INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

Topical Expert Meeting #98 on

Erosion of Wind Turbine Blades

IEA Wind Task 11

February 6-7, 2020

DTU Risø Campus, Roskilde, Denmark

Source : Vestas

Technical Lead and Host:
Raul Prieto – VTT Technical Research Centre of Finland
Joshua Paquette – Sandia National Laboratories
Leon Mishnaevsky – DTU Wind Energy

Operating Agent:
Nicolas El Hayek – Planair SA

Disclaimer:

Please note that these proceedings may only be redistributed to persons in countries participating in the IEA Wind TCP Task 11.

Participating countries are contributing financially and in-kind for this work and are therefore expecting that the results of their efforts stay within this group of countries.

The list of countries to which the documentation can be distributed is available in Appendix Five.

After one year the proceedings can be distributed to all countries, that is February 2021.

Copies of this document can be obtained from:

PLANAIR SA
Rue Galilée 6, 1400 Yverdon-les-Bains, Switzerland
Phone: +41 (0)24 566 52 00
E-mail: ieawindtask11@planair.ch

For more information about the IEA Wind TCP please visit www.ieawind.org.

Table of Contents

Executive Summary of TEM#98

Introduction

Wind turbine blade lifetime and performance are two central concerns for wind farm operators and blade manufacturers. Leading edge erosion has been identified as the main factor substantially reducing both blade lifetimes and energy output over time. The topic of leading edge erosion is highly multidisciplinary, with progress relying on a wide range of technologies and skills. Despite the large effort made by fundamental as well as advanced research worldwide, the phenomenon is not yet entirely understood and no satisfactory solution has been found so far.

Leading edge protective solutions currently in use by the industry (polyurethane coatings, polyurethane protective tape) degrade aerodynamic efficiency, can fail relatively early or require low, sub-optimal blade tip speeds to endure the envisaged operational lifetime of the turbines (beyond 20 - 25 years). Additionally, field repairs are costly due to lost availability and challenging access, work and weather conditions. It is estimated that the cost of blade erosion in terms of Net Present Value (NPV) of incurred costs and losses is in the order of 2-3% of the gross energy yield generated by the turbine over its lifetime. Finally, at the wind farm planning stage, the lack of validated methods to estimate the overall cost of erosion depending on various parameters such as the environment or weathering causes uncertainty in the investment decisions.

The objective of the International Energy Agency (IEA) Topical Expert Meeting (TEM) number 98 was to address this multidisciplinary topic by engaging in technical discussion on; drivers and causes of leading edge erosion, and which technologies and business practices have greatest promise in tackling blade erosion. Building on the presentations given during the preceding Symposium, TEM#98 aimed at understanding the near term and future needs and setting the scope for international collaboration.

Meeting Overview

TEM#98 on the Erosion of Wind Turbine Blades was hosted by VTT and DTU at its Risø Campus in Roskilde, Denmark on February 6th and 7th, 2020. It was convened by Raul Prieto and Josh Paquette, from VTT (Finland) and Sandia National Laboratories (USA) respectively. The event was co-located with the DTU International Symposium on Leading Edge Erosion of Wind Turbine Blades which took place at the same location from February 4th to 6th.

A total of 29 participants with expertise in the various areas of wind turbine blade erosion and stemming from research institutes, wind park and system operators, wind turbine OEMs and industry actors were in attendance. 14 presentations were given to complement the overview gained during the preceding Symposium and cover the following areas of blade erosion:

- Atmospheric modeling
- Droplet & particle trajectory physics
- Erosion mechanics
- Material properties & models
- Coating validation
- Erosion detection, classification & forensic analysis
- Economic losses associated to erosion

Specific discussions were then conducted in three smaller groups (erosion mechanics & material innovation; failure modes, testing & validation; effect of meteorological conditions and particle aerodynamics) to identify the key topics and prioritize the research areas for collaborative research. It resulted in a consensus to propose a new IEA Wind task on the erosion of wind turbine blades.

Main Results

The IEA TEM#98 has been a tool to exchange results and insights in the key topic of blade erosion among the participants.

Relevant R&D efforts in projects such as COBRA, BeLeB, BLEEP, DURALEDGE, EROSION, are shedding light on different aspects of this complex multidisciplinary problem. What is now needed is an international synthesis mechanism to integrate these insights and identify new research avenues.

Presentations from the TEM participants, as well as the co-located Erosion Symposium have demonstrated remarkable efforts are being undertaken by industry and academia to address the problem, and contributed greatly to set the scene before the breakout sessions.

These sessions have allowed firstly to grasp the vast range of topics playing a role in solving the problem, and secondly to help identify areas where the IEA Wind TCP could contribute.

The following key aspects were noted:

- Characterization of the meteorological drivers of erosion: the datasets of meteorological variables need to be collected at the relevant time scale, and harmonized in order to serve as input for the key aggregated metrics representative of erosion.
- An erosion classification of wind farm sites is deemed feasible.
- Laboratory testing of erosion requires still substantial effort to harmonize practices regarding equivalence of testing conditions to the field, comparability of results among test centres, preparation of samples, quality control and classification of observed damage.
- Erosion damage models, specific to different leading edge systems (coatings, shells, tapes, metallic shield), require well characterized material properties in the relevant time scale; as well as treatment of the interfaces between layers.
- Material microstructure resulting from the manufacturing/application process is essential driver of the observed macroscopic erosion properties
- The study of aerodynamic impingement is relevant to estimate the impact speed of particles/droplets and number of particles reaching the surface of the blade. It is an element of the modelling chain required to estimate erosion.
- The aerodynamic modelling of leading edge roughness is a prerequisite to the estimation of performance degradation associated to erosion.

Table 1 in the section “Conclusions & Next Steps” has been produced from the breakout session notes, and shows the possible scope of work for an IEA Task. The potential scope of work could cover the following overarching topics:

- Atmospheric conditions driving blade erosion
- Mitigating erosion with wind turbine control
- Particle impingement for erosion damage models
- Wind turbine performance in the context of erosion; effect of LE roughness
- Laboratory testing of erosion with a high fidelity and normalized process
- Erosion mechanics
- Material properties, microstructure and innovations

Summary of Presentations

The information in this section provides an overview and selected highlights of each of the presentations given during the meeting.

All presentations from TEM#98 are available on the IEA Wind website, on the TEM#98 community page. Access for download can be requested from the Task 11 Operating Agent.

Day 1: February 6, 2020

Introduction and General Framework

Raul Prieto from VTT welcomed all participants and thanked DTU for hosting the meeting at their premises. He then reminded briefly the agenda and gave the word to the next speaker.

Ignacio Marti from DTU, Executive Secretary of the IEA Wind TCP, provided an overview of the IEA Wind TCP. Background information and brief history were presented, and the value of participating to the TCP was highlighted: the IEA Wind is widely recognized and supports decision makers across the whole world through collaboration with the IEC towards standards. The participating countries can share experience on new technologies and work together to resolve the problems they face. The TCP relies on no external funding and hence ensures a truly independent exchange of information. Active Tasks and the Strategic plan 2019-2024 were also presented.

Nicolas El Hayek from Planair SA (Task 11 Operating Agent) gave a deeper insight into Task 11. Its operating agents and their activities were presented, covering Topical Expert Meetings, the Community Platform and Recommended Practices. In particular, the upcoming TEMs for 2020 on Floating Offshore Wind Arrays and Aviation System Cohabitation were advertised.

