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PROWESS Final Report

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PROWESS Final Report

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Contents

Summary

Offshore wind turbine design lifetime is currently 25 to 30 years. However for wind turbine blades (WTB), as critical components of the wind turbine, lifetime and performance are two central concerns for wind farm owners/operators and OEMs. Leading edge erosion (LEE) has been identified as the main factor to substantially reduce both blade lifetimes and energy output over time. Severe consequences of LEE effects are linked with blades' lifetime reduction, reflected on increasing the levelized cost of energy (LCoE) and higher CO2 emission rates at initial stages of the supply chain, involving more frequent blade repairs, inspections and early replacements.

Without the suitable information on LEE events, the decision making strategies on LEE measures, selection of the right coating, operational and maintenance activities are insufficient and the LCoE will continue increasing on this front. At the wind farm planning stage, the lack of validated methods to estimate the overall cost of erosion causes uncertainty in the investment decisions. Wind farm developers currently have access to detailed data on seabed and wind conditions, though virtually no useful information on offshore precipitation.

The goal of the PROWESS project is to lower the cost of damage caused by LEE. Offshore precipitation is measured in detail for the first time and accurately correlated the precipitation to other weather data over the Dutch North Sea. It is used by the market for existing wind farms and to strengthen the site surveys for future wind farm deployments. The sub-goals of the PROWESS project were:
1. Establish and execute a monitoring system network for LEE characterization: Identification of the optimum weather monitoring strategy over offshore wind farms to characterize erosion events and properties affecting blades.
2. Model precipitation prediction correlated with LEE at high resolution over the Dutch North Sea: Development of enhanced precipitation models capable of assimilating RADAR images to create a long-term erosion classes linked with severity of the precipitation and wind conditions.
3. Assess AEP losses and O&M future needs related to LEE: Through coupling the erosion atlas and O&M planning tool to evaluate the likely cost of maintenance with a certain coating choice in different parts of the Dutch North Sea and to estimate the expected AEP losses due to LEE at high resolution by selecting sites over the Dutch North Sea.

The project provides a reliable source of information that can be used by multiple players in the wind industry such as OEM's, utilities, blade manufacturers and coating developers that build intelligence on precipitation characterization related to LEE over the Dutch North Sea, improve accuracy of erosion models that predict the leading-edge blade coating systems; enable reliable decision-making on LEE mitigating measures, optimize operational and maintenance activities to reduce LCoE; support the estimation of the overall cost of erosion to reduce uncertainty in the investment decisions at the wind farm planning stage. Provide an upfront assessment of wind sites regarding the risk for LEE, and inform wind farm operation to optimize blade lifetimes (i.e. reduce rotational speed or even shut down under certain weather conditions, or consider different LEE protection systems). Model developments on precipitation patterns simulations at finer resolution using micrometeorological models and RADAR systems are a step beyond the state-of-the-art for other sector applications.

1 Introduction

1.1 Background of the PROWESS project

Offshore wind turbine design lifetime is currently 25 to 30 years. However for wind turbine blades (WTB), as critical components of the wind turbine, lifetime and performance are two central concerns for wind farm owners/operators and OEMs. Leading edge erosion (LEE) has been identified as the main factor to substantially reduce both blade lifetimes and energy output over time. Severe consequences of LEE effects are linked with blades' lifetime reduction, reflected on increasing the levelized cost of energy (LCoE) and higher CO2 emission rates at initial stages of the supply chain, involving more frequent blade repairs, inspections and early replacements.

Without the suitable information on LEE events, the decision making strategies on LEE measures, selection of the right coating, operational and maintenance activities are insufficient and the LCoE will continue increasing on this front. At the wind farm planning stage, the lack of validated methods to estimate the overall cost of erosion causes uncertainty in the investment decisions. Wind farm developers currently have access to detailed data on seabed and wind conditions, though virtually no useful information on offshore precipitation.

1.2 Goal of the project

The goal is to lower the cost of damage caused by LEE. Offshore precipitation will be measured in detail for the first time and accurately correlated the precipitation to other weather data over the Dutch North Sea. It will be used by the market for existing wind farms and to strengthen the site surveys for future wind farm deployments. The sub-goals are:

1. Establish and execute a monitoring system network for LEE characterization:

Identification of the optimum weather monitoring strategy over offshore wind farms to characterize erosion events and properties affecting blades.

2. Model precipitation prediction correlated with LEE at high resolution over the Dutch North Sea: Development of enhanced precipitation models capable of assimilating RADAR images to create a long-term erosion classes linked with severity of the precipitation and wind conditions.

3. Assess AEP losses and O&M future needs related to LEE: Through coupling the erosion atlas and O&M planning tool to evaluate the likely cost of maintenance with a certain coating choice in different parts of the Dutch North Sea and to estimate the expected AEP losses due to LEE at high resolution by selecting sites over the Dutch North Sea.

1.3 Short description of the project work packages

This project consisted of five work packages, each taking the following approach:

WP1: Monitoring system network for LEE characterization: instrumentation and monitoring campaign execution with precipitation sensors. Coupling information with existing weather stations across coastal and offshore locations to correlate weather related variables with LEE.

WP2: Modelling precipitation prediction correlated with LEE: generate short- and long-term prediction based on the erosion rates found in WP1 at difference sites to have a large spatial coverage over the Dutch North Sea and a long-term data.

WP3: O&M and AEP assessment related to LEE: implement existing O&M cost model with the erosion atlas to create the investment decision support system.

WP4: Knowledge dissemination and exploitation: promote the erosion atlas with AEP and O&M assessment related to LEE applicable for wind farm operators, internationalization and standardization.

WP5: Project Management: manage and align the approach and results of the individual work packages and activities. Administrate and report time and budget and take corrective actions if necessary.

1.4 Summary of the results of the project

The project will provide a reliable source of information that can be used by multiple players in the wind industry such as OEM's, utilities, blade manufacturers and coating developers that will

- Build intelligence on precipitation characterization related to LEE over the Dutch North Sea.
- Improve accuracy of erosion models that predict the leading-edge blade coating systems
- Enable reliable decision-making on LEE mitigating measures
- Optimize operational and maintenance activities to reduce LCoE.
- Support the estimation of the overall cost of erosion to reduce uncertainty in the investment decisions at the wind farm planning stage.
- Provide an upfront assessment of wind sites regarding the risk for LEE, and inform wind farm operation to optimize blade lifetimes (i.e. reduce rotational speed or even shut down under certain weather conditions, or consider different LEE protection systems).

