# IEA Wind TCP

**IEA Wind Task 46 Annual Progress Reports for IEA Wind TCP ExCo Meeting 91**

**Task 46: Erosion of wind turbine blades**

Date: 25 April 2023

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Co-Operating Agent Charlotte Bay Hasager, Danish Technical University (DTU)

## 1 Background and Goals

**Task Description:**

The purpose of the IEA Wind Task 46 Erosion of wind turbine blades is to improve understanding of the erosion driving factors, develop datasets and model tools to enhance prediction of leading edge erosion likelihood, identify damage at the earliest possible stage and advance potential solutions.

The task scope is aligned with two of the research priorities established by IEA TCP, namely:

- **Resource and site characterization**: Improving the practices in resource characterization regarding susceptibility to erosion at wind farm sites.
- **Advanced technology**: erosion damage models, material properties, characterization of erosion resistance; characterization and improvement of wind turbine operation with erosion.

The scope of work is divided into four technical work packages:

- **WP2 Climatic conditions driving blade erosion:** The science goals are to (i) provide a priori assessments of wind sites regarding the potential for excess LEE, and (ii) inform wind farm operation to optimize blade lifetimes. The long-term objective is to characterize erosion-relevant properties geospatially / temporally and generate GIS layers (with quality index/uncertainty) for inclusion in a manner similar to the Global Wind Atlas (https://globalwindatlas.info/). This WP is coordinated by **Sara Pryor** from Cornell University and **Marijn Verart** from Ørsted.

- **WP3 Wind turbine operations with erosion:** This work package has three key overarching objectives: (i) Promote collaborative research to mitigate erosion by means of wind turbine control, assessing the viability of erosion safe mode. (ii) Improve the understanding of droplet impingement in the context of erosion. (iii) Improve the understanding of wind turbine performance in the context of erosion, specially the effect of LEE surface roughness on aerodynamics. This WP is coordinated by **David Maniaci** from Sandia National Laboratories.

- **WP4 Laboratory testing of erosion:** The objective of this work package is to facilitate convergence of laboratory erosion testing practices to achieve a high fidelity test setup representative of the erosion phenomena observed in the field; and reduced uncertainty associated to the preparation of the samples and the testing process and the data analysis. This WP is coordinated by **Nicolai Frost-Jensen Johansen** from DTU.

- **WP5 Erosion mechanics & material properties:** The aim is (i) to understand the influence of the material parameters used for leading edge protection on the performance; and (ii) to understand the damage mechanisms and to identify appropriate damage models for accumulative droplet impact erosion attending operational conditions (droplet impact velocity, droplet size, number of impacts per unit surface, etc); and failure modes (surface wear, interface debonding, cracking of underlying layers etc). This work is coordinated **by Fernando Sanchez Lopez** from Universidad Cardenal Herrera.