Technical Presentations

Leon Mishnaevsky from DTU summarized the conclusions drawn during the Symposium and listed the many topics tackling blade erosion. He highlighted the typical challenges and indicated the five work directions that were identified. He concluded by answering the question “What can we learn from modelling?” and presented the main directions and their outputs. The most promising ones are structured coatings, AI & data management and the inclusion of manufacturing defects in models.

Kirsten Dyer from ORE Catapult presented a research plan including industry needs: lifetime prediction and material solutions. She highlighted the role of recovery and stressed the need to understand real damage types and to standardize data analysis. The main challenge is to make rain erosion tests as close to reality as possible.

Nikolai Grishauge from SGRE described how the failure modes caused by rotating arm rain erosion tests, with realistic speeds but accelerated rain, correlate well with field data (DuraLedge project). He presented state of the art modelling and mentioned further research needs towards understanding the governing parameters of blade erosion. According to him, the Cobra project represents a good starting point. Finally, he presented the existing leading-edge protection (LEP) types and research needs in this area as well, which lie mainly in the need for standardization within the industry.

Fernando Sánchez from University Cardenal Herrera – CEU started on presenting current results of his research on material properties and modelling; he tackled the erosion problem as an acoustic problem, investigating stress transmission through the different layers of a rigid body (blade model). This approach allows to decomplexify the model, and separates fatigue in two distinct categories: wear and delamination. Internal defects (bubbles) and their damping effect on the strain in LEP multilayer systems especially raised the interest of the audience.

Sara C Pryor from Cornell University provided an overview and assessment of use of the Weather Research and Forecasting (WRF) tool to estimate the leading-edge erosion (LEE) potential of a given location for current and future conditions. Results of simulations for the USA showed that, in regions prone to hail events, a curtailment of the turbine for 95 minutes per year could reduce the energy transfer from the environment to the blade by 96%! Forecasting these events could therefore contribute greatly to erosion mitigation. The open questions remain: which level of accuracy is required by the industry? Could the current works lead to a global LEE atlas?

Francesco Grasso from Vestas presented aerodynamic perspectives on blade erosion. He explained how erosion reduces the annual energy production (AEP) of wind turbines by increasing the drag on the blades due to the anticipated transition to a turbulent flow. Monitoring of the aerodynamic performance can therefore serve a maintenance strategy and reduce losses. After having presented five erosion classes and the challenges of testing and simulations, he concluded by highlighting the need of novel aerofoil designs that complement leading-edge protection (LEP) to anticipate erosion instead of only reacting to fix it.

Motofumi Tanaka from the National Institute of Advanced Industrial Science and Technology provided an Asian perspective on the current and future market, on the erosion and on activities tackling it in Japan. He raised the question of the transferability of western models to the Japanese context by presenting the numerous words used to describe "rain" in Japanese. Moreover, the topic of the effect of extreme events such as typhoons, which have a high occurrence, was mentioned. He concluded by presenting research activities and existing solutions against erosion, some of which have shown good durability for almost 10 years, and by stressing the need for collaboration between mature and younger markets.

David Maniaci from Sandia National Laboratories attempted to quantify the impact of leading-edge erosion (LEE) on the annual energy production (AEP). He showed various empirical (experimental data is publicly available) as well as numerical models, presenting the important parameters such as the Reynolds number or the turbulence intensity. The predicted loss for a reduction of 30% of the lift to drag ratio would lead to an AEP loss of up to 5% for wind classes II (IEC). The challenges in his view are the standardization of the LEE classification, and the inclusion of erosion in the cost model for wind projects from the start.

Day 2: February 7, 2020

Technical Presentations

Joshua Paquette from Sandia National Laboratories summarized the outcomes of the IEA Wind Topical Expert Meeting (TEM) #91 on the durability and damage tolerant design of wind turbine blades. The TEM, held in Bozeman, Montana in June 2018, brought together the wind and aerospace communities to identify synergies and differences and learn from each other's experience. It established a list of requirements on modeling & testing, manufacturing & inspection, operations and standards. For erosion, three main elements are wished: the analysis of the effects of leading-edge erosion (LEE) on the annual energy production (AEP), a better understanding of the environmental conditions and a geospatial mapping of erosion potential zones.

Gemma Gonzalez from SGRE presented the expectations of the industry regarding advanced leading-edge protection (LEP) materials, which she summarized in two key properties of LEP materials: they should be erosion resistant and easy to clean. First tests in a dirt tunnel (on its way to standardization) to assess the dirt accretion level of different material coupons were conducted, and field tests are planned for 2020. The ultimate goal is to classify erosion and dirt accretion to evaluate their contribution to annual energy production (AEP) losses and on wind turbine noise.

Poul Hummelshoj from METEK Nordic talked about a novel concept which aims at bridging a gap between the research and the industry: the use of a micro rain radar (MRR) to forecast precipitation events on a minute scale ("nowcast") and prevent erosion by curtailing the wind turbines during heavy weather events. He showed how the use of an existing technology, which robustness has been proven on the field, could represent a cost-effective solution to massively reduce erosion. Investigations and adaptation of the hard- and software are ongoing, and any input from the wind industry would be welcome.

Rebecca J Barthelmie from Cornell University was substituted by Sara Pryor, who showed the strong overlap between the spatial distribution of installed wind power capacity, wind, precipitation and hail in the US. The increasing size of wind turbine rotors, leading to higher tip speeds, increases also the erosion of the blades. Initial assessment of NWS Radar to estimate leading-edge erosion (LEE) potential based on kinetic energy transfer and taking into account hydrometeor sizes showed the excellent potential for the establishment of a global LEE atlas. Validation of the methodology is still pending.

Breakout Session Notes

The breakout session of Friday morning saw the participants split into three groups to discuss the state-of-the-art, identify research gaps and needs for future collaboration in the following three areas:

- Erosion mechanics and material innovations
- Failure modes, testing and validation
- Effect of climate and particle aerodynamics

The outcomes of each group were presented to and discussed with the full group. The following section provides a consolidated summary of the thoughts and notes from each of the focus groups. Raw notes from each of the three groups is provided in Appendix Four.

Erosion mechanics and material innovations moderated by Fernando Sánchez, CEU, reported the following key areas for future research:

1. Degradation model. Analytical and numerical models predicting the coating failure mode (surface wear or coating interface delamination) and key erosion metrics such as the incubation time or the rate of mass loss.

    A. Damage model specific/generic for liquid coatings, shells, tapes: degradation models may be a generic function of the operational conditions (impact velocity, droplet size, number of impacts per unit surface) but also specific to different erosion protective solutions. Different erosion protective solutions may be susceptible to specific failure modes and therefore require individualized modelling approach.

2. Leading edge protection (LEP) integration to the blade refers to the challenge of integrating the erosion protective material into the blade structure, namely the composite substrate of the leading edge. The state of the art in LEP being considered by the industry ranges from liquid LEP (coatings), tapes, flexible shells, and metallic LEP. In each case, integration in the blade results in a multilayer system which affects erosion performance differently depending on the layout.