Model developments on precipitation patterns simulations at finer resolution using micrometeorological models and RADAR systems are a step beyond the state-of-the-art for other sector applications

1.5 Project partners and roles

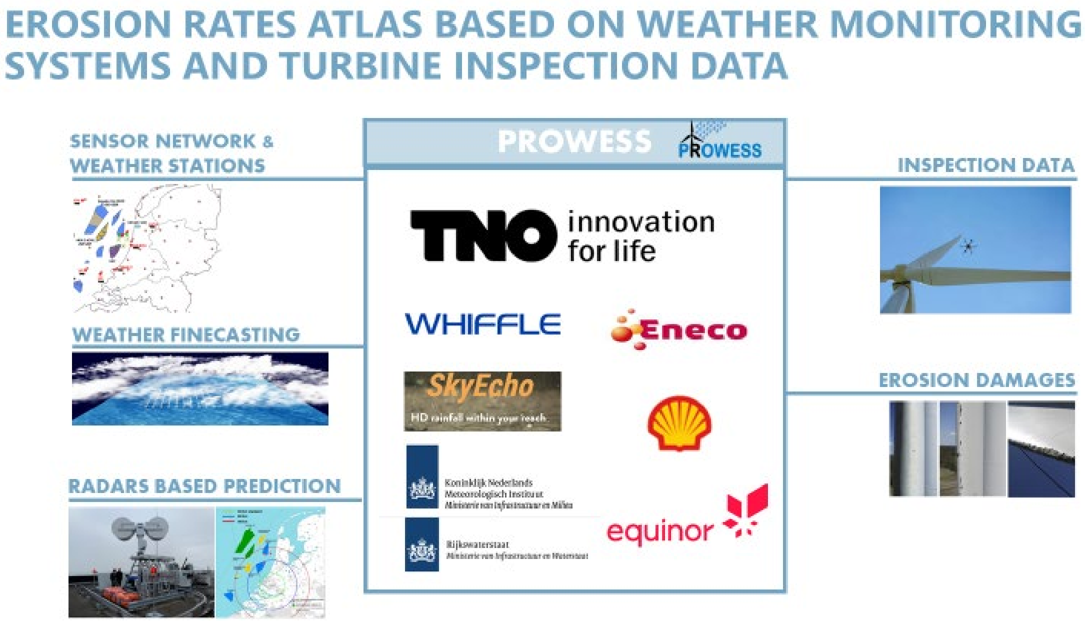


Table 1.1: Consortium and project roles

ID	Organisation	Type	Project role
D1	Whiffle	SME	Modelling wind farm level / micro meteo data
D2	Sky Echo	SME	Weather radar, HD precipitation data processing
D3	Equinor	Large company	End user, requirements and operational experience LEE in wind farms.
D4	Eneco	Large company	End user, requirements and facilitating in disdrometer monitoring offshore, operational data LEE offshore wind farms
D5	Shell Global Solutions International B.V.	Large company	End user, requirements and facilitating in disdrometer monitoring offshore, operational data LEE offshore wind farms
P1	TNO	RTO non profit	Coordinator, completion monitoring campaign, precipitation characterization and processing, long-term erosion rates atlas, LEE support system
Subcontracted by TNO			
-	KNMI	Large Company – part of the Ministry	Precipitation data and monitoring. (KNMI may not be a partner in the project due to subsidy rules and is therefore subcontracted)
-	Rijkswaterstaat	Large Company – part of the Ministry	Facilitating in disdrometer installation and operation
-	GROW Office	SME	Industry network, support in project management and dissemination

International committee			
-	VTT	RTO non profit	Alignment with related EU developments. Facilitator on precipitation characterization data and advisory on erosion rates atlas
-	DTU	RTO non profit	Alignment with related EU developments. Facilitator on precipitation characterization data and advisory on erosion rates atlas

2 Project overview of work and results

2.1 WP1 Monitoring system network for LEE characterization

This WP aimed at installing, maintaining and executing the measurement campaign at different sites with the use of advanced precipitation monitoring sensors (disdrometers). A previous evaluation of technical specifications on existing disdrometers suitable for offshore wind energy applications was completed from the WindCore project [1] and extended pre-study was done previous the project was granted. Existing TNO facilities and the partner contributions provided access to platforms to the selected locations.

The measurement database has been used to correlate the measured precipitation characteristics with erosion rates and wind climatology for a long-term historical period (over 30 years) thanks to the data availability of KNMI offshore and coastal weather stations

2.1.1 Task 1.1 Preparation of the disdrometer measurement campaign.

For the precipitation measurement campaign six location were foreseen. Two existing TNO measurement locations, EWTW and Haliade X, and four new measurement locations, see Figure 1 and see Figure 2. For the location Lichteiland Goeree (LEG), Prinses Amalia Wind Park (PAWP) and the Luchterduinen (LU) wind park a new measurement campaign was prepared by TNO. Location K14 was planned to be instrumented by Shell.
Based on experience gained in the existing TNO measurement campaigns as well as sensor specifications the sensor chosen for the new locations was the OTT Parsivel[2] disdrometer, which outputs the droplet distribution in more detail, compared to the other high level option, the Thies LPM.
Table 2 gives an overview of the TNO measurement locations specifics like sensor type and GPS coordinates.

Figure 1 PROWESS precipitation network, the TNO measurement locations in yellow and the Shell measurement location in green.

Table 2 Overview of the PROWESS measurements locations

Location	Installed by	Sensor type	GPS coordinates
EWTW	TNO	Thies LPM	52°48'59.81"N, 05°03'06.31"E
Rotterdam	TNO	OTT Parsivel[2]	51°57'46.79"N, 04°00'19.22"E
LEG	TNO	OTT Parsivel[2]	51°55'30.00"N, 03°40'06.38"E
PAWP	TNO	OTT Parsivel[2]	52°35'39.60"N, 04°12'45.10"E
LU	TNO	OTT Parsivel[2]	52°24'11.30"N, 04°09'54.50"E

No information on the K14 data is received by Shell.
All TNO measurement locations are part of the TNO company network. On a daily basis the measurement data is transferred to the project database server and automatically imported into the project database

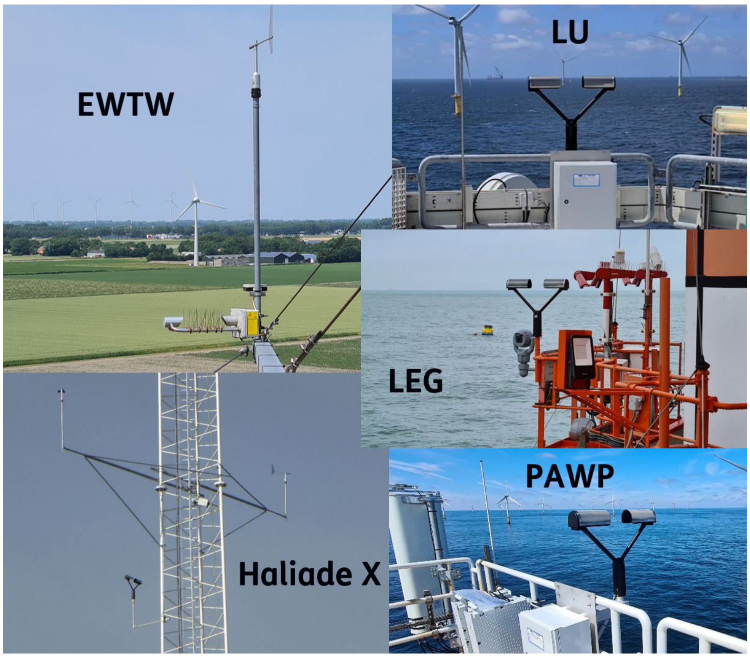


Figure 2 PROWESS precipitation network installed sensors.

2.1.2 Task 1.2 Operation and disdrometer monitoring campaign offshore

The availability of the individual measurement campaigns during the project measurement period, from 01-01-2022 up to 31-12-2023 is found in the figure 3. Note that due to technical issues with the sensor(s) at Luchterduinen the complete period of data must be handled with care and is advised not to use during analysis.