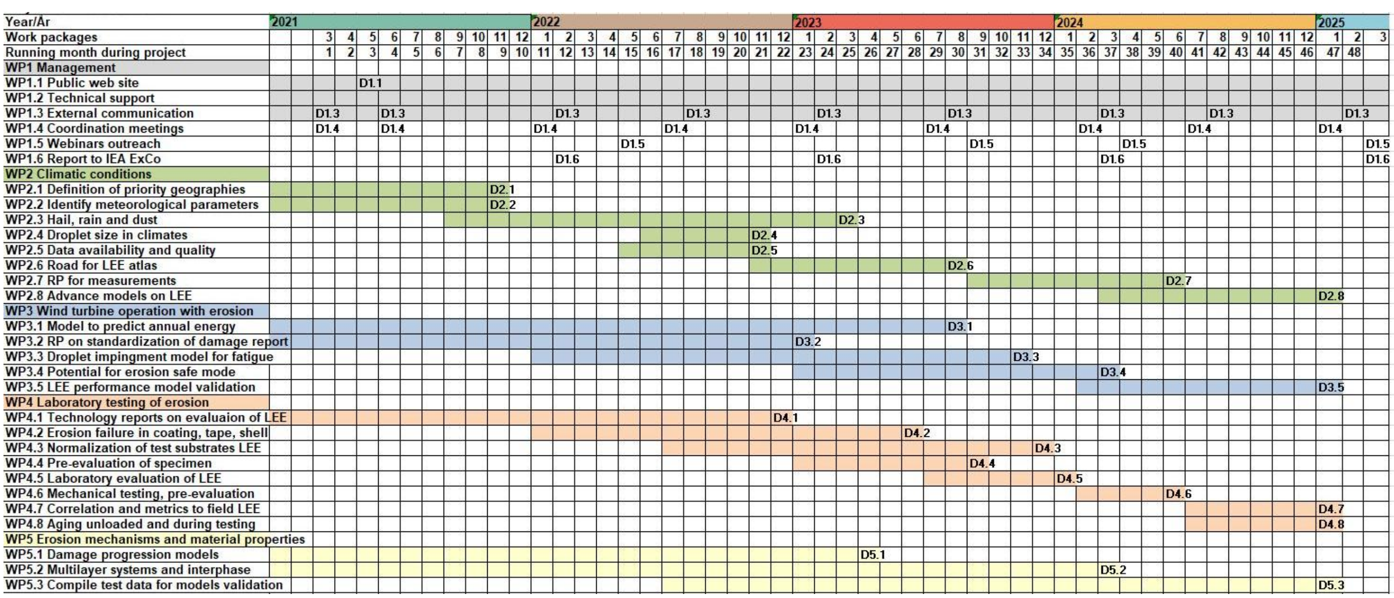
**Task Time Plan and Milestones:** Include milestone table

**Table 1. Milestone Table: Work Plan Milestones, Contributors, and Due Dates**

| No. | Deliverable | Lead organization | Month Due | Status |
|---|---|---|---|---|
| D1.1 | Public website | DTU | 3 | Delivered |
| D1.3, D1.4 | External communications, coordination meetings | OA | 1,4,11,12,17,18,23,24,29,30,36,37,41,42,47,48 | Delivered/On track |
| D1.5 | Webinars | OA | 15,31,38,48 | Delivered/On track |
| D1.6 | ExCo Report | OA | 12,24,37,48 | Delivered/On track |
| D2.1+D2.2 | Pryor et al. Technical Report: Atmospheric drivers of wind turbine blade leading edge erosion: Hydrometeors. | Cornell University | 9 | Delivered |
| D2.3 | Pryor et al. Technical report: Atmospheric drivers of wind turbine blade leading edge erosion: co-stressors | Cornell University | 25 | Delivered |

| | | | | |
|---|---|---|---|---|
| D2.4+D2.5 | Prior et al. "Atmospheric Drivers of Wind Turbine Blade Leading Edge Erosion: Review and Recommendations for Future Research" Energies 2022, 15(22), 8553. | Cornell University | 21 | Delivered |
| D2.6 | Roadmap for LEE atlas | Cornell University | 30 | planned year #3 |
| D2.7 | Recommended practice for measurement of LEE drivers | Cornell University | 40 | planned year #3 |
| D2.8 | Methods to perform V&V on LEE drivers | Cornell University | 47 | planned year #4 |
| D3.1 | Model to predict annual energy production loss on blade erosion class | Sandia National Laboratories | 30 | planned year #3 |
| D3.2 | D3.2 – Maniaci, D.C., MacDonald, H., Paquette, J., Clarke, R. Leading Edge Erosion Classification System | Sandia National Laboratories | 23 | Delivered |
| D3.3 | Droplet impingement model for use in fatigue analysis | Sandia National Laboratories | 33 | planned year #3 |
| D3.4 | Potential for erosion safe-mode operation | Sandia National Laboratories | 37 | planned year #4 |
| D3.5 | Accuracy of LEE performance loss model based on field observations (validation). | Sandia National Laboratories | 47 | planned year #4 |
| D4.1 | Finnegan W., Bech J.I., (Eds.) Technical report: Review on available technologies for laboratory erosion testing | DTU, NUI Galway | 22 | Delivered |
| D4.2 | Erosion failure modes in LE systems (literature review) | DTU | 28 | planned year #3 |
| D4.3 | Normalization of test substrates (recommended practice) | DTU | 34 | planned year #3 |
| D4.4 | Pre-evaluation of test specimens (recommended practice) | DTU | 31 | planned year #3 |
| D4.5 | Test data analysis, damage accumulation and VN curves (recommended practice) | DTU | 35 | planned year #3 |
| D4.6 | Simple mechanical test for screening of key parameters (report) | DTU | 40 | planned year #4 |
| D4.7 | Correlation between RET data and expected field service life (report and model) | DTU | 47 | planned year #4 |
| D4.8 | Aging – unloaded and during testing (literature review and RP) | DTU | 47 | planned year #4 |
| D5.1 | Damage models based on fundamental material properties (report) | Universidad Cardenal Herrera | 26 | pending |
| D5.2 | Multilayer systems (report) | Universidad Cardenal Herrera | 37 | planned year #3 |
| D5.3 | Microstructure and macroscopic material properties (Report) | Universidad Cardenal Herrera | 47 | planned year #4 |