    A. Multilayer system. Acoustic matching. Stress-wave dissipation. The consideration of the leading edge as a multilayer system, and the different modelling approaches. Modelling stress wave propagation including the effect of varying the acoustic impedances in the materials (acoustic matching). Reproducing the dissipation of stress waves.
    B. Interface/interphase chemical interactions and compatibility. Understanding the role of the interphase between different layers. Understanding the possible chemical interaction between layers; and between the leading edge and chemical compounds transported to the leading edge by wind and precipitation.
    C. Manufacturability. In-mould, out-mould, shell, repair. Progress in the integration of protective solutions in the manufacturing process of the blade. Investigating the relationship between application process, microstructure and resulting erosion performance. Constrains in the formulation related to the surface preparation and coating application process in the factory and in the field. Effectiveness of field repairs in terms of erosion resistance.

3. Material & interface testing, refers to specific challenges in materials science in the context of blade erosion:
    A. Microstructure polymer analysis. Correlation with macroscopic material properties. Effect of fillers, additives, polymer composition. Use of the most

suitable techniques to analyse the microstructure of polymers / materials, considering new samples as well as preconditioned and eroded samples. Investigating the effect of additives and fillers. Formulating and validating a theory which connects the observed macroscopic behavior with the polymer composition and microstructure.

B. Fatigue, high strain rate, interface-fracture energy. Characterization of material properties when materials are stressed in a characteristic time scale of microseconds which covers the impact and subsequent formation and evolution of stress waves. Understanding the drivers of the leading edge fatigue damage process, specifically the fatigue process in the interface between layers.

C. Ageing degradation, refers to the challenge of characterizing an extremely complex weathering cycle spanning across 20 - 25 years, combining the effect of precipitation, salt & chemicals transported to leading edge; solar radiation, and freeze-thaw cycles. Definition of an ageing test setup which is representative of the operational environment.

D. Input parameters for modelling, refers to the challenge of measuring the variables required to feed and validate the erosion models. This characterization may be difficult even in the controlled environment of a rain erosion test rig.

E. Define criteria for Key material & interface parameters, the key metrics representative of the erosion performance of the individual materials and the complete leading edge system need to be established.

Failure modes, testing & validation moderated by Rasmus Konge Johansen, Polytech.

In the context of the validation of erosion solutions by means of testing in controlled environments, the following aspects are considered relevant areas for future research or normalization:

1. Test specimens, definition of the test coupons.
    A. Standardized substrates. Normalization effort to define a set of standard substrates (this could be addressed with a Recommended Practice).

2. Manufacturing defects.
    A. Pre-evaluation of specimens for defects (Guideline / Recommended Practice)
3. Erosion testing, determination of representative test conditions from field measurement:
    A. Droplet diameter (already being addressed in the project *Erosion*, in Denmark)
    B. water flow, impact speed, air temperature
    C. Hail, representative conditions to test hail and sand events
    D. Sand, likewise
    E. Number of impacts (ensure that the number of impacts is well estimated, possible Recommended Practice)
    F. Aging
        1. Radiation type: UVA, UVB, Visible spectrum, use of Xenon.
        2. Salt mist
        3. Temperature
    G. Test cycles combining aging and RET, to achieve more realistic profile of erosion and weathering (this is being addressed by Cobra project)

   H. Test sequence
   I. Study of the recovery time from aging period to rain erosion (ORE Catapult has worked in this topic)
4. Evaluation of eroded specimens
   A. Definition of failure modes
   B. Quantitative evaluation: roughness, surface scanning
5. Repeatability
   A. Number of samples required
   B. Test facility to test facility variation
   C. RET test to field correlation: Estimating the erosion performance in the field from RET tests.

Effect of climate and particle aerodynamics moderated by Sara C Pryor, Cornell University.

Statement of objective: To advance (1) understanding of the atmospheric drivers of wind turbine blade leading edge erosion (2) quantification of geospatial variability of those drivers (3) metrology to better quantify leading edge erosion and (4) actions to mitigate leading edge erosion.

IEA relevance: IEA is essential as a mechanism to: 1) stimulate research, 2) coordinate research, 3) enable standardization, and 4) provide an 'endorsement' for those seeking research funding. IEA may also provide; 5) a mechanism for open data sharing following FAIR data principles (with discussion regarding actual data repository location pending).

Objective 1: To characterize erosion-relevant properties geospatially/temporally and generate layers (with quality index/uncertainty) for inclusion in a manner similar to the Global Wind Atlas (https://globalwindatlas.info/). Potentially this could be presented in erosion classes (akin to the old wind mean power density classes). The following is a roadmap that could be employed to achieving this goal and laying that foundation.

Objective 1. Step 1: Identify areas of high priority to LEE characterization;

(a) Areas of existing high installed capacity: Northern Europe (including North Sea) and Central Plains of the USA.
(b) Emerging markets: Offshore: US east coast, Taiwan, Japan, Onshore: China, Brazil, parts of Africa.

These both allow targeted research (and make the problem tractable) AND also allow consideration of very different climate regimes.
IEA products:

- Brief statement of selection criteria and regional specification.

Objective 1. Step 2: Prioritize which parameters are most crucial to WT blade LEE & build a hierarchy of additional meteorological parameters that also need to be considered.
Activity: Identify which data streams are available (e.g. from in situ instruments, RADAR, satellite observations and potentially meteorological model output) in the priority geographic areas for the following key parameters for climatologically relevant time spans

- Marginal probability distributions of wind speed
- Marginal probability of precipitation type and intensity.
- Joint probability distribution of wind speed and precipitation (hail, liquid precipitation) at high frequency. Note a key research question is (key question is: how long is long enough to characterize accurately/robustly the precipitation climate & joint probability with wind?).

- Precipitation droplet size distributions. This is essential to test the generalizability of existing droplet models (Marshall-Palmer, Best…) develop 'better' droplet size distribution models appropriate for different regions/seasons.

Note a component of this will be to characterize the inherent spatial scales of variability of each parameter. This will help to identify the needed or possible spatial resolution of the atlas. Once the above have been collated the suite of variables will be expanded to include additional properties that may be key to aging (or accelerating damage): e.g. UV (A,B,C), wind-blown dust, humidity, dry spell length, thermal cycling, freeze-thaw…... etc.
IEA products:

- Literature review of; to what extent has erosion from hail, rain & wind-blown dust been documented/demonstrated in target areas
- Literature review of; data availability/quality for key atmospheric parameters of relevance for LEE.
- Literature review of; droplet size distribution as a function of prevailing climate

Note: A co-benefit of improved understanding precipitation climate (e.g. precipitation frequency dry-spell length) will be enhanced understanding of potential AEP loss from soiling.

Objective 1. Step 3: Identify and CLOSE key knowledge and data gaps and standardize and harmonize data.
Activity: Apply standardized QA/QC for key parameters – note this is different from standard WMO QA/QC for meteorological data because we would emphasize quality where it counts for LEE (e.g. precipitation under high winds)

- Quantify uncertainty & spatial scales of variability.
- Quantify data completeness for existing data

IEA products:

- Report on best practice for use of meteorological data for determining LEE classes
- Report on a roadmap for a leading-edge erosion maintenance atlas

Objective 2: Metrology development and evaluation.

