent for detecting pit effects, though this requires a careful trade-off with signal attenuation.

Quantification Metrics

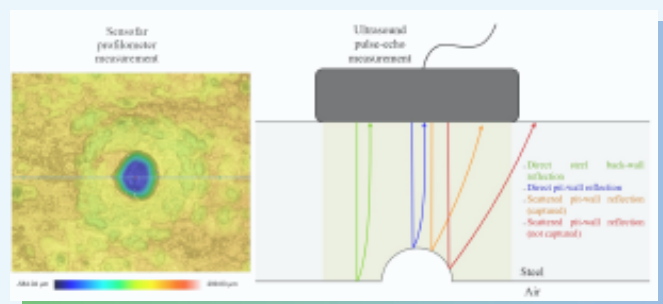
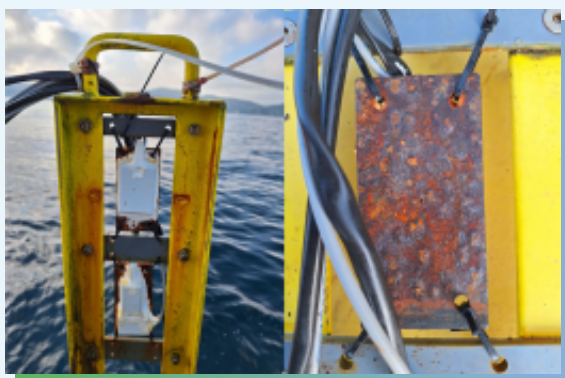
Researchers use a combination of time and frequency domain features to quantify damage, including **Signal-to-Noise Ratio (SNR)** (larger pits result in lower SNR), **temporal width** (deeper pits appear wider), and peak distances in echo envelopes or impulse responses.

Pitting Methodology

A specific framework is designed to detect localized degradation in low-carbon steel, a critical requirement for maintaining structural integrity in marine environments where chloride-induced pitting is common. The methodology forms a core part of the project's data-driven approach to identifying structural flaws that are too small for traditional wide-area inspection tools.

Field Validation (HARSHLAB)

Autonomous sensor nodes deployed on the HARSHLAB marine platform successfully tracked a cylindrical pit in a 5 mm steel sample. Despite increased surface roughness from uniform corrosion, the system recorded an approximate **100 μm increase in pit depth over four months**.

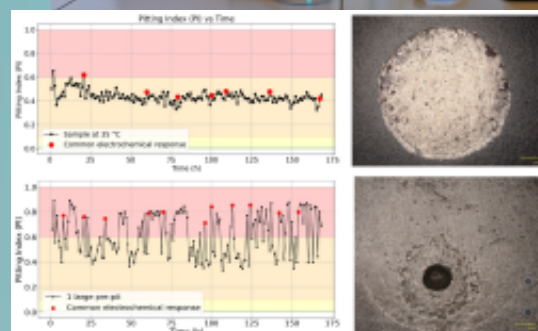


Electrochemical Techniques Monitoring Validated: Key Outcomes

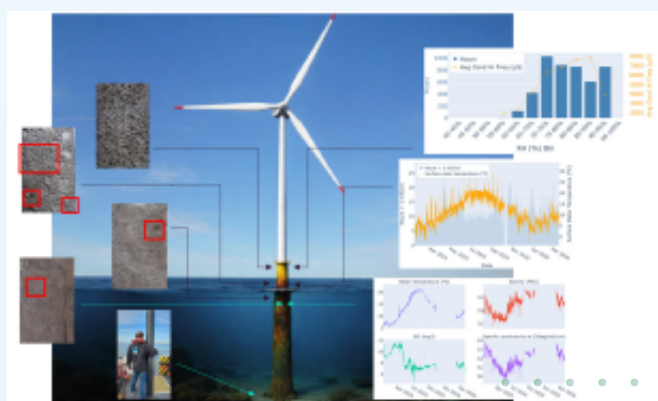
Electrochemical techniques have been successfully validated in the laboratory on both low and high corrosion activity samples. A **key outcome** is the development of an **algorithm for automated pitting activity detection, enabling the screening of aggressive environments in offshore applications**. This represents an important step forward, as no proven monitoring method for pitting corrosion of carbon steels in marine environments previously existed.

How?

- The influence of metallurgical factors and surface condition on pitting behaviour was investigated using pre-pitted samples with varying pit sizes and configurations, including samples with one or three mechanically induced defects.
- A key finding emerged: surface defects act as concentration points for pit growth, triggering the formation of multiple pits in their vicinity and significantly increasing overall pitting activity, and therefore its detectability.
- This insight has important implications for the design of monitoring strategies on aged or damaged offshore structures.



Pitting monitoring in offshore test site



To better understand the development of pitting and corrosion in different offshore monopile zones, monitoring activities have been carried out at the offshore test site:

- Corrosion mapping across the different offshore monopile zones has been carried out using corrosion coupons, revealing zone-specific corrosion morphologies.
- During the same time, water and atmospheric parameters were collected and their correlation will be further investigated until the end of the project.
- Understanding what happens in each zone will enable targeted protection strategies and provide valuable input for informed lifetime assessment of offshore structures.



II. Coating Degradation: Beyond Visible Damage

Ultrasound Insights



A breakthrough outcome of the project is a hybrid framework that combines an **ultrasound deconvolution model with a 1D Convolutional Neural Network (1D-CNN)** to monitor protective coatings.

The Problem of Overlapping Echoes

Traditional ultrasound often fails when coatings are thin because the reflections from the steel-coating and coating-air interfaces overlap. The deconvolution model cancels out the acquisition system's impulse response by comparing two consecutive backwall echoes, isolating the reflectivity sequence of the coating layer itself.

Massive Data Training

The 1D-CNN architecture was trained on a dataset of **10,000 synthetic signals** generated using the **k-Wave MATLAB toolbox**, which simulates ultrasound propagation through three-layer physical models (coating-steel-coating).