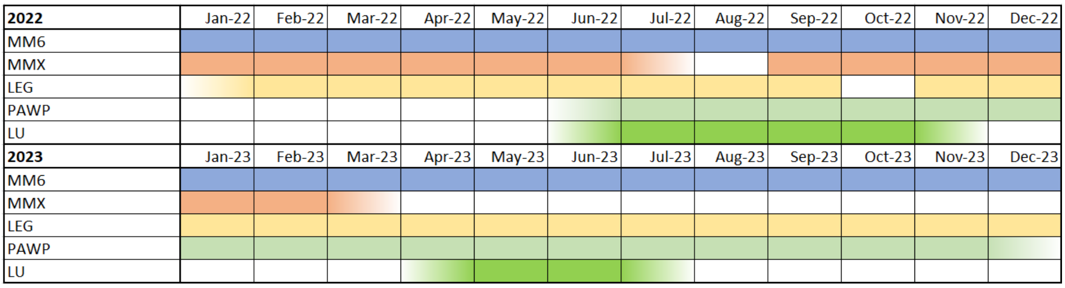


Figure 3 PROWESS measurement monthly availability.

The data is exported as csv files and stored at a TNO sftp server for data sharing with the project partners.

The data consists of two type of data files, the first type is of 1-minute statistics of the single value disdrometer output signals, like intensity, SYNOP type etc. The second type of data files contains the droplet distribution. The droplet distribution is a matrix of # velocity classes x # droplet size classes. See the figure 4 for an overview of the droplet distribution classes for the OTT Parsivel[2] as well ass the Thies LPM.

Particle diameter class		
Class	Diameter [mm]	Class width [mm]
1	≥ 0.125	0.125
2	≥ 0.250	0.125
3	≥ 0.375	0.125
4	≥ 0.500	0.250
5	≥ 0.750	0.250
6	≥ 1.000	0.250
7	≥ 1.250	0.250
8	≥ 1.500	0.250
9	≥ 1.750	0.250
10	≥ 2.000	0.500
11	≥ 2.500	0.500
12	≥ 3.000	0.500
13	≥ 3.500	0.500
14	≥ 4.000	0.500
15	≥ 4.500	0.500
16	≥ 5.000	0.500
17	≥ 5.500	0.500
18	≥ 6.000	0.500
19	≥ 6.500	0.500
20	≥ 7.000	0.500
21	≥ 7.500	0.500
22	≥ 8.000	∞

Particle speed class		
Class	Speed [m/s]	Class width [m/s]
1	≥ 0.000	0.200
2	≥ 0.200	0.200
3	≥ 0.400	0.200
4	≥ 0.600	0.200
5	≥ 0.800	0.200
6	≥ 1.000	0.400
7	≥ 1.400	0.400
8	≥ 1.800	0.400
9	≥ 2.200	0.400
10	≥ 2.600	0.400
11	≥ 3.000	0.400
12	≥ 3.400	0.800
13	≥ 4.200	0.800
14	≥ 5.000	0.800
15	≥ 5.800	0.800
16	≥ 6.600	0.800
17	≥ 7.400	0.800
18	≥ 8.200	0.800
19	≥ 9.000	1.000
20	≥ 10.000	10.000

Classification according to particle speed

Class number	Mid-value of class [m/s]	Class spread [m/s]
1	0.050	0.100
2	0.150	0.100
3	0.250	0.100
4	0.350	0.100
5	0.450	0.100
6	0.550	0.100
7	0.650	0.100
8	0.750	0.100
9	0.850	0.100
10	0.950	0.100
11	1.100	0.200
12	1.300	0.200
13	1.500	0.200
14	1.700	0.200
15	1.900	0.200
16	2.200	0.400
17	2.600	0.400
18	3.000	0.400
19	3.400	0.400
20	3.800	0.400
21	4.400	0.800
22	5.200	0.800
23	6.000	0.800
24	6.800	0.800
25	7.600	0.800
26	8.800	1.600
27	10.400	1.600
28	12.000	1.600
29	13.600	1.600
30	15.200	1.600
31	17.600	3.200
32	20.800	3.200

Classification according to volume-equivalent diameter

Class number	Mid-value of class [mm]	Class spread [mm]
1	0.062	0.125
2	0.187	0.125
3	0.312	0.125
4	0.437	0.125
5	0.562	0.125
6	0.687	0.125
7	0.812	0.125
8	0.937	0.125
9	1.062	0.125
10	1.187	0.125
11	1.375	0.250
12	1.625	0.250
13	1.875	0.250
14	2.125	0.250
15	2.375	0.250
16	2.750	0.500
17	3.250	0.500
18	3.750	0.500
19	4.250	0.500
20	4.750	0.500
21	5.500	1.000
22	6.500	1.000
23	7.500	1.000
24	8.500	1.000
25	9.500	1.000
26	11.000	2.000
27	13.000	2.000
28	15.000	2.000
29	17.000	2.000
30	19.000	2.000
31	21.500	3.000
32	24.500	3.000

Note:
Class 1 and class 2 are limits and are not evaluated at the current time in measurements using the OTT Parsivel[2] since they are outside the measurement range of the device.

Figure 4 Thies LPM and Ott Parsivel[2] speed and diameter classes

A complete description of the executed measurement campaign and detailed information on the project database is found in the PROWESS Precipitating network, Instrumentation Report, TNO 2024 R10535.

2.1.3 Task 1.3 Operation and radar monitoring campaign

The aim of this task was to evaluate the capacity of an advance X-band radar system to monitor rain (rainfall rate and rain accumulation) with high precision in part of the North Sea. For this task, an advanced research X-band radar system (MESEWI radar), deployed on top of the Electrical Engineering faculty at TU Delft (Figure 5- MESEWI radar (the one on the right of the image) installed on top of the EWI building at TU Delft) has been used. This rain radar has quad-pol Doppler features with the capacity to remove most of unwanted clutter and observe rainfall events at an unprecedented resolution of 1 min | 100 m resolution. Such features allows a fine monitoring of the complex heterogeneity and behaviors of (extreme) rainfall events.

The initial coverage of MESEWI is 25 km around the radar location, which is not enough to cover part of the North Sea. For the purpose of PROWESS, research has therefore been carried out by SkyEcho BV to assess to extend the domain size and cover a bigger part of the North Sea.

Figure 5- MESEWI radar (the one on the right of the image) installed on top of the EWI building at TU Delft

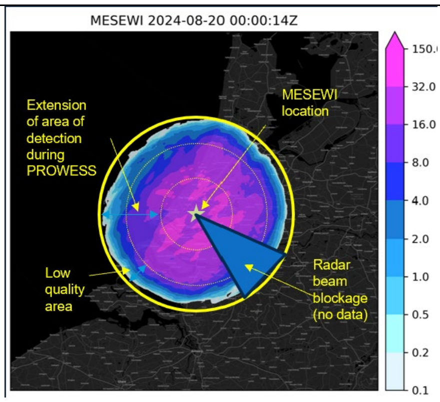


Figure 6 – total daily rainfall accumulation as measured by MESEWI for the 20 August 2024 – the yellow circle feature the 60km max range detection. The dotted yellow is the 50km range for qualitative information.