Objective 2. Task 1: There is a need to stimulate and enhance instrumentation innovation and to conduct rigorous evaluation for improved characterization of key atmospheric parameters of relevance for LEE.
Activity: Design of inter-comparison experiments. Possible sites for instrumentation inter-comparison and robustness activities could be (i) Onshore: US Department of Energy ARM site in Oklahoma (for high wind, high hail, heavy rainfall) and (ii) Offshore: Østerild in Denmark (characteristic of offshore, northern Europe). Any system is to be identified as standardized best practice for site assessment should be able to cope with both!
IEA products:

- Report on establishing best practice for measurements of LEE drivers.
- Report describing needed metrology development and prospects for establishing 'super sites' for product testing

Objective 2. Task 2: Design a coordinated project designed to assess viability and cost-benefit of leading edge erosion safe mode operation.
Task: Articulate possible approach. The information cascade could be as follows: 1) Day ahead forecasts of LEE potential (e.g. from WRF) to aid with planning of next day supply to market. 2) Near-term warning of potential for LEE from regional RADAR (or similar). 3) Dynamic operation of wind farm from micro-RADAR (or similar) for 'now casting'.
IEA products:

- Report describing potential for leading edge erosion safe mode operation for use in seeking participation from industry and research funders.

Objective 3: Improve understanding of aerodynamics of droplet impingement and LEE roughness. The following is a roadmap that could be employed to achieve this goal. The results will enable owner-operators to make an educated, data based decision on when to make a repair, add protection, or invest in other blade add-ons.

Objective 3. Step 1: Characterization of aerodynamics for droplet impingement probability.
Activity: Develop a standard model for droplet impingement, validated with wind tunnel experimental data.
IEA product:

- Droplet impingement model for use in fatigue analysis.

Objective 3. Step 2: Quantification of performance degradation (loss of AEP) as a function of roughness and 'erosion climate'.
Activity: Standardization of damage reports for validation of any erosion potential assessment and to allow effective integration of data from operators with laboratory derived estimates. Develop a common model of aerodynamic performance loss due to leading edge roughness and erosion standardized classes.

IEA product:

- Recommendations regarding standardization of damage reports based on erosion observations.
- Model to predict annual energy production loss based on blade erosion class.

Objective 3. Step 3: Validation of performance loss model using wind tunnel and field observations.

Activity: Carry out iterative aerodynamic loss benchmarks with model development and new wind tunnel testing for calibration and validation. Validation of complete performance loss model using probabilistic analysis of field observations. Adapt models to simulate high roughness values (up to P20).

IEA product:

- Report on the quantified accuracy of leading edge erosion performance loss model based on field observations. Validation cases will include roughness values from low to severe roughness.

Conclusions & Next Steps

The participants agreed on the fact that wind turbine blade erosion is a complex, multidisciplinary topic that would benefit from international collaboration. In fact, a large number expressed interest in the formation of a new IEA Wind Task.

Table 1 (next page) is intended as a starting point for a discussion on the scope of a Task proposal. It summarizes objectives linked to the identified topics of interest and proposes a list of deliverables to reach each of the objectives.

Discussions among the many interested parties will be led by Raul Prieto of VTT, and will continue during May-August aiming at a proposal to be presented at the autumn Executive Committee meeting.

A tentative schedule is outlined below:

- Week 21 (18th May) Request for expressions of interest from participants (opening of collaborative workspace to contribute to task scope)
- Week 24 (8th June) review session of Task proposal - draft (teleconference)
- Week 32 (5th Aug) 2nd review session of Task proposal – final (teleconference)
- Week 35 (26th Aug) Task proposal submitted to ExCo for consideration