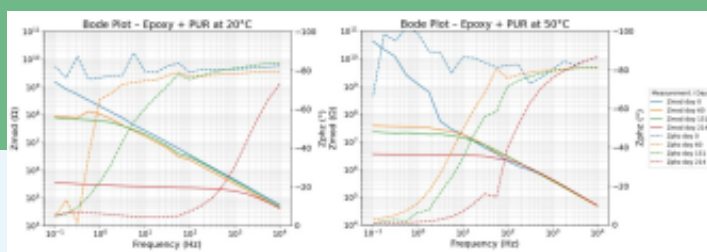
Performance Benchmarks

- **Broad Detection Range:** The model successfully estimates front coating thicknesses ranging from 60 μm to 740 μm applied over 5 mm steel substrates.
- **Exceptional Accuracy:** On synthetic data, the model achieves a thickness prediction accuracy of approximately $\pm 8 \mu\text{m}$.
- **Sub-Wavelength Resolution:** The system can detect coatings as thin as $\lambda/5$ (roughly 60 μm for an 8 MHz transducer), surpassing standard industrial resolution limits.

Electrochemical Insights



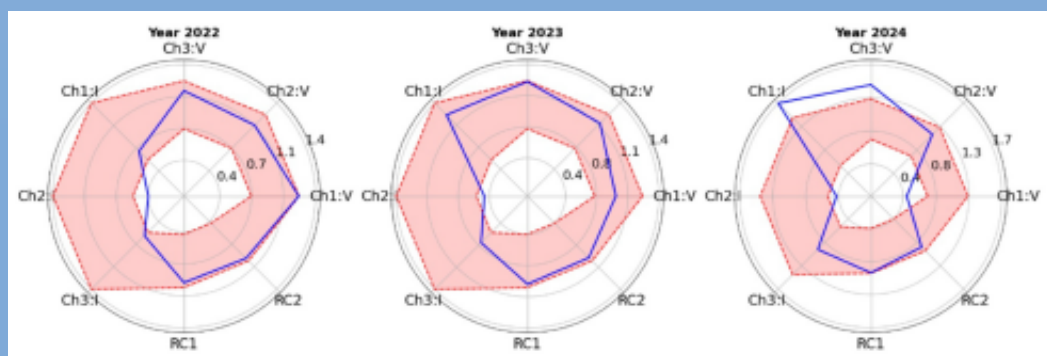
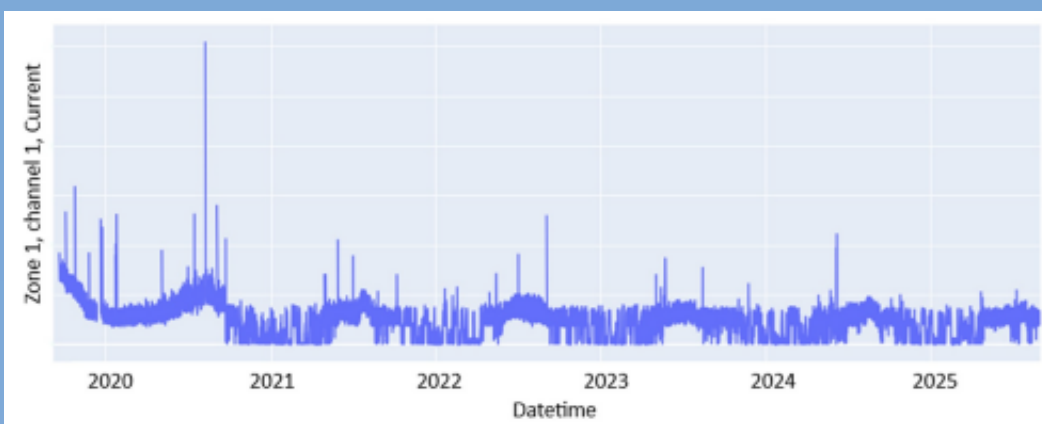
We have conducted accelerated laboratory testing to compare coating systems under controlled conditions, correlating data from both commercial and laboratory sensors. This data forms the foundation for prognostic models aimed at predicting coating lifetime, directly supporting informed maintenance planning for offshore asset owners.





III. Monitoring the Cathodic Protection of Offshore Structures

Finally, a new tool for Impressed Current Cathodic Protection (ICCP) visual monitoring and fault analysis has been developed. By converting time series data into radar plots, the tool allows monthly and yearly averages to be compared against predefined limits, flagging disturbances and enabling trend and drift analysis per turbine. Since ICCP data is already being recorded on most assets, no additional investment is required for implementation.





IV. The Coating & Corrosion Monitoring System (CCMS) and the CQM Method

Traditional monitoring methods are often invasive, costly, and provide visual feedback only after substantial material degradation or structural damage has already occurred. The Corrosion Condition Monitoring System (CCMS) solves this problem through continuous, multi-frequency electrochemical interrogation.



Dual-Sensing Measurement Principle

- The CCMS employs permanent embedded sensors utilizing Linear Polarization Resistance (LPR) for precise, direct measurement of real-time steel corrosion rates, and Electrochemical Impedance Spectroscopy (EIS) in accordance with the ISO 16773-2 standard for precise coating degradation monitoring.

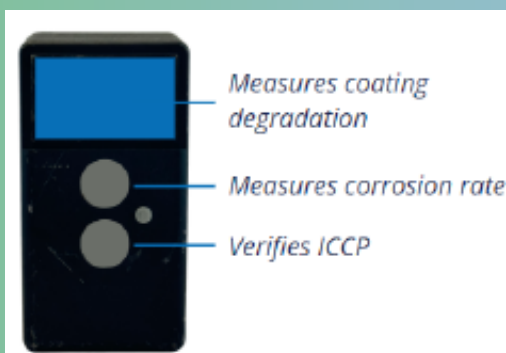
The CQM Phenomenological Metrics

To make complex EIS raw data actionable for inspectors and asset owners, the CQM method was developed. This approach translates frequency response characteristics into two direct indices:

- → **Barrier Index (BI):** Extracted from low-frequency data, the BI measures the coating's overall resistance to active ion diffusion and underlying steel passivation. A BI of 100% represents an ideal vacuum-like protection barrier, while values dropping below 50% ($106 \Omega \cdot \text{cm}^2$) signify the onset of possible under-film corrosion.
- **Permeability Index (PI):** Derived from high-frequency capacitive behaviour (the constant phase element α or n -value), the PI quantifies the degree of water absorption and the creation of microscopic conductive pathways reaching the steel substrate.