## Figure 1: Schedule: Work Packages, Deliverables, Dates



M**ilestones for past 6 months:**

The deliverables D2.1,D2.2 , D2.3, D2.4, D2.5 D3.2 and D4.1 were completed.

Further, WP5 participants contributed to the European Conference on Composite Materials (ECCM 2022) with a peer-reviewed publication summarizing the multilayer material configurations of Leading Edge Protection (LEP) used in the wind industry, and the modelling techniques used to predict erosion ( Alexandros Antoniou et al "Multilayer leading edge protection systems of wind turbine blades: A review of material technology and damage modelling". Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability. ISBN 978-297016140-0 ).

The Task 46 has been presented in the 4th Erosion Symposium (Feb/2023), by the Operating Agents which communicated the task work and outcomes.

A Task workshop (face to face) was held in Roskilde on the 10th of February, with 29 participants who contributed to plan the incoming deliverables.

A first outreach webinar on 31st May 2022, where progress was presented by the work package leaders and operating agents. The webinar was followed online by 39 attendees.

## 2 Progress Toward Goals

The Task continues advancing according to plan. Key results in 2022 include two main deliverables (technical reports) and two peer-reviewed journals, as well as dissemination in a first outreach webinar and the 3rd Erosion Symposium. The material is available in the Task website https://iea-wind.org/task46/.

## 3 List of Participants

The 39 participating organizations from 12 countries represent the key wind energy actors relevant to the erosion challenge: owners, wind turbine manufacturers, leading edge protection suppliers, and the research community.

The participants are: Engie (Belgium), WEICan (Canada), DTU, Hempel and Ørsted A/S (Denmark), VTT (Finland), Fraunhofer IWES, Covestro, Emil Frei (Freilacke), Nordex Energy, DNV, Mankiewicz and RWE Renewables (Germany), University of Limerick, IT Carlow, and NUI Galway (Ireland), Osaka University, AIST, Tokyo Gas Co. and Asahi Rubber Inc (Japan), TU Delft, Eneco, Suzlon and TNO (the Netherlands), Equinor and University of Bergen (Norway), Aerox, Cener, Nordex Energy Spain, Siemens Gamesa Renewable Energy and University Cardenal Herrera (Spain), ORE Catapult, University of Bristol, Lancaster University, Imperial College London and Vestas Technology UK (United Kingdom), and Cornell University, Sandia National Laboratories and 3M (US).
Table 2: Task participants (next page).