The following activities have been accomplished over the past years:

- **Radar system adaptation**: the transmit power of the radar system has been increased from 5W to 20W so that a further distance can be reached. Hardware filters and the radar processing software developed by SkyEcho have also also adapted to accommodate for this new power.
- **Test max range operation**: Several maximum ranges were tested in operation: 45km, 60km and 120km. Below are the main results assessed by SkyEcho:
  - Side-lobe radar beam largely affected for all tested ranges – several windowing techniques of the range processing were tested to mitigate the issue. The Tukey-window provided the best results.
  - Resolution volume increase: the radar beam is increasing the further you are from the radar location. For some specific weather case, the radar beam is reaching the cloud, drastically contaminating the rainfall information. Some research has been conducted to improve the azimuthal resolution of the radar and reduce the resolution volume by a factor 4, using signal deconvolution techniques.
  - Signal attenuation and saturation: the increase of the radar transmitted power increases the risk of radar signal saturation (too much signal is reflected back to the radar antenna. On the contrary, when heavy rainfall is occurring, signal can be attenuated by the rain drops, reducing the opportunity to detect rain after a certain distance.
  - To mitigate quality challenges of the radar data, SkyEcho developed new radar parameters able to evaluate the quality of each radar pixels. It was unfortunately not possible to further analyze them for operational integration.
- **Multi-sensor quality assessment:** A total of 20 raingauges (KNMI, Delfland), 7 disdrometers (TNO, TU DELFT) and 2 C-band radars (KNMI) have been evaluated to assess the quality of the X-band radar extension. 15 of these sensors out of the 27 sensors were selected based on their quality and availability for comparison. **Based on the above-mentioned points, the evaluation revealed that a maximum attenuation of 60km could be achieve for rain detection, and 50km for qualitative information (see** Figure 6**).**

Deliverables:
MESEWI radar dataset: for ease of use, all MESEWI data created within the PROWESS project have been integrated into SkyEcho Rain portal (https://rainportal.sky-echo.eu/map) that allows easy visualization of the radar output for any given time and day.

Conference paper (Poster presentation): the work of WP1 has been presented within two different conferences [2], [3]

2.1.4 Task 1.4 Multi-scale precipitation data correlation with erosion rates

2.1.4.1 Evaluation of wind turbine blades' rain-induced leading edge erosion using rainfall measurements at offshore, coastal and onshore locations in the Netherlands

The impingement of rain drops on wind turbine blades determines leading edge erosion (LEE) which is a factor driving high maintenance costs. In order to better quantify rain-induced LEE, we carried out detailed rainfall measurements, by means of disdrometers, in conjunction with wind speed measurements. Measurements were performed at three different Dutch sites, encompassing an offshore, a coastal and an onshore location (see Figure 1). Based on rainfall and wind speed measurements, and assuming a virtual 15 MW wind turbine, we estimated the blade's LEE using a fatigue-based model. Developed by means of different published rotating arm erosion data, our fatigue model relates the measured rainfall characteristics to the LEE incubation period, here assumed as the leading edge protection (LEP) system's end of life. Assuming a polyurethane LEP system, results indicate that the blades' incubation period is around 3.9 years at the offshore location, 6.6 years at the coastal location and 8.3 years at the onshore location. These results are connected to the higher wind speeds during rainfalls, and higher occurrences of very intense rainy events which, according to the measurements, progressively occur at the onshore, coastal and offshore locations.

Figure 7 Map showing the measured Dutch sites, including an offshore location (LEG), a coastal location (GEHALX) and an onshore location (EWTW).

This study demonstrates that the pace at which wind turbine blades erode as a consequence of rain is highly site-specific. Our results suggest that wind speed during rainfalls and occurrences of high rain rate events largely dictate the rain-induced erosion on blades. From onshore to offshore areas, wind speed and occurrences of high rain rate events progressively increase according to our measurements. We estimated that offshore, the lifetime of the leading edge protection system is roughly 50% shorter than onshore. At the offshore site, only few hours are responsible for a large portion of damage. The site-specific differences in the drop size distribution seems to play a smaller role on determining the differences in the sites' erosion rates. To estimate erosion it is therefore crucial to accurately measure at least, besides wind speed, rain intensity and amount. In this work we performed rain measurements using disdrometers. As well as more established measurement systems like rain gauges and radars, disdrometers can determine the rain intensity and amount. Furthermore, unlike rain gauges and radars, disdrometers can measure the drop size distribution. During our campaign we dealt with severe disdrometer corrosion issues, and acknowledged uncertainties affecting measurement accuracy. In order to gain more confidence in disdrometer measurements, extensive efforts should be invested in tackling these challenges in future campaigns. A comparative approach to estimate erosion, since the site-specific differences in the drop size distribution seem to have a secondary effect on the erosion rate among the sites, could be based on more established rain gauges and radar measurements which can be coupled to analytical models to define the size distribution.

For more details of this study the reader is referred to Caboni et al. [4].

2.1.4.2 Inspection reports of blade damages evaluation

The aim of this task is to find a relationship between the results of the carried out precipitation monitoring campaign and the damage to the blades as a result of LEE.
The research conducted into the correlation of LEE rates with field experience was carried out in collaboration with Eneco and Equinor. Based on the analysis of data from meetings with experts and blade inspection reports of operational offshore wind farms, the following conclusions can be drawn;

Based on the available data, no direct link could be deduced between the start of the initial stage of LEE damage (incubation period) and the operational period of the turbines in the wind farms examined;

The evaluated wind turbine blades for both the offshore wind farms of Eneco and Equinor, LEE damage occurs within a period of 10 years for blades that are not equipped with a LEP system;

The quality of the adhesive mounting of the softshell on the LE of the blade has a major influence on its lifetime. It should be noted that there is only a limited exposure time of ~3 years to the applied softshell protection system, so there is no indication of the expected time to incubate LEE damage to this LEP system.

To study the correlation between practice and theory, monitoring will have to be carried out starting from the installation of the wind turbine and on annual basis. For the monitoring high-resolution video images must be compared from exactly the same locations on the blade. Recommended is to monitor the critical area of the blade for LEE which is about 25% from the tip. If possible, 3D scanning techniques can be applied to monitor the surface morphology on microscale with the inspections to distinguish between imperfections and damage occurred due to LEE.

2.1.5 Learnings

The partners defined the following general learnings from the WP1 both the measurements and the correlation

- Offshore, the incubation period of the leading edge protection system is 50% shorter than onshore.
- From onshore to offshore areas, wind speed and occurrences of high rain rate events progressively increase.
- At the offshore location 30% of the yearly damage is accumulated over just 12 hours, in which the wind speed is ≥ 17.5 m/s and the rain rate is ≥ 7.5 mm/h.
- During our campaign we dealt with disdrometer corrosion issues, and acknowledged uncertainties affecting measurement accuracy.
- In order to gain more confidence in disdrometer measurements, extensive efforts should be invested in tackling these challenges in future campaigns (involving distrometer manufacturers).

Regarding the radar related activities:

- High spatial and temporal rainfall heterogeneity is detected both over land and sea. Pics of high rain rate intensity occurring within a few minutes is often present in the data and validated with a multi-sensor approach.
- Observations at 1 min | <500 m is strongly recommended to capture most of the rainfall heterogeneity
- The quality of the rainfall information can strongly be affected when extended the radar coverage. A quality assessment framework based on new radar quality proxi and multi-sensor approach would need to be further developed to support the results of this study.