Data Communication Architecture

- A robust, cloud-connected data workflow was standardized. Embedded probes integrate local printed circuit boards (PCBs) that transmit raw data via the RS485 protocol over industrial cables up to 100 meters long to a central receiver and Industrial PC (IPC) housed in a secure cabinet. The IPC automatically uploads the records to the AWS cloud using Wi-Fi or cellular connections, where predictive algorithms process the data and feedback actionable life-prognosis plots to a real-time web dashboard.





V. Combining US with Thermography

While ultrasound provides localized, high-precision thickness data, the WILLOW project also explored **Infrared Thermography** for wider area scans.



Complementary Detection Capabilities

Results revealed that thermography can detect early-stage corrosion—evidenced by changes in thermal patterns—even before ultrasound detects measurable thickness loss. This suggests that thermal properties degrade before structural thinning occurs.

Quantitative Correlation

Using the **Mean Normalized Cauchy-Schwarz Correlation** (DCS), researchers found that healthier samples maintain higher thermal correlation values, while corroded spots show more erratic, "chaotic" thermal behavior and slower temperature stabilization.

Active Stimulus Potential

Experiments showed that applying a heat stimulus could highlight "cold spots" indicative of underlying corrosion, even when the damage is on the non-visible side of the steel.

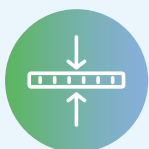
VI. Multi-Sensor Corrosion Monitoring: Electrochemical–Ultrasound Integration

A significant achievement of the project has been the integration of **electrochemical (EC) and ultrasound (US)** sensing technologies, enabling the simultaneous assessment of corrosion activity and structural degradation.



Electrochemical Monitoring (LPR)

- Indirect assessment of corrosion activity.
- Corrosion-rate estimation through **Linear Polarization Resistance (LPR)** measurements.
- Determination of **corrosion current density** and material loss rates.



Ultrasound Monitoring (ToF)

- Direct assessment of structural condition.
- Wall-thickness measurements based on **Time-of-Flight (ToF)**.
- Detection of thickness loss and material degradation.



Sensor Fusion



- Physical integration of the US sensor behind the EC probe.
- Data collected from the same inspection location.
- Improved correlation between corrosion activity and actual material loss.
- Enhanced detection of:
 - Localized pit growth
 - Surface roughness changes
 - Fouling and biocide layer accumulation



ICCP-Compatible Operation

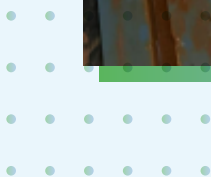


A synchronized monitoring approach allows reliable measurements on assets protected by **Impressed Current Cathodic Protection (ICCP)** systems. During the short duration of the LPR sweep, the ICCP current is temporarily interrupted to avoid polarization interference while maintaining asset protection.

Next Steps



Ongoing developments aim to increase the overlap between the **US acoustic beam** and the **EC active area**, further improving the correlation between direct thickness measurements and electrochemical corrosion-rate estimations.





VII. Advanced Laboratory Validation and Temperature-Dependent Degradation Modelling

To ensure the high fidelity of the predictive algorithms and validate sensor robustness, project partners carried out comprehensive experimental campaigns.



Accelerated Coated Coupon Testing

Laboratory experiments were carried out on submerged coated sensors immersed in 3.5 wt% NaCl solutions across three distinct temperature profiles: 20°C, 35°C, and 50°C. These tests allowed to simulate decades of marine exposure within a compressed timeline, tracking the decline of the BI and PI metrics to build reliable probability-based gamma distribution degradation models.

Pitting Corrosion Benchmarking

Specialized low-carbon steel panels were produced featuring drilled and eddy-modified artificial pits of varying aspect ratios (width/depth factors of 1, 1/2, and 1/4). Exploratory evaluation under varying chemistries (such as brackish water and iron chloride FeCl_2 solutions) established the electrochemical signature of stable pitting vs. uniform baseline corrosion. Additionally, an innovative experimental sample was developed where the bottom of the pit was entirely electrically insulated from the surrounding plate surface, allowing isolated tracking of deep pit growth dynamics without signal bleeding.

VIII. Field Implementations: CCMS technologies and Mudline Deployments at the Blue Accelerator

Sensor Deployment and Corrosion Monitoring



Following a survey of sensors suitable for operation in aggressive marine environments, solutions capable of delivering reliable long-term performance in splash, tidal, submerged and sediment exposure conditions were identified.

SPLASH ZONE



Corrosion sensors were deployed in the atmospheric splash zone, one of the most severe corrosive environments for offshore structures due to continuous oxygenation, salt deposition and mechanical wave impact. These sensors provide real-time environmental corrosivity data and support the assessment of corrosion risks under highly dynamic exposure conditions.





TIDAL ZONE

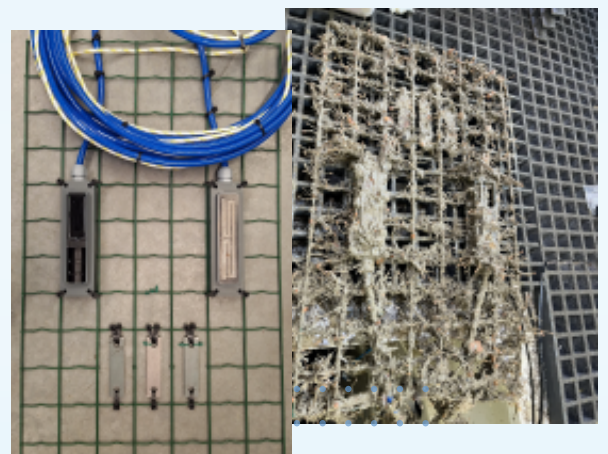
Additional monitoring probes were installed in the tidal zone, where cyclic wetting and drying create complex corrosion mechanisms. Continuous monitoring in this area will help improve understanding of material degradation under fluctuating environmental conditions.