| Country/Sponsor | Participant Organization | Expert Participant | WP2 | WP3 | WP4 | WP5 |
|---|---|---|---|---|---|---|
| Belgium | Engie | Nicolas Quiévy | 1 | 1 | 1 | 0 |
| Canada | WEICan | Marianne Rodgers | 1 | 1 | 0 | 0 |
| | | Jessica Ma | 1 | 1 | 0 | 0 |
| Denmark | DTU | Charlotte Hasager | 1 | 0 | 1 | 0 |
| | | Jakob Ilsted Bech | 0 | 0 | 1 | 1 |
| | | Ásta Hannesdóttir | 1 | 0 | 0 | 0 |
| | | Leon Mishnaevsky | 0 | 0 | 0 | 1 |
| | | Nicolai Frost-Jensen Johansen | 0 | 0 | 1 | 0 |
| | | Ebba Dellwik | 1 | 0 | 0 | 0 |
| | | Christian Bak | 0 | 1 | 0 | 0 |
| | | Ole Bang | 0 | 0 | 1 | 0 |
| | | Anders Smærup Olsen | 0 | 1 | 0 | 0 |
| | | Alexander Meyer Forsting | 0 | 1 | 0 | 0 |
| | | Christian Rosenberg Petersen | 0 | 0 | 1 | 0 |
| | | Coraline Lepre | 0 | 0 | 1 | 0 |
| | Hempel | Pablo Bernad | 0 | 0 | 1 | 1 |
| | | Maral Rahimi | 0 | 0 | 1 | 1 |
| | Ørsted A/S | Marijn Veraart | 1 | 0 | 0 | 0 |
| | | Jacob Kronborg Andersen | | | | |
| Finland | VTT | Raul Prieto | 1 | 1 | 0 | 0 |
| Germany | Fraunhofer IWES | Cate Lester | 0 | 0 | 0 | 0 |
| | | Steffen Czichon | | | | |
| | Covestro | Pantea Nazaran | 0 | 0 | 1 | 1 |
| | | Laura Woods | 0 | 0 | 1 | 1 |
| | Emil Frei (Freilacke) | A Loeffler | 0 | 0 | 1 | 1 |
| | | Heiko Blattert | 0 | 0 | 1 | 1 |
| | | Lena Sühling | 0 | 0 | 1 | 0 |
| | Nordex Energy SE | Steffen Heinz | | | | |
| | DNV | Margarita Ahne | | | | |
| | | Christopher Harrison | | | | |
| | | Amilcar Zambrano | 1 | 1 | 1 | 0 |
| | | Jorge García | 1 | 1 | 1 | 0 |
| | Mankiewicz | Philipp Costa | | | 1 | 1 |
| | | Alexander Weinhold | | | | |
| | RWE | Birgit Junker | | | | |
| | | Sandro di Noi | | | | |
| | | Guillermo Lozano | | | | |
| Ireland | Institute of Technology Carlow | Edmon Tobin | 0 | 0 | 1 | 0 |
| | NUI Galway | William Finnegan | 0 | 0 | 1 | 1 |
| | University of Limerick | Trevor Young | 0 | 0 | 1 | 1 |
| | | Mohammad Ansari | 0 | 0 | 1 | 1 |
| Japan | AIST | Motofumi Tanaka | 1 | 1 | 1 | 1 |
| | | Aya Aihara | 0 | 1 | 0 | 0 |
| | | Hirokazu Kawabata | 0 | 1 | 0 | 0 |
| | Osaka University | Nobuyuki Fujisawa | 0 | 0 | 1 | 0 |
| | | Tomoo Ushio | 1 | 0 | 0 | 0 |
| | TOKYO GAS Co. | Yoko Nishida | 0 | 0 | 0 | 1 |