2.2 WP2 Modelling precipitation prediction correlated with LEE

2.2.1 Task 2.1 High resolution short-term radar based prediction

The goal of this task is to integrate the X-band radar data adapted in WP1 in short-term based rain prediction (so-called rain nowcast) over the North Sea. As X-band radars are limited in domain size to 50-60 km range, a two steps approach has been developed for this task:

Step 1: extension of the rain observation domain, using rain compositing methodology, that integrate the X-band radar data with other sensors to cover a large part of the North Sea up to the coast of the UK. This step is required to feed the smaller domain size of the rain nowcast with enough rain information to offer a lead time beyond 1h.

Step 2: processing of the rain composite to create the short rain forecast using optical flow methodology.

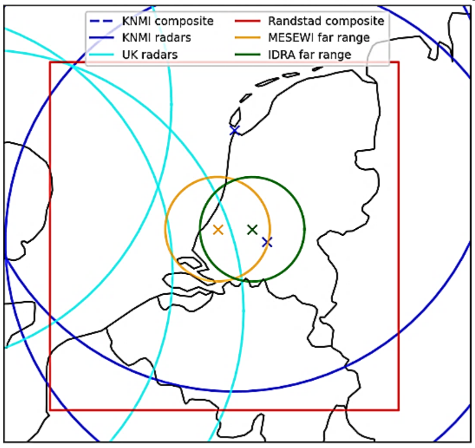


Figure 8- Radar sensor considered for PROWESS rain composite, showing overlap of different measurement domains – after analysis, only KNMI radars and MESEWI radar has been used.

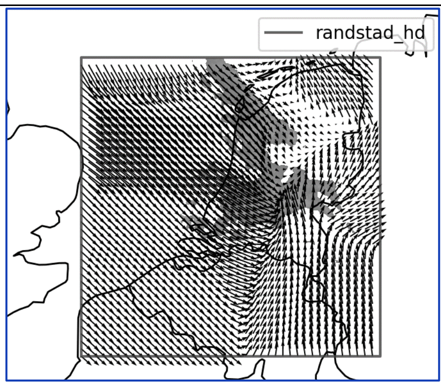


Figure 9 – 2D wind map based on rain cells advection

The following activities have been accomplished over the past years:
Rain Composite Development and testing (Figure 8 **and** Figure 5): SkyEcho developed an algorithm to fuse rain data from different sensor on an near-real time operation basis. Only the IRC radar composite of KNMI and the MESEWI data were selected so that the merging is performed on consistent radar dataset with similar rain conversion principles, altitude of observation and resolution. Several steps were made to create the rain composite:

a. Data collection and format transformation: The collected data were calibrated with each other and format/resolution uniformized
b. Several merging criteria were tested to optimize the final rendering
c. Real-time operation testing: the domain size and resolution were tested for real-time operation. **A final resolution of 500m | 5 min was adopted to guarantee the robustness of the real-time processing operation**
d. Real-time rain composite is produced and archived in our servers **since July 2024**.

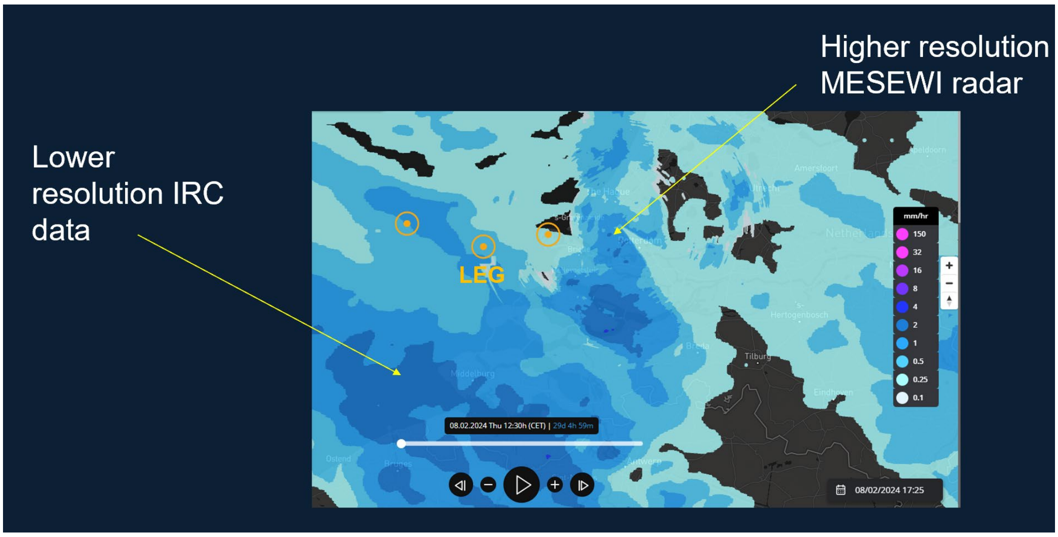


Figure 10 – Example of rain composite obtained for PROWESS

Nowcasting development (Figure 9 **)**: the short-term forecast of maximum 2h has been developed based on the above-mentioned rain composite creation

e. The forecast uses optical flow PYRAD method
f. In this method, the 2D wind field is first retrieved by determining contour and advection of rain cells from images to images.
g. From the extrapolation of the 2D wind field, the rain cell is then moved via rotation and translation
h. Result: due to the simplicity of the nowcasting methodology, only short lead time could be achieved with consistent outputs.

Deliverables:
MESEWI radar dataset: for ease of use, a HD rain composite layer created within the PROWESS project have been integrated into SkyEcho Rain portal (https://rainportal.sky-echo.eu/map) that allows easy visualization of the radar output for any given time and day.

2.2.2 Task 2.2 Long-term precipitation modelling over the Dutch North Sea

Whiffle has developed a version of the large eddy simulation (LES) model ASPIRE that can simulate precipitation in real weather conditions on a large domain over long periods of time. Simulations of real historical weather conditions are performed by coupling large-scale reanalysis data from ERA5 [5] to the boundaries of a meso-scale version of the model. In a similar manner, this meso-scale simulation is in turn coupled to the boundaries of a nested high-resolution LES. Both the meso-scale simulation and the LES use an implementation of the microphysics model by Grabowski [6] which locally calculates the rate of rain droplet formation and simulates the subsequent precipitation. Since ASPIRE works with model time steps of a few seconds, it is able to capture the typically short-lived high rain rate events that are of special interest for this study.

To create a long-term atlas of the precipitation climate over the Dutch North Sea, two simulations have been done: a stand-alone 10-year meso-scale simulation (2014 – 2023) with a domain size of over 1,000 kilometres, and a smaller but much higher resolution 1-year LES (March 2022 – March 2023, i.e. the year with the highest disdrometer data availability). The output of these simulations is provided at 60-minute intervals and 1-minute intervals, respectively, and consists of two-dimensional grids of time series for multiple variables, including local rain rate and wind speed.