SUBMERGED ZONE



Sub-external



Sub-internal

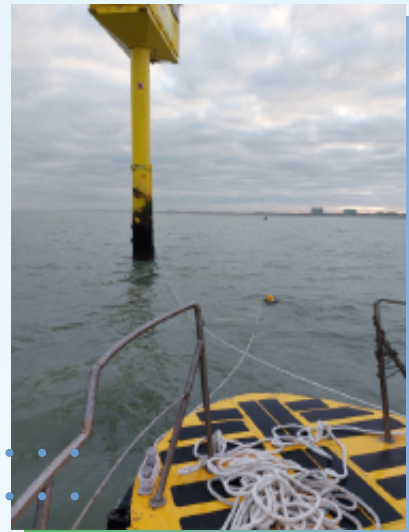
Monitoring systems were deployed both inside and outside the submerged sections of the structure. The external submerged zone operates in conjunction with active Cathodic Protection (CP) infrastructure, enabling assessment of environmental corrosivity alongside corrosion mitigation measures. Antifouling solutions implemented in the submerged zone proved effective in limiting biofouling settlement, locally, on the sensors surface, provided that periodic maintenance is adequately planned and executed.



Mudline monitoring campaign

Recognising that the seabed mudline is subject to distinct anaerobic, biological and mechanical degradation mechanisms, a dedicated monitoring campaign was initiated at the Blue Accelerator test site. In October 2025, a joint offshore operation involving Antwerp Underwater Solutions and Brabo Maritime Services resulted in the successful deployment of specialised corrosion monitoring probes at the seabed level. One probe was positioned directly at the mudline surface, while a second was installed 40–50 cm within the sediment.

This long-term field exposure experiment aims to assess corrosion severity in organically active sediment environments, where very limited data currently exists. Autonomous data logging and scheduled retrieval campaigns are expected to **provide one of the first localised datasets on corrosion behaviour and steel loss rates in this poorly understood benthic zone.**





Assesing Underwater Acoustics for More Sustainable Offshore Wind Energy





Assessing Underwater Acoustics for More Sustainable Offshore Wind Energy

Phase I: Deployment in the North Sea (October 2025)

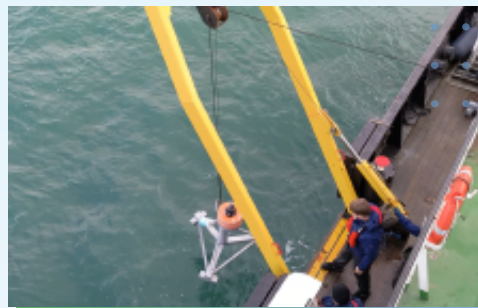
An autonomous acoustic monitoring system was successfully deployed near a turbine at the **Norther offshore wind farm** in collaboration with the **Flanders Marine Institute (VLIZ)**.

Key objectives

- Deploy a long-term hydrophone system on the seabed.
- Continuously record ambient underwater noise levels.
- Monitor underwater radiated noise (URN) from wind turbine operations.
- Capture acoustic data across different turbine operating conditions.



Pre-deployment



Deployment

Phase II: System Recovery and Data Validation (April 2026)

Following several months of offshore monitoring, all acoustic instrumentation and data logging systems were successfully recovered.

Key achievements

- Safe retrieval using a remote acoustic release mechanism.
- No diving operations required.
- Excellent equipment condition after long-term underwater deployment.
- Full continuity and integrity of recorded datasets confirmed.



Retrieval



Post-retrieval



Ongoing Data Analysis

The collected acoustic dataset is currently being processed and analysed to assess the environmental impact of **underwater radiated noise (URN)** at the Norther wind farm.

Expected Outcomes

- Improved understanding of offshore wind turbine acoustic signatures.
- Assessment of potential environmental impacts on the marine environment.
- Generation of evidence-based knowledge for sustainable offshore renewable energy development.

Looking Ahead

The final results will be integrated into the **WILLOW platform** and shared with project partners, the Advisory Board and the wider scientific community, contributing to future research and informed decision-making in the offshore renewable energy sector.



Data-Driven Insights for Lifetime Extension of Offshore Wind Farms





Data-Driven Insights for Lifetime Extension of Offshore Wind Farms

Turning data into actionable asset intelligence

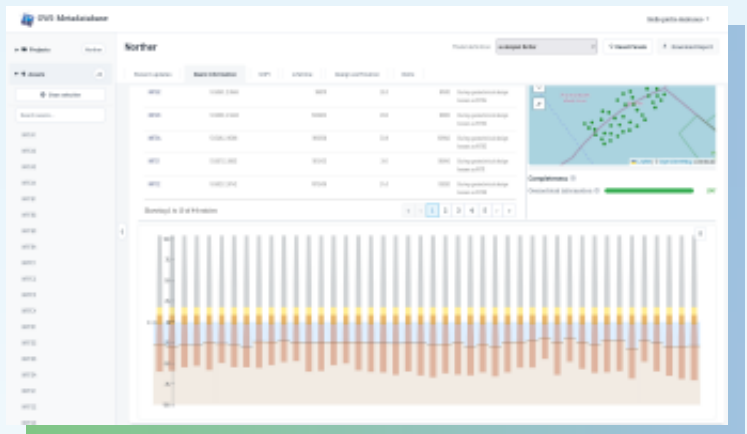
Over the course of the WILLOW project, significant effort has been dedicated to transforming large volumes of monitoring data into meaningful insights for offshore wind farm operators. Building on data acquisition and sensing technologies, the project has developed the analytical backbone needed to scale this information from individual turbines to full wind farm level.

By combining data integration, machine learning techniques and engineering expertise, this approach enables **continuous, data-driven assessment of structural health, fatigue loading and remaining lifetime across entire wind farms**. This was achieved by combining advanced data integration, machine learning, and engineering expertise into a cohesive and scalable framework.