| | Asahi Rubber Inc. | Nobuyoshi Watanabe | 0 | 0 | 0 | 1 |
| | | Kiyoshi Minegishi | 0 | 0 | 0 | 1 |
| Netherlands | TU Delft | Julie Teuwen | 0 | 0 | 1 | 1 |
| | | Dominic von Terzi | 0 | 1 | 0 | 0 |
| | TNO | Harald van der Mijle Meijer | 1 | 0 | 0 | 0 |
| | | Iratxe Gonzalez Aparicio | 1 | 0 | 0 | 0 |
| | | Henk Slot | 0 | 0 | 0 | 1 |
| Norway | Equinor | Bernt Karsten Lyngvær | 0 | 0 | 0 | 1 |
| | | Helene Konstantia Vrålstad | 0 | 0 | 0 | 1 |
| | | Gunnar Hognestad | 0 | 0 | 0 | 1 |
| | University of Bergen | Bodil Holst | 0 | 0 | 1 | 1 |
| | | Joachim Reuder | 1 | 0 | 0 | 0 |
| | | Stephan Kral | 1 | 0 | 0 | 0 |
| | | Justas Zaliekas | 0 | 0 | 0 | 1 |
| Spain | Aerox | Asta Šakalytė | 0 | 0 | 0 | 0 |
| | Cener | Beatriz Méndez | 0 | 1 | 0 | 0 |
| | Nordex Energy Spain | Elena Llorente | 0 | 1 | 0 | 0 |
| | | Rubén Gutierrez | 0 | 1 | 0 | 0 |
| | | Sergio Diaz | 0 | 0 | 1 | 1 |
| | Siemens Gamesa Renewable Energy | Gemma Gonzalez | 0 | 0 | 0 | 0 |
| | | Jairo Escudero | 0 | 0 | 0 | 0 |
| | | Dimitris Siorikis | | | | |
| | Universidad Cardenal Herrera – CEU | Fernando Sánchez | 0 | 0 | 1 | 1 |
| | | Luis Doménech | 0 | 0 | 0 | 1 |
| UK | ORE Catapult | Kirsten Dyer | 1 | 1 | 1 | 1 |
| | | Hamish Macdonald | 0 | 1 | 0 | 0 |
| | | Peter Kinsley | | | | |
| | | Stephen Jones | | | | |
| | Univ Bristol | Terence Macquart | 0 | 1 | 1 | 0 |
| | | Ian Hamerton | 0 | 0 | 1 | 0 |
| | | Matt Bone | 0 | 0 | 0 | 0 |
| | Lancaster University | Sergio Campobasso | 0 | 1 | 0 | 0 |
| | | Alessio Castorrini | 1 | 1 | 0 | 0 |
| | Imperial College | Hao Hao | 0 | 0 | 0 | 1 |
| | | Alex Taylor | 0 | 0 | 0 | 1 |
| | | Maria Charalambides | 0 | 0 | 0 | 1 |
| | | Yannis Hardalupas | 0 | 0 | 0 | 1 |
| | | Antonis Sergis | 0 | 0 | 0 | 1 |
| | Vestas UK | Tomas Vronsky | | | | |
| | | Francesco Grasso | 0 | 1 | 0 | 0 |
| US | Cornell University | Sara C Pryor | 1 | 0 | 0 | 0 |
| | | Rebecca J Barthelmie | 1 | 0 | 0 | 0 |
| | Sandia National Laboratories | Josh Paquette | 0 | 1 | 0 | 0 |
| | | David C Maniaci | 0 | 1 | 0 | 0 |
| | | Lawrence Cheung | 0 | 1 | 0 | 0 |
| | | Kenneth Brown | 0 | 1 | 0 | 0 |
| | 3M | Benton Free | 0 | 0 | 0 | 0 |