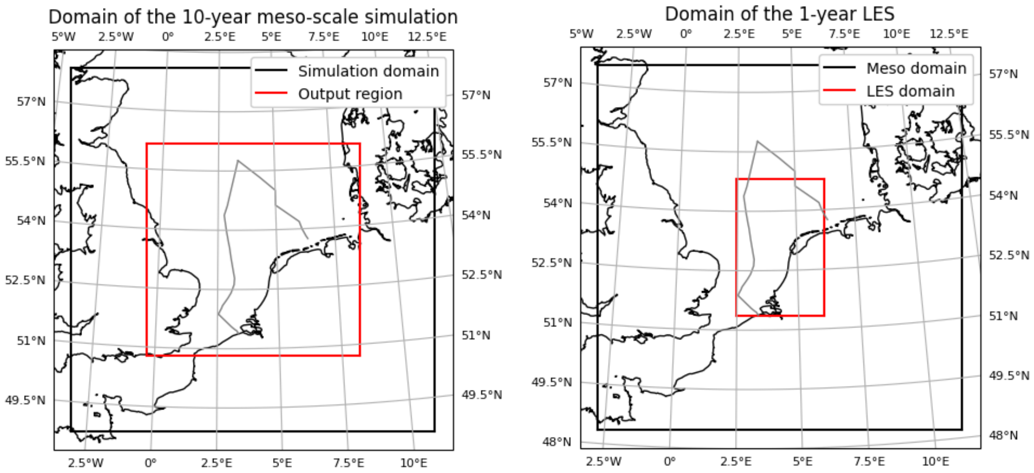


Figure 11 Example of the simulations of the higher resolution of the LES model

The simulations revealed a south-westerly gradient in the average rain rate over the Dutch North Sea, with the average rain rate in the south-west being lower than in the north-east by 50 – 100 millimetres per year (See Figure 12 and section 2.2.3) Furthermore, analyses of the two simulations highlighted a strong influence of the time interval of the output on the rain rate distribution: while both the mean local rain rate and wind speed of the meso-scale simulation are in line with the disdrometer data as well as the LES, the meso-scale data strongly underestimates the frequency of high rain rate events. The reason for this is that events shorter than the 60-minute intervals are lost through averaging, such that short-lived high rain rate events are not fully represented in the instantaneous rain rate distribution. As erosion rates are affected by both the average rain rate and the rain rate distribution, we conclude that short sampling intervals are necessary for the modelling of erosion rates. Further challenges identified during this study include matching the modelled (rain) clouds with the real clouds (e.g. from satellite measurements), and the modelled droplet size distribution with those observed by the disdrometers. In addition to developing better methods for sampling the distribution of the instantaneous rain rate, future campaigns should therefore focus on assimilation of cloud observations and improving the model's droplet size distribution.

2.2.3 Task 2.3 Long-term erosion rates modelling over the Dutch North Sea

We developed a rain-induced leading edge erosion atlas for wind turbine blades over the Dutch North Sea using large eddy simulations over a period of 10 years. According to the simulations, rainfall erosivity varies across the Dutch North Sea. The incubation period is around 8 years in the southwestern part of the Dutch North Sea, while it is around 7 years in the northeastern part (see Figure 2).

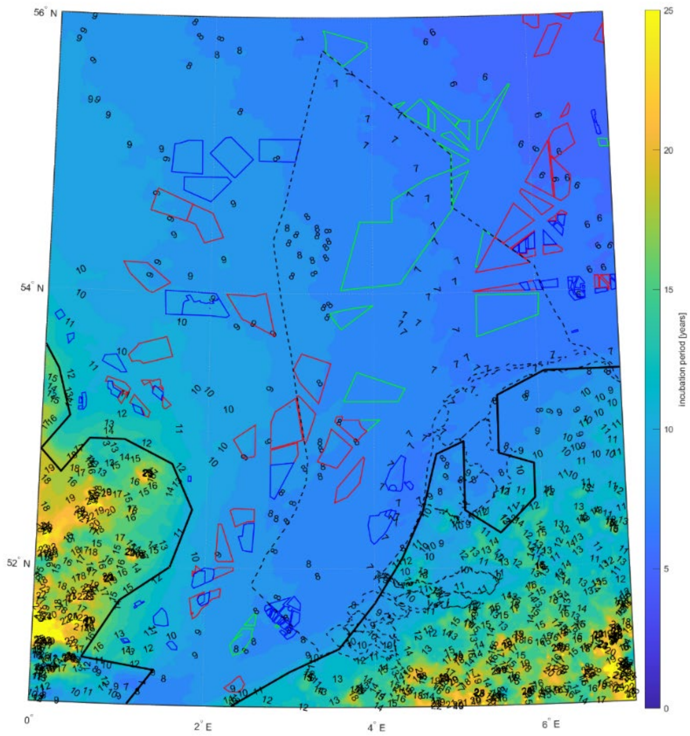


Figure 12 Contour map of yearly accumulated damage based on 10 years of large eddy simulations. Zones of currently operational wind farms are depicted in blue, while areas of wind farms planned to be operational before 2030 and search areas for wind farms to be commissioned after 2030 are depicted in red and green, respectively. Dashed lines depict the boundaries of the Dutch North Sea.

For more details of this study the reader is referred to Caboni and van Dalum [7].

The leading edge erosion atlas provides and additional layer of spatial information necessary for strategic planning required for offshore system integration—i.e., for coordinating the planning and operation of activities of various offshore-energy-disciplines. For example, the atlas can provide insight into where wind turbines will require design/operation and maintenance strategies to mitigate leading-edge damage. Furthermore, combining the atlas with shipping and helicopter routes (as in Figure 3) can be beneficial to understand how accessible the areas prone to leading edge damage are by vessels/helicopters for repair-work. Just as the knowledge of the proximity of windfarm areas to potential routes of hydrogen backbones (described in Figure 3) could aid in the planning of offshore power-to-gas infrastructure; or how the knowledge of the location of ecologically sensitive areas or fishing zones within designated wind-areas could inform windfarm developers of the opportunities for multiuse of offshore space, the leading edge erosion atlas developed in this study provides new spatial data to support the offshore wind sector.

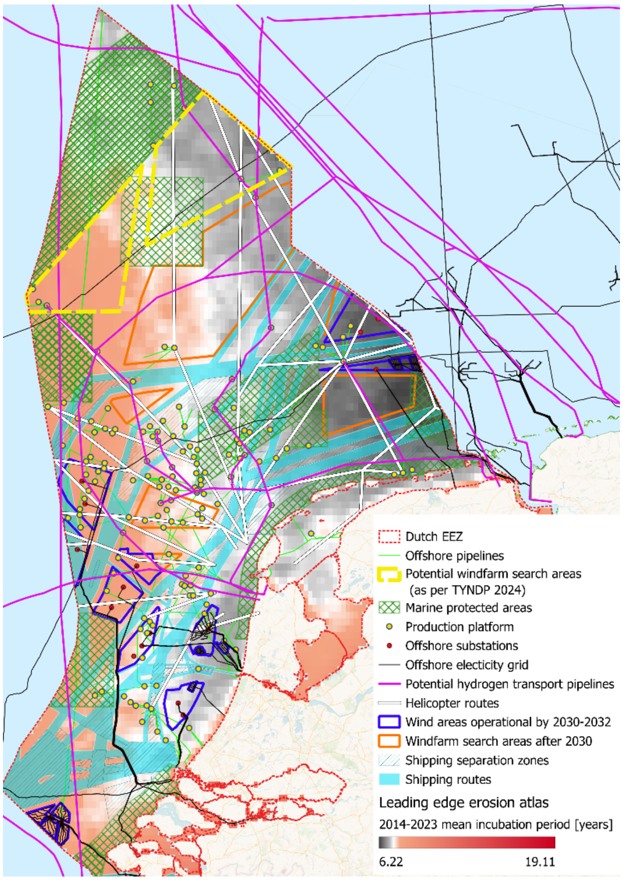


Figure 13: The leading edge erosion atlas set in the background of other offshore activities falling in the category of offshore energy production and transport, shipping and helicopter transport and marine protection.