A unified platform for wind farm data

A key achievement has been the development of a **robust data platform** capable of handling the diverse and complex data streams typical of offshore wind farms. This includes:

- High-frequency sensor data (e.g. accelerations, SHM measurements)
- SCADA operational data
- Design and inspection information
- Derived outputs from predictive models



Screenshot: Data-platform for Design and inspection information



Screenshot: Data-platform for High-frequency sensor data (e.g. accelerations, SHM measurements) and SCADA data

By centralising these data sources into a single architecture and enabling access through modern APIs, the platform ensures that data can be **consistently accessed, analysed and reused across applications and stakeholders**.

Beyond data storage, the platform also allows for **direct integration of predictive models**, enabling users to request not only raw data but also processed insights such as fatigue estimates or anomaly indicators.

This development lays the foundation for **digital twin implementations at wind farm scale**, where data continuously feeds into models and supports real-time decision-making.



Scaling from turbine to wind farm

One of the major challenges in offshore wind is the limited availability of direct measurements across all turbines. Installing high-end instrumentation everywhere is neither practical nor economically viable. To address this challenge through the further development of the **“fleet-leader” concept**, where:

- A limited number of turbines are instrumented in detail
- Data-driven models are used to extrapolate results to the entire fleet

Using this approach, we developed advanced **machine learning models** capable of predicting **fatigue loads across all turbines** based on a combination of:

- SCADA data
- Environmental conditions
- Low-cost sensor data

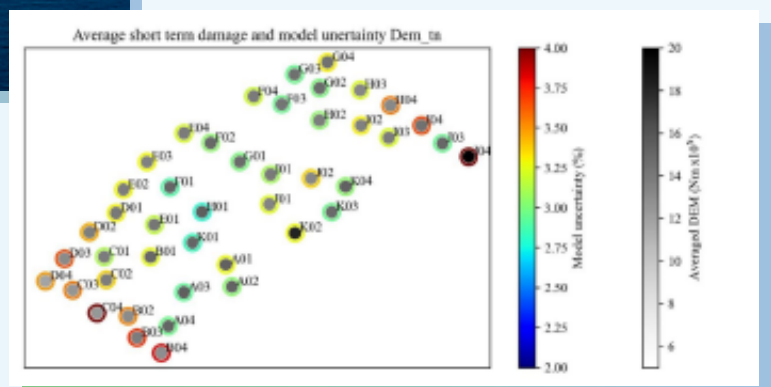
Different modelling approaches were explored, including:

- Artificial Neural Networks
- Bayesian Neural Networks (introducing uncertainty awareness)
- Acceleration-based models (independent of SCADA data)
- Graph Neural Networks capturing spatial interactions (e.g. wake effects)

These models demonstrated high accuracy and robustness, enabling **reliable estimation of fatigue loads across an entire wind farm**, even in the presence of incomplete data:



Fleetleader concept + typical result using Bayesian Neural Networks
(introducing uncertainty awareness)





We also developed a methodology for **fleet-wide corrosion monitoring**, enabling operators to assess degradation across the entire wind farm rather than at individual turbines only.

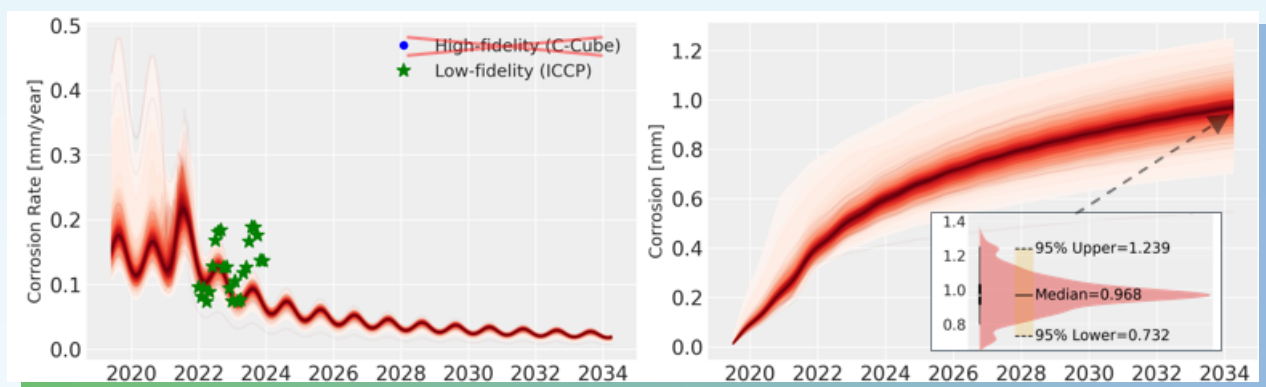
This approach combines:

- ICCP (SCADA) data available for all turbines
- Detailed corrosion sensor data from selected “fleet leaders”
- Environmental inputs and external measurements

Using a **multi-fidelity Bayesian data fusion framework**, high-quality measurements from fleet leaders are used to calibrate models that are then applied across the full fleet. For turbines without direct sensors, corrosion behaviour is inferred using **proxy indicators derived from ICCP data**.

This allows continuous estimation of corrosion progression at wind farm level, including **quantification of uncertainty**, which is essential for reliable lifetime assessment.

Overall, the methodology enables corrosion monitoring to evolve from a local measurement activity into a **predictive, fleet-wide capability**, supporting risk-based inspection strategies and integration into CL/RUL assessments.