## 4 Statement of Accounts and Value of Contributions

**Status of accounts and cost of participating**:

Unused budget from years #1,#2 ( 11 352 € , travel & other) moved to year #3.

Total fee for year # 3 is 41 643 €. Fee per country is 3 470.25€ ( 12 countries ).

Table 3: Annual Operating Agent Costs
(years #1, #2 and #3)

| Cost item | Annual use (Person-months) | person months VTT | Person months DTU | EUR/Unit VTT | EUR/Unit DTU | EUR/year |
|---|---|---|---|---|---|---|
| Technical support, website & data platform | 0.5 | 0.30 | 0.15 | € 18,400 | € 29,500 | € 9,945 |
| Internal coordination teleconferences | 0.8 | 0.50 | 0.30 | € 18,400 | € 29,500 | € 18,050 |
| Outreach webinars | 0.4 | 0.25 | 0.15 | € 18,400 | € 29,500 | € 9,025 |
| Reporting | 0.4 | 0.25 | 0.15 | € 18,400 | € 29,500 | € 9,025 |
| Travel costs | 3 meetings (2 Task meetings + 1 ExCo) | | | € 1,500 | | € 4,500 |
| Other | website, yearly meeting venue | | | € 2,450 | | € 2,450 |
| **TOTAL** | | | | | | **€ 52,995** |

| | |
|---|---|
| Total fee (accounts for funds transferred from years #1 & 2) | **€ 41,643** |

**Value of in-kind activities.**

The Task has allowed the wind energy community to work together on the complex and multidisciplinary topic of blade erosion. The forum formed by 107 persons from 39 organizations produces not only the deliverables, but also technical discussions in the periodic meetings of the topical work packages, and in the plenary sessions.

The two key outcomes of the task are:

- a deeper knowledge about the erosion topic by the participants, which feeds to the wider energy sector thru the deliverables and the dissemination sessions.

- a strong and well aligned research portfolio in the topic of erosion, thanks to the communication between 39 organizations involved, which helps focus the efforts to solve the challenge.

## 5 New Developments Since Last Report

A description of the crucial meteorological parameters driving blade erosion, as well as the techniques required for field measurements was produced in work package WP2 ( Pryor et al. 2022 IEA Wind Task 46 Technical Report: Atmospheric drivers of wind turbine blade leading edge erosion: Hydrometeors). This technical report was released with an accompanying spreadsheet describing the available public datasets relevant to the characterization of hydrometeors causing erosion ( Pryor et al. 2022 IEA Wind Task 46 Technical Report: Atmospheric drivers of wind turbine blade leading edge erosion: Hydrometeors – accompanying spreadsheet DOI: 10.5281/zenodo.5648211 ).

Also on this topic, the participants produced a peer-reviewed publication ( Pryor et al. 2022 Energies. Atmospheric Drivers of Wind Turbine Blade Leading Edge Erosion: Review and Recommendations for Future Research https://www.mdpi.com/1996-1073/15/22/8553 ).

WP3 progressed on the formulation of a leading edge erosion classification system, aiming at standardizing the assessment of erosion severity in wind turbine blades. The proposed classification was presented in Task plenary meeting in Sept/22 ( David C Maniaci et al "Development of a Standard Erosion Classification System" Proceedings of 4th Plenary meeting of IEA Wind Task 46 Erosion of wind turbine blades, 22-23 September 2022 ), and was delivered in early 2023 (Maniaci, D.C., MacDonald, H., Paquette, J., Clarke, R. (2023) Leading Edge Erosion Classification System ).

Table 4: Proposed Erosion Classification System for wind turbine blades.

| | Severity Level | | | | | |
|---|---|---|---|---|---|---|
| **Evaluation Criteria** | **0** | **1** | **2** | **3** | **4** | **5** |
| **Visual Condition (LEP)** | Initial factory condition | Lightly worn external coating/LEP<br><br>Instances of reduced LEP adhesion | Notable areas of localized damage on external coating/LEP<br><br>Individual Instances of LEP adhesive failure. | LEP is largely compromised over a large area and no longer providing protection to underlying layers | Delamination of topcoat with immediate layer underneath clearly visible and exposed | Notable damage to substrate |
| **Visual Condition (No LEP)** | | Erosion barely visible or pinholes | Localized pitting | Widespread or coherent pits, some gouges | | |
| **Mass-loss** | | Coating <10%, Laminate 0% | Coating 10-50%, Laminate 0% | Coating 50-100%, Laminate <10% | Coating 100% Laminate 10-100% | Coating 100%, Laminate 100% |
| **Aerodynamic Performance** | | Normal surface roughness<br><br>Region 2 Power loss 0 -1% | Region 2 Power loss 1%-2% | Region 2 Power loss 2%-3% | Region 2 Power loss 3-4% | Region 2 Power loss >4% |
| **Blade Integrity** | | Initial erosion of topcoat | Erosion through topcoat | Initial exposure of immediate laminate layers | Erosion through immediate laminate layers | Exposure of structural laminate layers |

WP4 produced a technical report on the review and assessment of technologies employed for laboratory testing of erosion, covering rain erosion tests, impact and fatigue tests, characterization of viscoelastic properties , fracture mechanics of layered properties; and non-destructive and microstructure analysis (Finnegan W., Bech J.I., (Eds.) 2022 Review on available technologies for laboratory erosion testing).