Topic	Overarching objectives	Scope	IEA Product
Climatic conditions driving blade erosion	To characterize erosion-relevant properties geospatially/temporally and generate layers (with quality index/uncertainty) for inclusion in a manner similar to the Global Wind Atlas). Potentially this could be presented in erosion classes.	Step 1: Identify areas of high priority to LEE characterization; (a) Areas of existing high installed capacity: Northern Europe (including North Sea) and Central Plains of the USA. (b) Emerging markets: Offshore: US east coast, Taiwan, Japan, Onshore: China, Brazil, parts of Africa. These both allow targeted research (and make the problem tractable) AND also allow consideration of very different climate regimes.	Definition of high priority geographic areas for erosion mapping: Brief statement of selection criteria and regional specification. (Report)
		Step 2: Prioritize which parameters are most crucial to WT blade LEE & build a hierarchy of additional meteorological parameters that also need to be considered. Activity: Identify which data streams are available (e.g. from in situ instruments, RADAR, satellite observations and potentially meteorological model output) in the priority geographic areas for the following key parameters for climatologically relevant time spans • Marginal probability distributions of wind speed • Marginal probability of precipitation type and intensity. • Joint probability distribution of wind speed and precipitation (hail, liquid precipitation) at high frequency. Note a key research question is (key question is: how long is long enough to characterize accurately/robustly the precipitation climate & joint probability with wind?). • Precipitation droplet size distributions. This is essential to test the generalizability of existing droplet models (Marshall-Palmer, Best…) develop 'better' droplet size distribution models appropriate for different regions/seasons.Note a component of this will be to characterize the inherent spatial scales of variability of each parameter. This will help to identify the needed or possible spatial resolution of the atlas. Once the above have been collated the suite of variables will be expanded to include additional properties that may be key to aging (or accelerating damage): e.g. UV (A,B,C), wind-blown dust, humidity, dry spell length, thermal cycling, freeze-thaw. etc.	Definition of crucial erosion parameters, and additional meteorological parameters (Report) Listing of reference data streams for meteorological parameters (Report) Literature review of; to what extent has erosion from hail, rain & wind-blown dust /sand been documented/demonstrated in target areas (Report) Literature review of; data availability/quality for key atmospheric parameters of relevance for LEE (Report) Literature review of; droplet size distribution as a function of prevailing climate (Report)
		Step 3: Identify and CLOSE key knowledge and data gaps and standardize and harmonize data. Activity: Apply standardized Quality Assurance / Quality Control for key parameters – note this is different from standard WMO QA/QC for meteorological data because we would emphasize quality where it counts for LEE (e.g. precipitation under high winds) • Quantify uncertainty & spatial scales of variability. • Quantify data completeness for existing data	Best practice for use of meteorological data for determining LEE classes (Report) Roadmap for a leading-edge erosion atlas (Report)
	Metrology development and evaluation.	Step 1: There is a need to stimulate and enhance instrumentation innovation and to conduct rigorous evaluation for improved characterization of key atmospheric parameters of relevance for LEE. Activity: Design of inter-comparison experiments. Possible sites for instrumentation inter-comparison and robustness activities could be (i) Onshore: US Department of Energy ARM site in Oklahoma (for high wind, high hail, heavy rainfall) and (ii) Offshore: Østerild in Denmark (characteristic of offshore, northern Europe). Any system is to be identified as standardized best practice for site assessment should be able to cope with both!	Report on establishing best practice for measurements of LEE drivers (Report). Report describing needed metrology development and prospects for establishing 'super sites' for product testing (Report)
Mitigating erosion with wind turbine control	Erosion Safe mode operation of wind turbines	Design a coordinated project designed to assess viability and cost-benefit of leading edge erosion safe mode operation. Task: Articulate possible approach. The information cascade could be as follows: 1) Day ahead forecasts of LEE potential (e.g. from WRF) to aid with planning of next day supply to market. 2) Near-term warning of potential for LEE from regional RADAR (or similar). 3) Dynamic operation of wind farm from micro-RADAR (or similar) for 'nowcasting'.	Report describing potential for leading edge erosion safe mode operation for use in seeking participation from industry and research funders (Report).
Particle impingement for erosion damage models	Improve understanding of aerodynamics of droplet impingement	Step 1: Characterization of aerodynamics for droplet impingement probability. Activity: Develop a standard model for droplet impingement, validated with wind tunnel experimental data.	Droplet impingement model for use in fatigue analysis (Report).
Wind turbine performance in the context of erosion; effect of LE roughness	Improve understanding of aerodynamics of LEE roughness. The results will enable owner-operators to make an educated, data based decision on when to make a repair, add protection, or invest in other blade add-ons.	Step 2: Quantification of performance degradation (loss of AEP) as a function of roughness and 'erosion climate'. Activity: Standardization of damage reports for validation of any erosion potential assessment and to allow effective integration of data from operators with laboratory derived estimates. Develop a common model of aerodynamic performance loss due to leading edge roughness and erosion standardized classes.	Recommendations regarding standardization of damage reports based on erosion observations (Report). Model to predict annual energy production loss based on blade erosion class (model)
		Step 3: Validation of performance loss model using wind tunnel and field observations. Activity: Carry out iterative aerodynamic loss benchmarks with model development and new wind tunnel testing for calibration and validation. Validation of complete performance loss model using probabilistic analysis of field observations. Adapt models to simulate high roughness values (up to P20).	Report on the quantified accuracy of leading edge erosion performance loss model based on field observations. Validation cases will include roughness values from low to severe roughness. (Report)
Laboratory testing of erosion with a high fidelity and normalized process	Definition of the test coupons / test specimens	Standardized substrates. Normalization effort to define a set of standard substrates.	Recommended practice on standardization of test substrates for rain erosion testing (Recommended practice)
	Control of manufacturing defects in rain erosion testing	Pre-Evaluation of specimens for defects	Recommended practice on pre-evaluation of test specimens before rain erosion testing (Recommended Practice)
	Erosion testing, determination of representative test conditions from field measurement:	Droplet diameter (already being addressed in the project Erosion, in Denmark), water flow, impact speed, air temperature , number of impacts	Generation of rain erosion test parameters from meteorological parameters & reference wind turbine operational conditions (Recommended practice)
		Procedure for aging of RET samples (solar radiation UVA, UVB, Xenon, salt mist and temperature cycles)	Procedure for aging of RET samples from reference meteorological parameters conditions (Recommended practice)
		Representative test conditions to test hail events	Lab testing hail events in wind energy (Recommended Practice)
		Representative test conditions to test dust/sand events	Lab testing dust/sand events in wind energy (Recommended Practice)
	Test repeatability	Number of samples required	Brief note / Recommended Practice
	Laboratory-to-field correlation	Estimating the erosion performance in the field from RET tests.	Correlation model to read accross laboratory erosion metrics to field erosion metrics (model)
	Evaluation of eroded specimens	Classification of erosion failure modes (surface wear, delamination, etc)	Literature survey: erosion failure modes in leading edge systems: coating, tape, shell (Report).
		Quantitative evaluation of eroded samples (roughness, scanning, etc)	Available technologies report: laboratory evaluation of erosion (Report)
Erosion mechanics	Damage models	Damage model Specific/generic for Liquid coatings, shells, tapes: Degradation models may be a generic function of the operational conditions (impact velocity, droplet size, number of impacts per unit surface) but also specific to different erosion protective solutions. Different erosion protective solutions may be susceptible to specific failure modes and therefore require individualized modelling approach.	Literature survey on damage models for rain erosion, applicability to coatings, shell, tape, metallic. (Report)
	Multilayer systems	Multilayer system. Acoustic matching. Stress-Wave dissipation. The consideration of the leading edge as a multilayer system, and the different modelling approaches. Modelling stress wave propagation including the effect of varying the acoustic impedances in the materials (acoustic matching). Reproducing the dissipation of stress waves. Interface/interphase chemical interactions and compatibility. Understanding the role of the interphase between different layers. Understanding the possible chemical interaction between layers; and between the leading edge and chemical compounds transported to the leading edge by wind and precipitation.	Literature survey on multilayer systems: interphase modelling (Report).
Material properties, microstructure and innovations	Material properties for modelling of erosion	Input parameters for modelling, refers to the challenge of measuring the variables required to feed and validate the erosion models. This characterization may be difficult even in the controlled environment of a rain erosion test rig. Further, there is the characterization of material properties when materials are stressed in a characteristic time scale of microseconds which covers the impact and subsequent formation and evolution of stress waves.	Literature survey on available test data for materials relevant to the erosion process. (Report)
	Microstructure and macroscopic properties	Microstructure polymer analysis. Correlation with macroscopic material properties. Effect of fillers, additives, polymer composition. Use of the most suitable techniques to analyse the microstructure of polymers / materials, considering new samples as well as preconditioned and eroded samples. Investigating the effect of additives and fillers. Formulating and validating a theory which connects the observed macroscopic behavior with the polymer composition and microstructure.	State of the art in polymers and additives (Report)

Table 1: Draft plan for and IEA Task: topics, objectives, scope and deliverables identified from the breakout sessions.

APPENDIX ONE – TEM#98 Introductory Note

INTRODUCTORY NOTE

IEA WIND TASK 11 TOPICAL EXPERT MEETING # 98

ON

EROSION OF WIND TURBINE BLADES

Raul Prieto – VTT Technical Research Centre of Finland

Joshua Paquette – Sandia National Laboratories

BACKGROUND

Leading edge protective solutions currently in use by the industry (polyurethane coatings, polyurethane protective tape) fail relatively early or require low, sub-optimal blade tip speeds to endure the envisaged operational lifetime of the turbines (20 years onshore, 25 years offshore).

Field repairs are costly due to lost availability, and challenging access, work and weather conditions. It is estimated that the cost of blade erosion in terms of NPV is in the order of 2-3% of the gross energy yield generated by the turbine during its lifetime.

Finally, at the wind farm planning stage, the lack of validated methods to estimate the overall cost of erosion, causes uncertainty in the investment decisions.

OBJECTIVES

Wind blade erosion is a multidisciplinary subject, where progress relies on a wide range of technologies and skills. The intent of this TEM is to engage in technical discussion on which business practices and technologies will have the most impact in tackling blade erosion.

1) Weather modeling: climate correlation with erosion, measurement of relevant meteorological conditions
2) Droplet/particle trajectory physics, collision efficiency, impact speed/angle
3) Erosion mechanics: droplet/particle/hailstone impact modelling, stress wave propagation, effect of overlapping stress fields, leading edge failure modes (damage mechanisms) such as coating failure, degradation of putty, degradation of laminate, debonding; damage accumulation model
4) Material properties & models: static & fatigue properties of coating and substrate, viscoelastic/damping properties, elastic/plastic behavior at high loading rate, effect of ageing: UV, humidity, salinity, temperature, freeze-thaw, material modifications

(reinforcing particles, nanoparticles, additional layers, polyurethane modifications), fracture of interface between layers, chemistry to modulate physical properties, substrate compatibility, coating application process (factory vs field)

5) Coating validation: review of existing standards, considering applicability to wind blades, Rain Erosion Whirling Arm Test, Jet Impingement,Sand Erosion Test, Tensile strength & elongation, flexibility, Pull-off adhesion, Effect of UV, Pot life - viscosity - density, gloss colour, alternative validation procedures
6) Erosion detection, classification & forensic analysis: Severity classification, early detection, analysis of microstructure, validation datasets for erosion models
7) Economic losses associated to erosion: power curve drop and energy loss, repairs and downtime

TENTATIVE PROGRAM

TEM#98 will be hosted in DTU premises in Roskilde, Denmark on the 6th and 7th of February 2020. This TEM will be co-located with the International Symposium on Leading Edge Erosion of Wind Turbine Blades organised by DTU from February 4th to 6th at the DTU Risø Campus (https://www.conferencemanager.dk/LEEWTB).