Towards reliable lifetime assessment

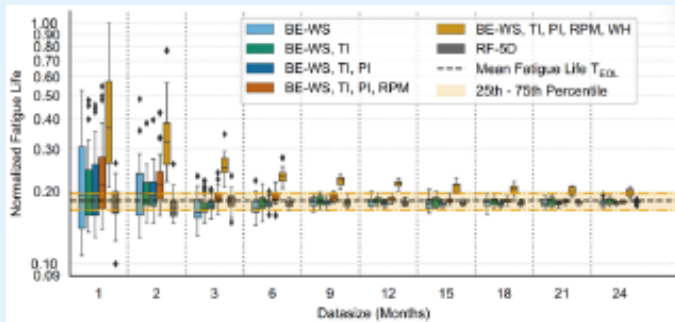
A central ambition of WILLOW is to enable better-informed decisions regarding lifetime extension of offshore wind assets. In WILLOW we directly contributed to this by developing a **data-driven framework for lifetime monitoring**, focusing on:

- **Consumed Lifetime (CL)**: how much structural fatigue has already accumulated
- **Remaining Useful Life (RUL)**: how long the asset can continue operating safely

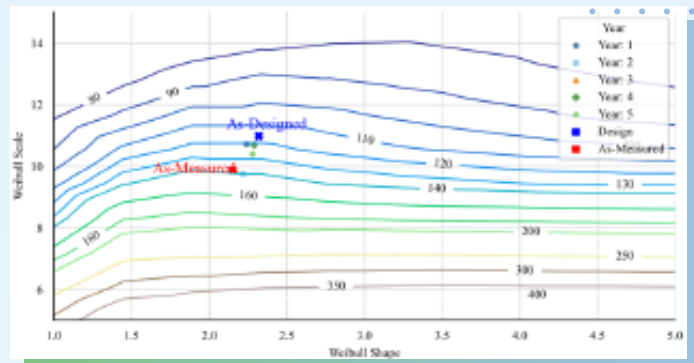
Different approaches were evaluated for time-based extrapolations, from classical extrapolation methods to more advanced machine learning techniques. The key findings include:

- Machine learning approaches provide **more reliable predictions**, especially when data is limited
- Approximately **9 months of monitoring data** is sufficient to achieve stable lifetime estimates

In addition, we introduced the concept of “**iso-life curves**”, which allow operators to visualise how changes in operating conditions or environment impact structural lifetime. This provides a powerful tool for **scenario analysis and strategic decision-making**.



Comparing binning strategies and machine learning for time based extrapolation + iso-life curves enabling scenario studies



Detecting anomalies at fleet level

Beyond predicting normal behaviour, in WILLOW we also introduced **novel methods to detect abnormal behaviour across the wind farm**.

Traditional monitoring approaches typically analyse each turbine individually. In contrast, WILLOW adopts a **population-based perspective**, where turbines are compared to each other under similar conditions.

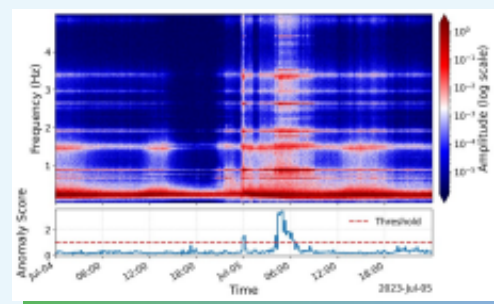
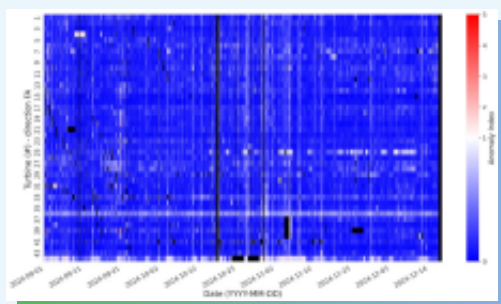
Two complementary approaches were developed:

- **Uncertainty monitoring**: identifying when model predictions become unreliable, indicating unusual behaviour
- **Self-supervised learning**: enabling turbines to develop their own “fingerprints” based on vibration patterns

This allows early detection of:

- Structural deviations
- Unexpected operational behaviour
- Emerging damage conditions

Importantly, these methods **do not require labelled failure data**, which is often unavailable in real-world offshore environments.