Further, WP5 participants contributed to the European Conference on Composite Materials (ECCM 2022) with a peer-reviewed publication summarizing the multilayer material configurations of Leading Edge Protection (LEP) used in the wind industry, and the modelling techniques used to predict erosion (Alexandros Antoniou et al “Multilayer leading edge protection systems of wind turbine blades: A review of material technology and damage modelling”. Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability. ISBN 978-297016140-0 ).

Table 5: Mean number concentration of rain droplets per unit diameter spectrum (#/m3/mm) for selected sites compared to theoretical distributions Marshall-Palmer and Best. The large differences between sites show that in-situ measurements are required to estimate accurately the effect of erosion in wind turbine blades.

| | RR = 21 $mmhr^{-1}$ | |
|---|---|---|
| Theoretical distribution | R = 1 mm | R = 2 mm |
| Marshall-Palmer | 104 | 1.4 |
| Best | 37 | 2.9 |
| | RR = 21-26 $mmhr^{-1}$ | |
| Observations (probability of precipitation: RR > 0.2 $mmhr^{-1}$ in %) | R = 1 mm | R = 2 mm |
| [&]Norway: Bergen (13%) | 22 | 0.2 |
| [%]Canada: WEICAN (N/A) | N/A | N/A |
| USA: SGP-Lamont (2.4% impact, 3.2% laser disdrometer) | 81 | 3.9 |
| USA: SGP-Billings (3.0%) | 88 | 2.9 |
| [$]UK: Cairngorm (14%) | 42 | 5 |
| [$]UK: Reading (6%) | 71 | 1.1 |
| [$]UK: Weybourne (6%) | 31 | 3.2 |
| [%]UK: NOAH (4.2%) | 42 | 0.01 |
| [%]UK: Levenmouth (6.1%) | 58 | 0.03 |
| Denmark: Horns Rev 2 (5.8%) | N/A | N/A |
| Denmark: DTU-Risoe (3.8%) | 131 | 1.7 |

Regarding work on the characterization of hydrometeors, a key outcome of this analysis is that the characteristics of rain vary significantly across all analysed sites. The mean number concentration of droplets at rain rates 21-26mm/h in droplet radiuses 1mm – 2mm spans a factor of nearly five (showing in general a large departure from the theoretical distributions of Marshall-Palmer and Best).

## 6 Future Milestones

The deliverables planned for year #3 are presented above in table 1.

## 7 Detailed work plan for coming year

The planned activities are to continue the work in the four technical work packages. This work included development of a roadmap to create a methodology to make an atlas for erosion risk. Furthermore, the work will be to provide input to recommended practice on rain-erosion test data analysis to better assess expected lifetime of blade coatings. There will be activity to assess the erosion safe mode operation of turbines to limit erosion during control. Finally, the understanding of damage processes from experiments and modelling will be continued.

# 8 Publications, presentations, dissemination

### Publications, presentations, dissemination

Publications are described above in sections 1 and 5.

### Participation in the Task meetings

Further, the Task 46 held a first outreach webinar on 31st May 2022, where progress was presented by the work package leaders and operating agents. The webinar was followed online by 39 attendees.

Task 46 started in March 2021, ramping up the work in the context of the pandemic. It was only in September 2022, that the first face-to-face plenary meeting took place, hosted by Ørsted A/S in Copenhagen. There were 22 participants participating on site, and many others joined remotely.

Figure 2: Photo: Task 46 plenary meeting in Copenhagen hosted by Ørsted A/S.