Participants are encouraged to attend both meetings.

Ahead of TEM#98, a brief anonymous survey will be sent to participants to elicit key areas of focus and define breakout sessions topics.

Thursday February 6, 2019

13:00 Arrival, check-in and introductions

13:30 Welcome and meeting overview

13:45 Task 11 presentation

14:00 Technical content (including survey results, key take-aways from DTU symposium and additional presentations from selected participants)

16:30 Summary and wrap-up

17:00 Adjourn

19:00 Dinner

Friday February 7, 2019

08:30 Welcome and day 1 summary

09:00 Breakout sessions: split in different groups according to areas of focus (tentatively four parallel sessions based on feedback from survey). A few questions will be provided, to facilitate debate:

- State-of-the-art: which actions have been more impactful in reducing the cost of erosion.
- Identification of research gaps and technological challenges

- Expectations regarding future research technologies and required steps towards maturity

11:15 Summarizing the results of the breakout session

12:00 Lunch break

13:00 Presentation of IEA Wind Task Framework

13:15 IEA Tasks in the context of erosion mitigation

15:30 Wrap-up session, identify responsibilities for next steps

16:30 Adjourn

INTENDED PARTICIPATION

The TEM experts are anticipated to come from industry (wind turbine manufacturers, blade manufacturers, blade maintenance companies, wind farm owners, certification bodies) and academia (universities, research centers, test facilities).

Participants and invited experts (even if not participating) are kindly requested to complete the following survey (2 min) ahead of the event: https://www.surveymonkey.com/r/7R76R9S.

EXPECTED OUTCOMES

- Results from the anonymous survey poll
- Presentations from the participants
- A briefing on key practices and technologies which will help to tackle blade erosion, their level of maturity, challenges ahead and potential role of IEA.

APPENDIX TWO - Meeting Agenda

IEA WIND TASK 11 TOPICAL EXPERT MEETING #98

EROSION OF WIND TURBINE BLADES

FEBRUARY 6-7, 2020, ROSKILDE, DENMARK

Organisers:

Raul Prieto – VTT Technical Research Centre of Finland

Joshua Paquette – Sandia National Laboratories

The meeting will be hosted in DTU premises at Risø Campus, DTU Wind Energy, Frederiksborgvej 399, 4000 Roskilde, Denmark.
https://www.vindenergi.dtu.dk/english/

TEM#98 is co-located with the International Symposium on Leading Edge Erosion of Wind Turbine Blades organized by DTU at the same location on February 4-6.

AGENDA

Tuesday 4th February, 9:00 – Thursday 6th February, 13:00

International Symposium on Leading Edge Erosion of Wind Turbine Blades

Thursday 6th February

- 14:00 Welcome & introductions
- 14:10 Ignacio Marti, Executive Secretary of the IEA Wind TCP, "*Presentation of IEA Wind TCP framework"*
- 14:20 Raul Prieto, VTT "*Meeting overview"* & Nicolas El Hayek, Planair SA "*IEA Wind Task 11 activities"*
- 14:30 Technical presentations (including key take-aways from DTU symposium)
  - 14:30 Leon Mishnaevsky, DTU "*Computational modeling and micromechanisms of leading edge erosion: What can we learn from the modelling?*"
  - 14:50 Kirsten Dyer, ORE Catapult "*Challenges of testing LEP materials*"
  - 15:10 Nikolai Grishauge, SGRE "*Rain Erosion: further research needs seen from an industry perspective*"
  - 15:30 Fernando Sanchez, Univ. Cardenal Herrera & Enrique Cortés, Polymer Innovation Force *"On the tools and criteria development for erosion performance analysis"*
  - 15:50 Coffee break
  - 16:10 Sara Pryor, Cornell University "*Using WRF to characterize atmospheric drivers of leading edge erosion*"
  - 16:30 Francesco Grasso, Vestas "*Aerodynamic modelling of blade erosion*"

- 16:50 Motofumi Tanaka, National Institute of Advanced Industrial Science and Technology "*Activities tackling erosion in Japan*"
- 17:10 David Maniaci, Sandia "*Predicting Leading Edge Erosion Performance Degradation Through Experimental Measurement and CFD Modeling of Wind Turbine Airfoils*"
- 17:30 Joshua Paquette, Sandia *"Recap of TEM#91 on Durability and Damage Tolerant Design of Wind Turbine Blades"*

- 17:45 Adjourn
- 19:00 Informal dinner at Snekken Trattoria, Vindeboder 16, 4000 Roskilde

Friday 7th February

- 08:30 Welcome
- 08:40 Resume technical presentations
  - 08:40 Gemma Gonzalez, SGRE "*Frontiers in LEP Solutions for Onshore Wind Business*"
  - 09:00 Poul Hummelshoj, METEK Nordic "*Is it possible to forecast precipitation events on minute scale using a Micro Rain Radar?*"
  - 09:20 Rebecca Barthelmie, Cornell University "*Quantifying atmospheric drivers of leading edge erosion using remote sensing*"
  - 09:40 Coffee break

  10:00 Breakout sessions. Split in different groups according to topics identified as important by participants in the questionnaire. A few questions will be provided to facilitate debate and help identify research gaps as well as collaboration needs.

  Group #1: Erosion mechanics and material innovations

  Moderator: Fernando Sánchez, Universidad Cardenal Herrera - CEU

  Group #2: Failure modes, testing & validation

  Moderator: Rasmus Konge Johansen, Polytech

  Group #3: Effect of climate and particle aerodynamics

  Moderator: Sara Pryor, Cornell University

- 12:15 Summarizing the results of the breakout session
- 13:15 Lunch
- 14:15 Debate on IEA Tasks in the context of erosion mitigation

  Chair: J. Paquette, R. Prieto

- 15:00 Coffee break
- 15:20 Wrap-up session including additional plenary discussion for identification of responsibilities and next steps (N. El Hayek, R. Prieto)
- 16:30 Adjourn

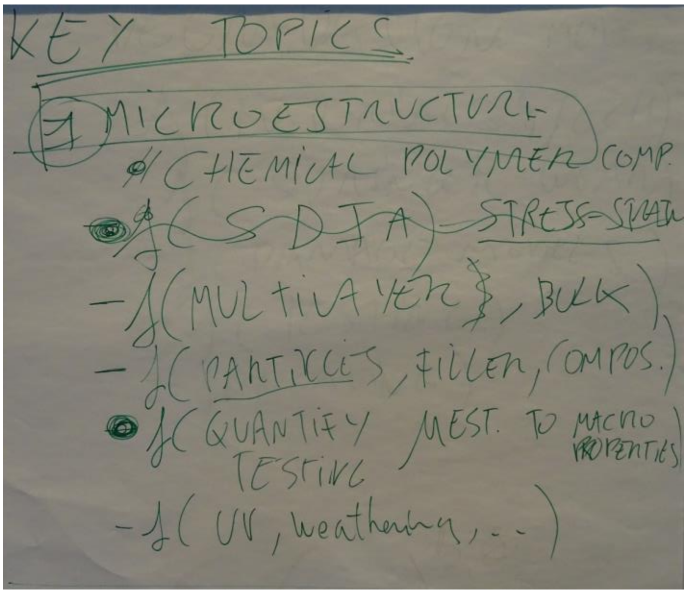
- **APPENDIX THREE - Meeting Participants**