2.2.4 Learnings

The partners defined the following general learnings from the WP2

The most erosive area is situated in the northeastern part of the Dutch North Sea. Assuming a virtual 15 MW wind turbine implementing blades using a polyurethane-based leading edge protection system, the incubation period in this area is 6 years. This portion includes search areas for wind farms to be commissioned after 2030.

Under the same assumptions, the incubation period of blades operating in currently operational wind farms in the south part of the Dutch North Sea is 8 years.

The level of erosivity is dictated by a combination of high wind speed and high precipitation. The leading edge erosion atlas provides and additional layer of spatial information necessary for strategic planning required for offshore system integration

Regarding the demo of the case study of the radar and its model implementation:

- Comparing different rain sensor output for quality evaluation is very difficult challenge. The complexity is driven by the difficulty to individually assess the intertwined influence of hardware/software sensor(s) uncertainties, strong spatial/time rain heterogeneities and

reference-based validation bias, combined. Further improving rain assessment quality remains key for the future development of multi-sensor strategies
- Multi-sensor rain fusion to create single composite clearly leverage single sensor observation limitations, improving the overall rain information quality, even though challenges on quality assessments are found, as mentioned in the first point.
- Optical flow nowcasting based on rain observation composite alone is only working for a short lead time. Additional weather observation (vertical cloud structure, and thermodynamic state) as well as combination with specific modeling (LES, AI) may help to increase the lead time further.

In relation to the LES model:
- • Short sampling intervals are necessary to be able to measure the short-lived high rain rate events that are most relevant for leading edge erosion.
- • Assimilation of cloud observations and improved modelling of the droplet size distribution would allow ASPIRE to provide more accurate forecasts of the events with the highest rainfall erosivity.

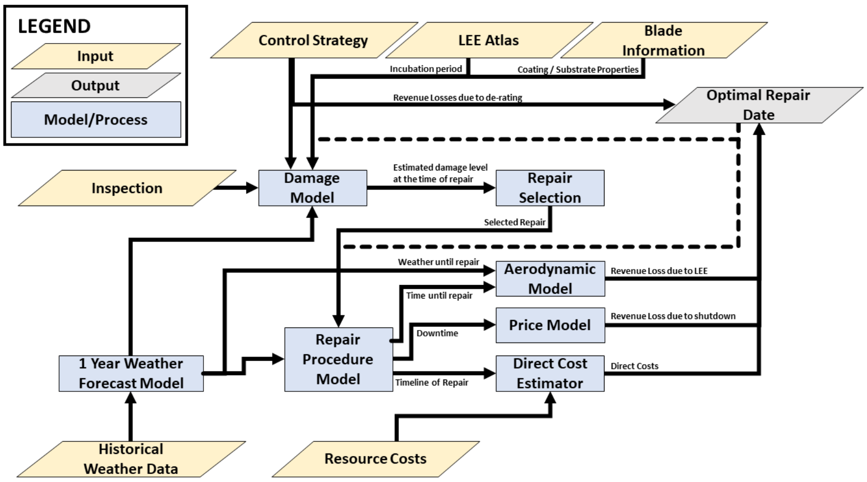
2.3 WP3 O&M and AEP assessment related to LEE

The main goal of this WP was to deliver support on O&M strategies and on the selection of different coating systems, and the expected AEP losses for existing and future wind farm operations based on the erosion atlas related to precipitation characteristics. This was carried out by the implementation of an existing Operation and Maintenance planer with the erosion atlas.

2.3.1 Task 3.1 Upgrading O&M planner tool with the erosion Atlas

The O&M planner tool was used in Task 3.2 to estimate the operational feasibility of performing repair procedures on blades damaged by leading edge erosion (LEE) , by using hourly meteorological data to simulate weather delays. Repair procedures were simulated assuming damage at two distinct levels of severity: one where the topcoat would need to be repaired, and one where the laminate would need to also be repaired. These stages follow the typical damage progression of LEE.

This investigation assumed the damage to already exist, meaning that the incubation period has already been reached and exceeded. To correlate the O&M planner tool with the erosion atlas, the relationship between the incubation period and the operational feasibility of performing LEE repair was investigated by suggesting a possible predictive maintenance algorithm, that attempts to calculate an optimal repair date. This investigation, which was done as a consideration for future work, highlights the possible working of a tool that uses the erosion atlas as a damage progression model to estimate how soon one would need to repair a blade at a higher severity level, which is a more operationally challenging repair. This estimation, when coupled with the O&M Planner tool, would allow the user to estimate the risk of waiting until damage is higher, albeit potentially with the benefits of more weather windows, lower resource costs, etc. This tool could also incorporate other benefits of drawbacks that change depending on the time of the year one decides to perform this repair.



2.3.2 Task 3.2 Mapping expected AEP losses and O&M for Wind resource assessments

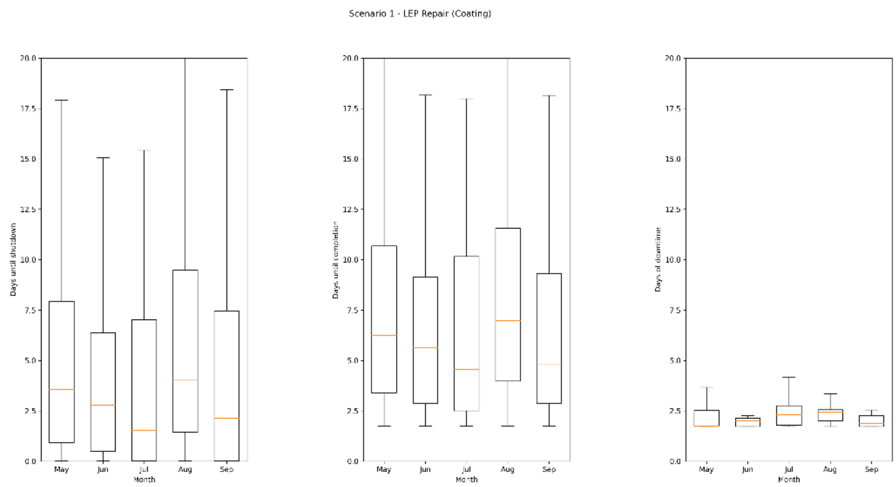
The O&M Planner tool was used to estimate the feasibility of performing repair procedures on blades damaged by leading edge erosion (LEE). Repair procedures were constructed for 4 scenarios:

- Damage to a roll-on coating leading edge protection (LEP) system
- Damage to a softshell LEP system
- Damage to the laminate layer of a blade, assuming a roll-on coating LEP system
- Damage to the laminate layer of a blade, assuming a softshell LEP system

Each repair procedure was constructed with the assistance of project partners, at the level where each step in the repair (e.g. transit to the turbine, set up rope access, apply the LEP, wait for it to cure, etc.) was individually defined. Each step was given a time duration and specific weather conditions. The relative humidity and precipitation requirements of the repair (especially when related to the chemicals used), were considered in the appropriate steps of the repair.