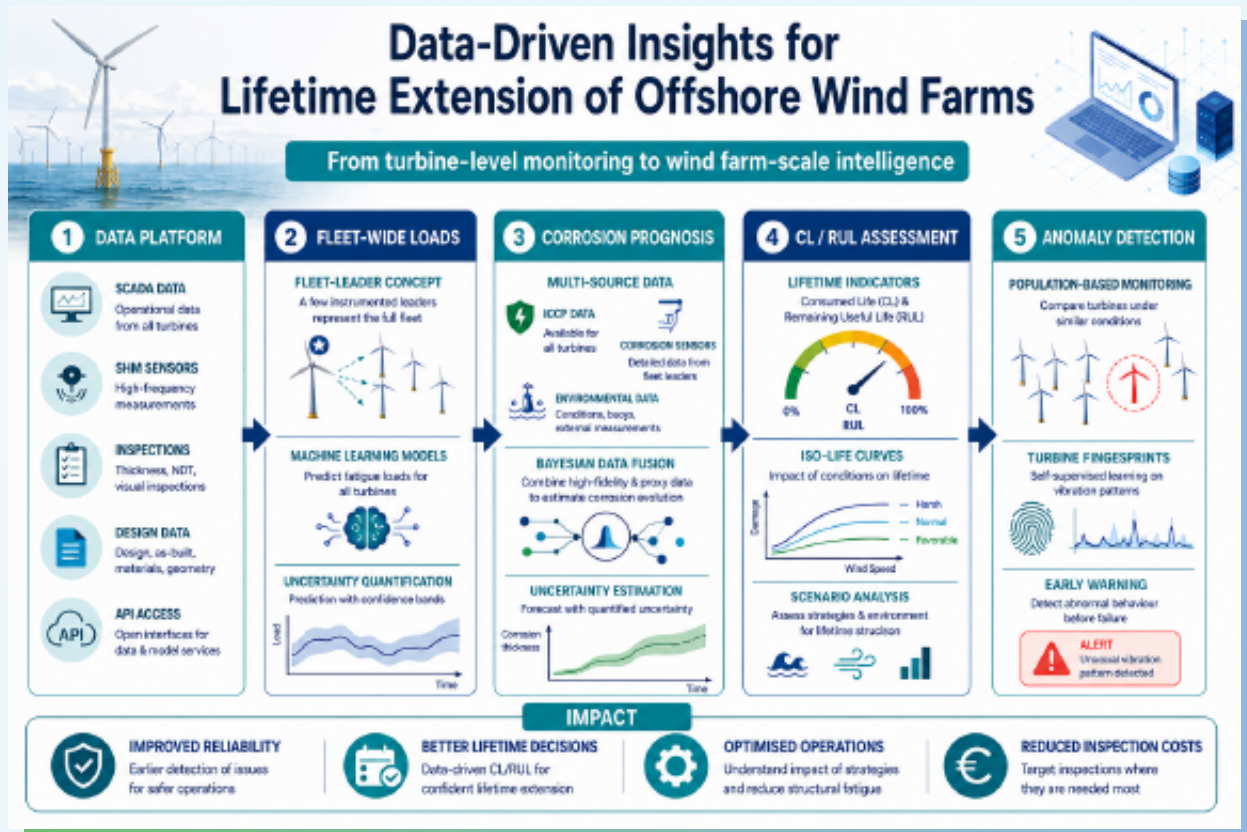
Impact and Outlook

These results demonstrate that it is now possible to move towards **continuous, data-driven management of offshore wind assets at fleet scale**. This has several important implications:

- **Improved reliability** through earlier detection of abnormal behaviour
- **Better lifetime management**, supporting extension beyond original design life
- **Optimised operations**, by understanding how operational strategies impact structural fatigue
- **Reduced costs**, through more targeted inspections and maintenance

By combining physics-based understanding with advanced data-driven methods, WILLOW contributes to making offshore wind energy not only more sustainable, but also more efficient and cost-effective.

As the industry moves towards larger wind farms and longer operational lifetimes, the methodologies developed provide a **strong foundation for next-generation asset management and decision-support tools**.





Health Aware Wind Farm Operation





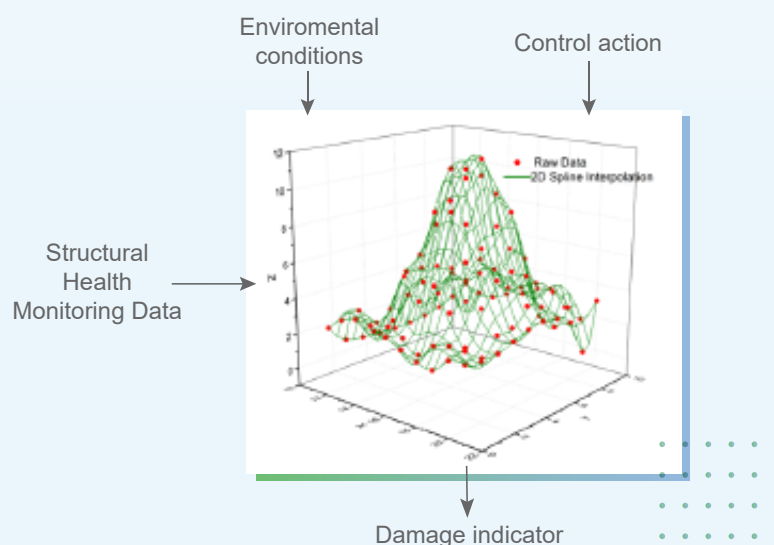
Introduction: Managing Wind Farm Lifetime Through Smart Curtailment

As offshore wind farms increasingly participate in electricity markets and provide flexibility services to the grid, curtailment events are expected to become more frequent. WILLOW addressed this challenge by developing health-aware operation strategies that combine structural health information, lifetime assessment, wind farm control and future grid scenarios. The objective is to reduce curtailment-induced damage while maintaining operational and market requirements.

I. Lifetime Consumption Matrix

WILLOW developed a wind-farm-wide Lifetime Consumption Matrix that translates operational and environmental conditions into estimates of structural lifetime consumption. The matrix is derived from operational measurements and Structural Health Monitoring data, providing turbine-specific information on current degradation and damage accumulation. To complement this measurement-based approach, physics-based simulations were used to investigate operating conditions that are difficult to observe directly, including curtailment transients and future operating scenarios.

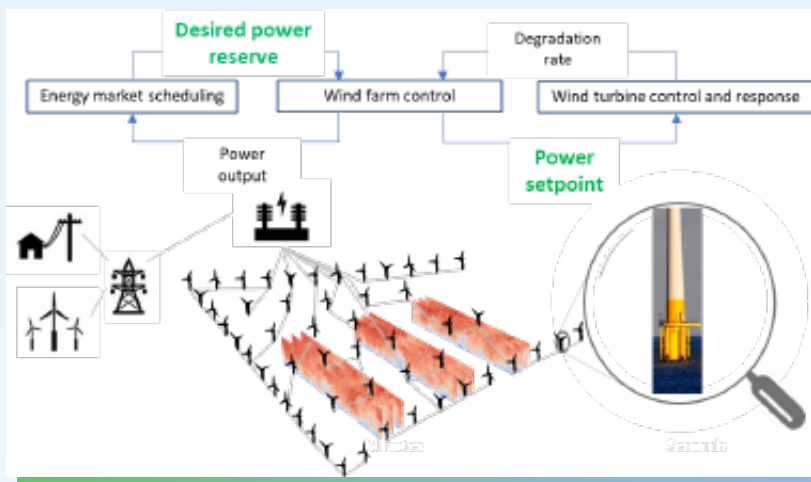
- Data-driven Lifetime Consumption Matrix based on operational measurements and SHM information.
- Farm-wide ranking of turbines according to accumulated fatigue consumption.
- Identification of turbines experiencing elevated lifetime consumption relative to the fleet average.
- Physics-based simulations are used to analyse curtailment transients and evaluate future operating scenarios.