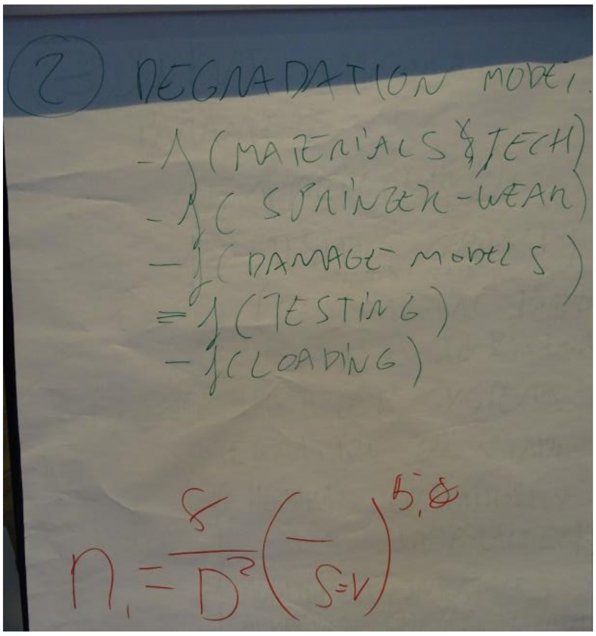
The meeting was attended by 29 participants from 12 countries. Following is the list of participants and their affiliations.

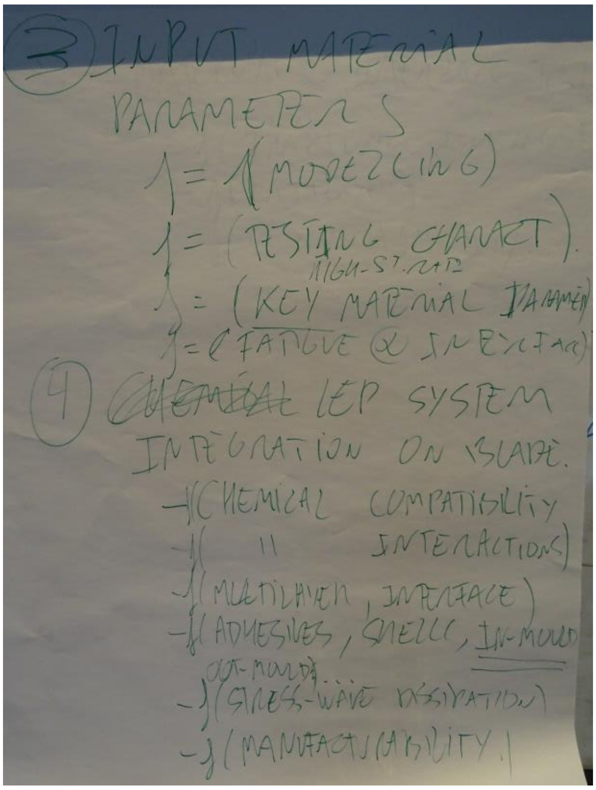
Name	Country	Company/Organization
Nicolas Quievy	Belgium	Engie-Laborelec
Carrie Houston	Canada	WEICan
Anna-Maria Tilg	Denmark	DTU
Charlotte Bay Hasager	Denmark	DTU
Jakob Bech	Denmark	DTU
Leon Mishnaevsky	Denmark	DTU
Nicolai Johansen	Denmark	DTU
Javier Ozores Arconada	Denmark	Bladena
Martin Bonde Madsen	Denmark	RD Test systems
Nikolai Grishauge	Denmark	SGRE
Poul Hummelshoj	Denmark	METEK Nordic
Rasmus Buch Andersen	Denmark	R&D Test Systems A/S
Rasmus Konge Johansen	Denmark	Polytech
Raul Prieto	Finland	VTT (Organiser)
Mark Hardiman	Ireland	University of Limerick
Motofumi Tanaka	Japan	AIST
Sandro Di Noi	Netherlands	Suzlon
Gunnar Hognestad	Norway	Equinor
Beatriz Mendez	Spain	CENER
Enrique Cortés	Spain	Polymer Innovation Force
Fernando Sanchez	Spain	Universidad Cardenal Herrera - CEU
Gemma Gonzalez	Spain	SGRE
Nicolas El Hayek	Switzerland	Planair SA - Task 11 Operating Agent
Francesco Grasso	UK	Vestas
Kirsten Dyer	UK	ORE Catapult
David Maniaci	USA	Sandia National Laboratories
Joshua Paquette	USA	Sandia National Laboratories (Org.)
Rebecca J Barthelmie	USA	Cornell University
Sara C Pryor	USA	Cornell University

APPENDIX FOUR – TEM#98 Raw Breakout Session Notes

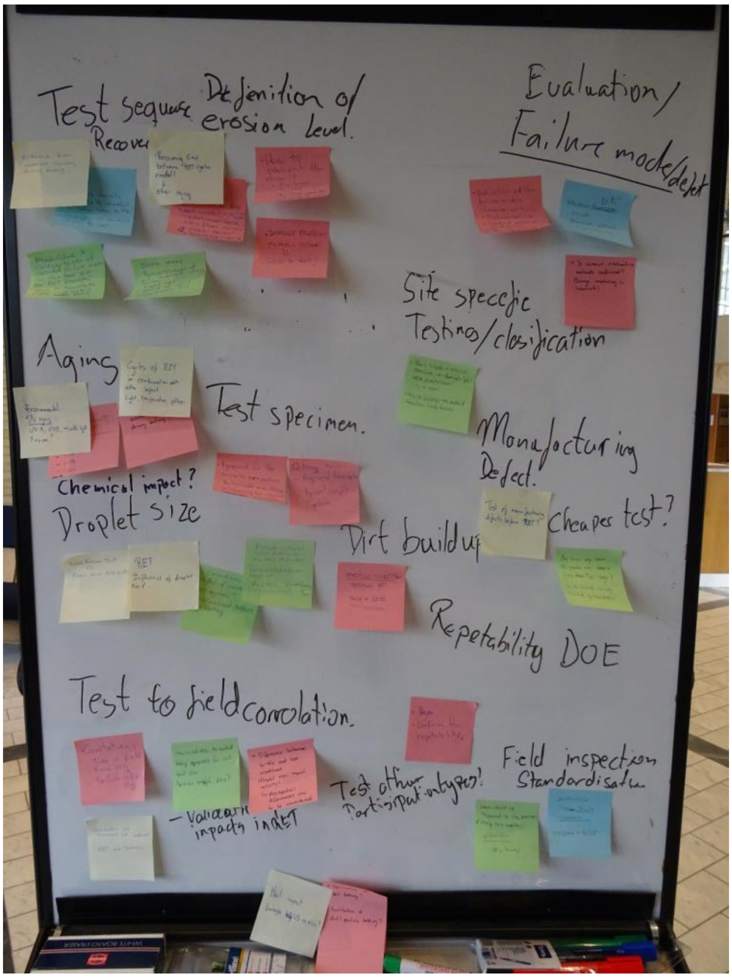
<u>Erosion mechanics and material innovations</u> moderated by Fernando Sánchez, CEU