These repair procedures were simulated at varying times in the summer (when these repair typically happen), using hindcast data from several weather years obtained from a TNO meteorological campaign at the IJmuiden Ver location. The statistical distributions per month of the following KPIs were then plotted and compared:

- Days until repair - the number of days, from the simulation start date, until a suitable weather window for repair is found, and the turbine shuts down
- Days until completion – the number of days, from the simulation start date, until the repair is completed and the turbine resumes production
- Shutdown – the days that the turbine is shut down for repair, and the difference between the above two values.



2.3.3 Learnings

Two main conclusions were obtained from this investigation:

1. Regardless of damage level, the difference in operational feasibility between performing repairs with a roll-on coating LEP and a softshell LEP were not large, indicating that the difference in operational requirements for these two LEP systems was not enough to result in significant differences in how feasible it was to perform the repair, for the IJmuiden Ver location. This suggests that the application of softshell systems, which theoretically have a longer lifetime, would not lead to longer downtimes for application, and could thus be worth their additional upfront cost. This may differ from site to site, however, meaning that the choice of LEP system could vary between locations.

2. For both LEP systems, the downtimes associated with repairing laminate damage (which occurs at a later stage of damage progression than damage to the LEP), were up to 4 times higher. This indicates that the risk of waiting until there is more damage entails significantly more revenue losses due to that downtime. This should be considered in the context of other factors, which is discussed in Task 3.1.

2.4 WP4 Knowledge dissemination and exploitation

TNO has acted as the coordinator (*Penvoerder*) of the Prowess project. During the project quarterly project meetings were organized where the partners shared their progress and discussed the coming period. The intermediate results were presented in powerpoint sheets and stored on the Prowess project site enabled by Grow .

Before the closure of the project, when the major results were being finalized, a meeting with all partners were held where it was discussed the potential follow-up, the research gaps that still are pending after the project in order to propose a continuation on the topic.

At the end of the project, October 8th 2024, the consortium organized a closing meeting at TNO Amsterdam offices were the project results were discussed and agreements on the final report were made.

2.4.1 Outcomes for the continuity of the research topic

Several stakeholder meetings were held during the last year of the project, focusing on the continuity and follow-up on the PROWESS project. Main outcomes are included herein:

In order to gain more confidence in disdrometer measurements, extensive efforts should be invested in tackling these challenges in future campaigns (involving disdrometer manufacturers).
More experiments, possibly including disdrometer manufacturers, to Provide guidelines for calibration Improve sensor durability in highly corrosive offshore environment
Development best-practice for disdrometer deployment
Use of wind shields to reduce wind disturbance
Development of techniques to avoid contamination due to insects or sea spray
Development best-practice for disdrometer analysis to allow comparability across different campaigns: Quality checks, Synopsis characterization, Rain parameters, Qualify and reduce differences between disdrometer and rain gauge measurements
Development of disdrometer network to allow for long term characterization of offshore rain and hail conditions: Use disdrometer information to calibrate RADAR systems
Erosion safe modes. How would an operator do that? Do we need disdrometers? They might not be ready to be deployed and unreliable. Evaluate the difference between the disdrometer and other methods. Also look at how we can measure the hail.
Operational assets. Set up test nowcasting on turbine operations asset. Keeping the turbine running and even to stops. Understanding the robustness. Making the learning operational.
Erosion between different sides of the wind farm. To see if there is a difference. Also between different wind farms. Environmental impact and effect of microplastics on the food chain in the wind farm.
Calculations on incubation time. Material properties. Improvement disdrometer monitoring.
Field test data which was made available during the project was too far in the process. Damage already occurred. We need data for the time leading up to damage. Standardizing blade inspections. To improve the monitoring campaign. Calibration of the disdrometers and to make it more offshore proof.
More accurate forecasting models for O&M. What would the best time be to perform a repair?. Optimal repair date. Erosion safe mode vs. benefits of performing less O&M compared to productivity.

Network of radars and other sensors like bird detecting. National level a more structure monitoring campaign is needed. Data infrastructure and business case why it is worth the investment. Bird detection: no radar to see when they are going to fly which is causing windfarms to shut down for a longer period which might not be necessary.

2.4.2 Dissemination

The following activities have been carried out during the project:

- GROW project website (https://www.grow-offshorewind.nl/project/sawop [8])
- GROW newsletter
- GROW to Go podcast
- Oral presentation at 5th International Symposium on Leading Edge Erosion of Wind Turbine Blades (5th International Symposium on Leading Edge Erosion of Wind Turbine Blades | The Event (conferencemanager.dk)).
- Oral presentation at TORQUE 2024 (Torque 2024).
- RainPortal for data vizualisation access: https://rainportal.sky-echo.eu/map.

SkyEcho's Rain Portal was adapted to be populated with MESEWI radar and Rain composite information created within the PROWESS project. The objective is to improve the dissemination and useability of the project output without any pre-processing required.

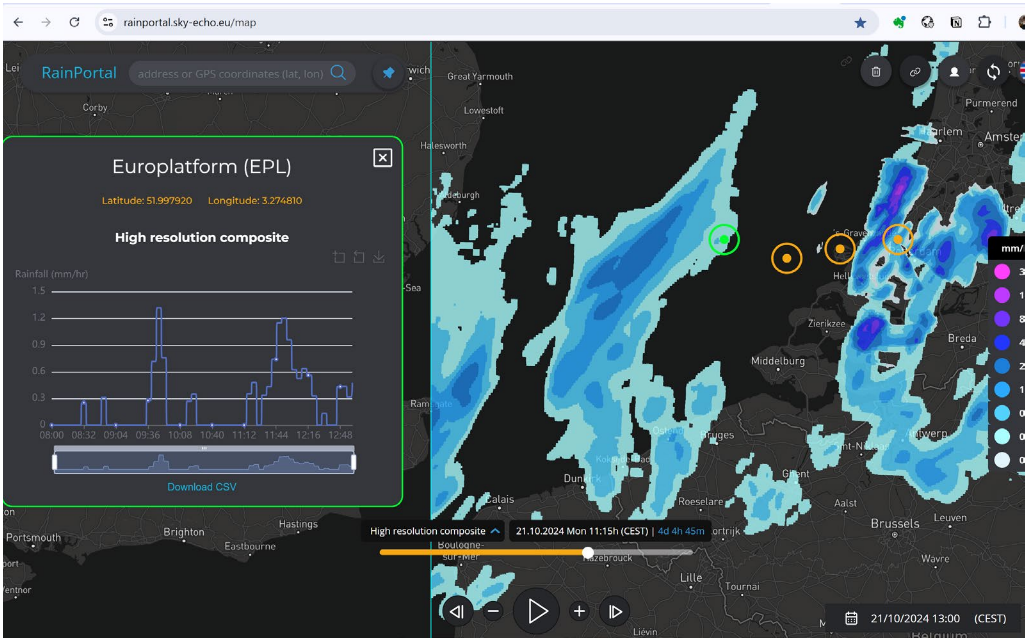


Figure 14 – Screenshot from the SkyEcho Rain Portal adapted for the PROWESS project

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