II. Smart Curtailment Strategies

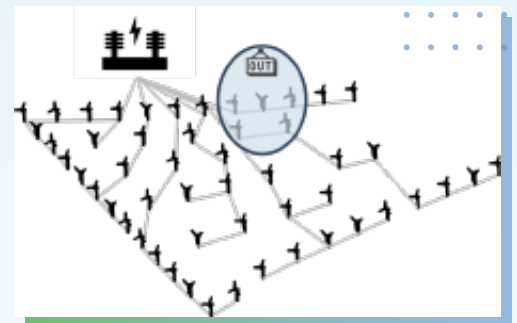
WILLOW investigated several approaches to reduce the lifetime impact of curtailment while maintaining the required power reduction. The main idea is to use information about turbine condition and operating environment when deciding how curtailment should be distributed across the wind farm. Multiple levels of complexity are considered:

- Excluding vulnerable turbines from curtailment
- Distributing power reductions according to turbine health status and local wind conditions
- Continuously adapting turbine power setpoints to dynamically balance grid requirements and structural lifetime considerations



Full picture

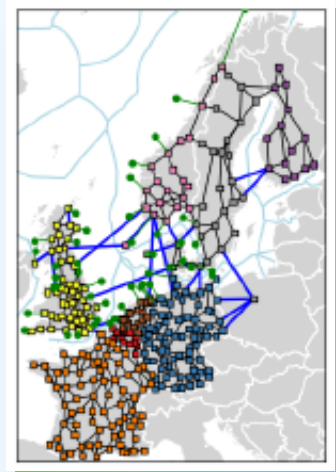
Simplified



III. Quantifying Curtailment in Future Grids

Future energy systems are expected to rely increasingly on renewable generation and flexibility services. WILLOW therefore analyses future European power-system scenarios to understand how often curtailment may occur and how these future operating conditions may affect wind farm lifetime.

- Assessment of a 2040 North Sea power-system scenario.
- Renewable-energy curtailment levels ranging from approximately 2% to 35% depending on region.
- Analysis of the relationship between renewable availability and curtailment occurrence.
- Open and reusable modelling framework for future curtailment studies.

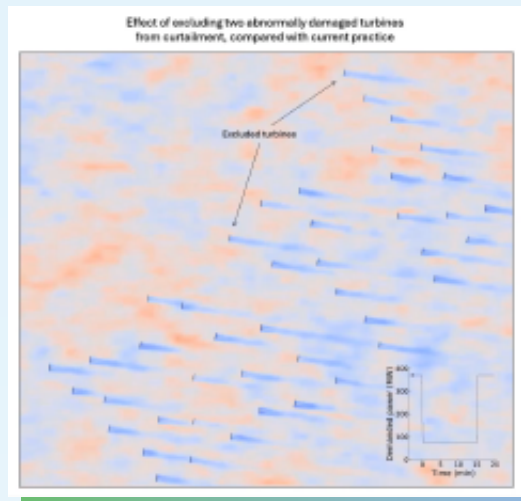




IV. Smart Curtailment Tool

A flagship result is the Smart Curtailment Tool. The tool combines turbine health information, lifetime-consumption models, curtailment strategies and future-grid scenarios into a decision-support framework for wind farm operators. The objective is to evaluate the lifetime impact of operational decisions before they are implemented in practice.

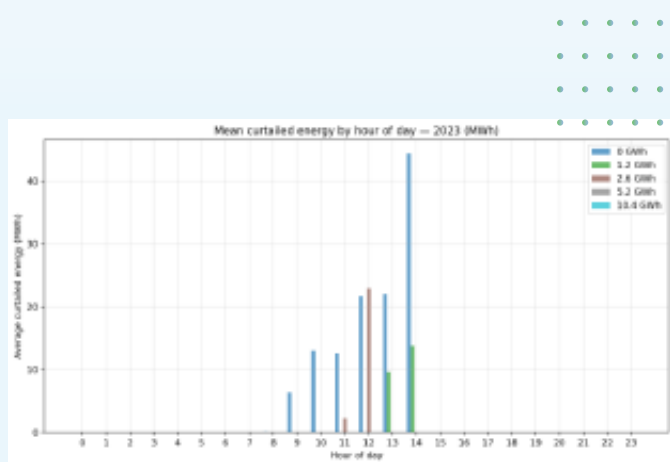
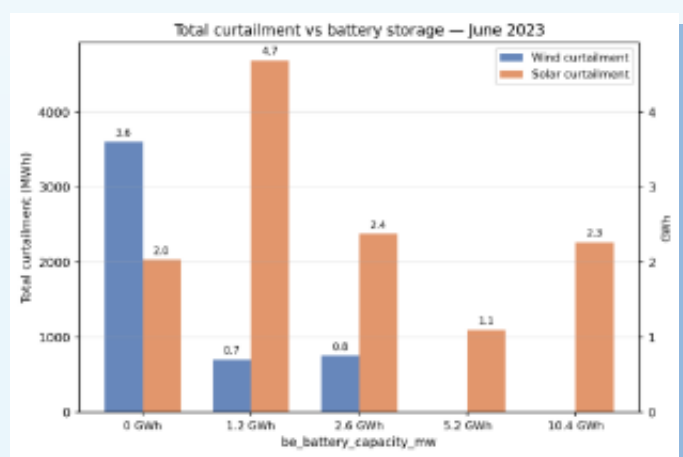
- Evaluate the lifetime impact of alternative curtailment strategies.
- Compare different power dispatch solutions.
- Assess the benefits of protecting vulnerable turbines.
- Support long-term operational planning under future grid scenarios.
- Provide decision support combining turbine health, control and economics.



V. Open-Source Tools for Health-Aware Operation

WILLOW delivered an open-source toolbox supporting the full workflow from wind-condition modelling to lifetime-aware operational decision-making. The tools enable the simulation of wind conditions across large offshore wind farms, estimation of structural lifetime consumption, optimisation of curtailment strategies and assessment of future operating scenarios. Key results include ground-breaking progress in:

- Modelling wind conditions across entire wind farms, from atmospheric conditions to wakes via farm-wide turbulence, with focus on computational efficiency.
- Designing and integrating wind turbine and farm control encompassing curtailment.





WHOLISTIC AND INTEGRATED DIGITAL TOOLS FOR EXTENDED LIFETIME AND PROFITABILITY OF OFFSHORE WIND FARMS



As we reach the final edition of the WILLOW Newsletter, we would like to thank you for following our journey. We hope you have found these updates valuable and inspiring.

The consortium



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