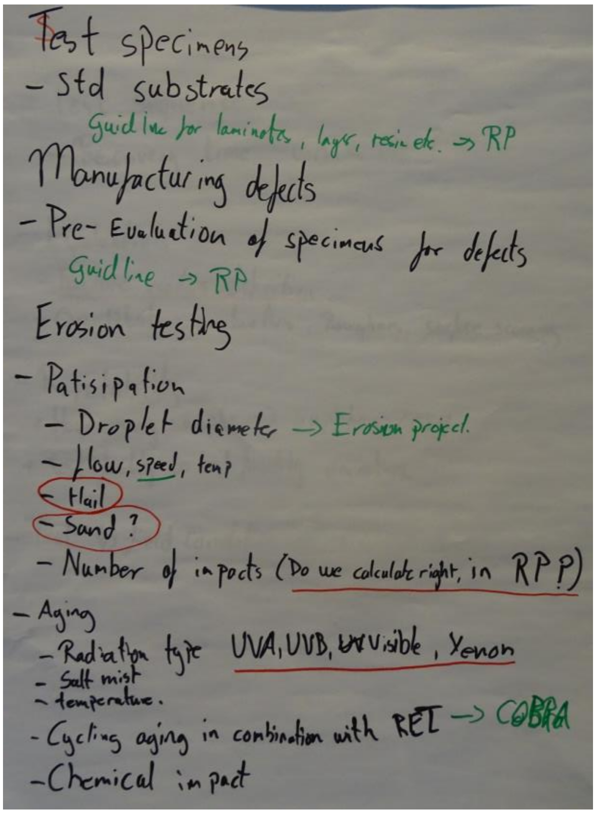


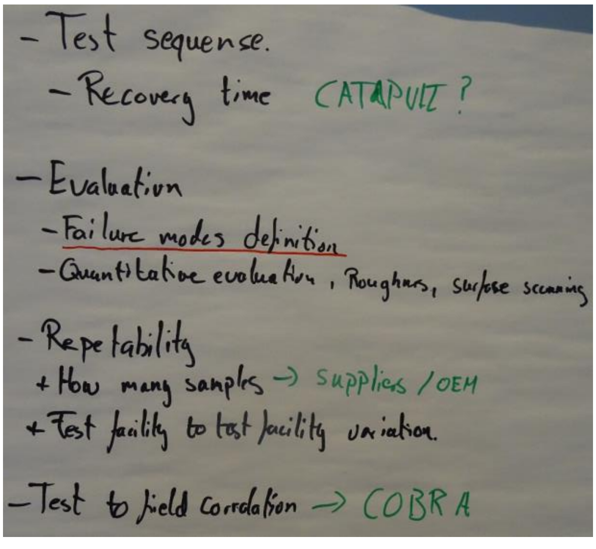




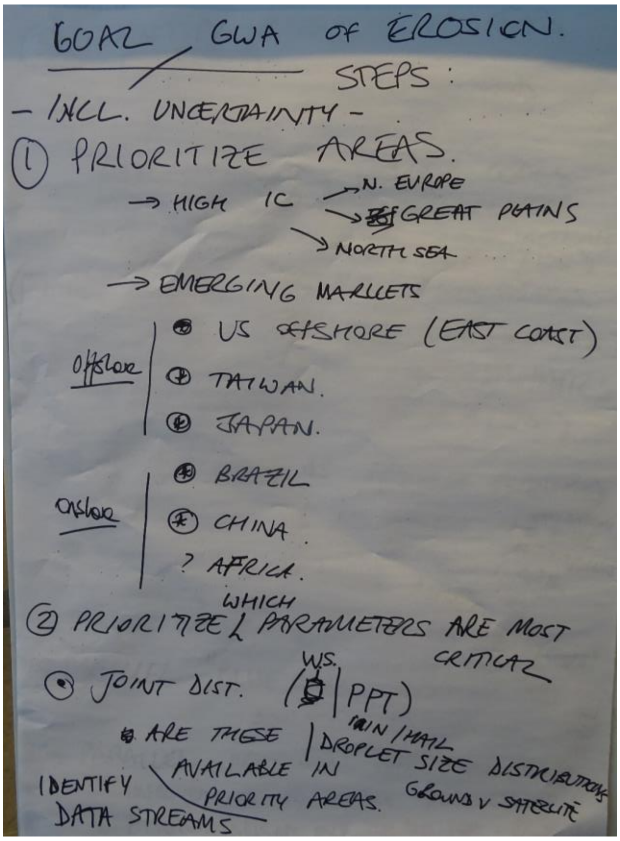
Failure modes, testing & validation moderated by Rasmus Konge Johansen, Polytech

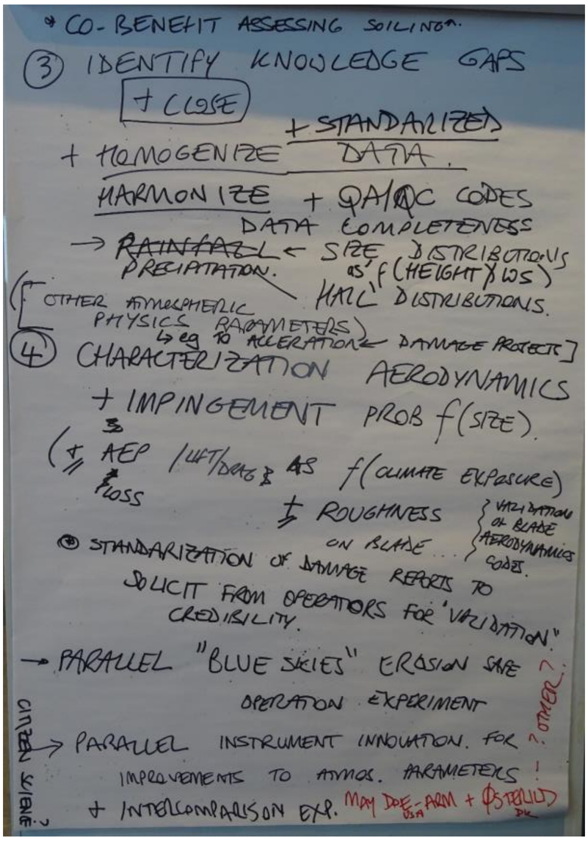


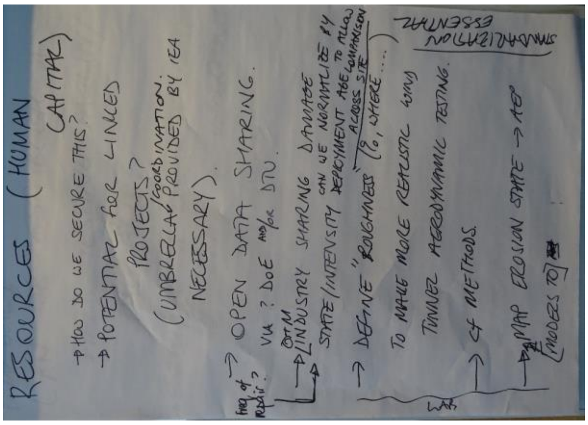


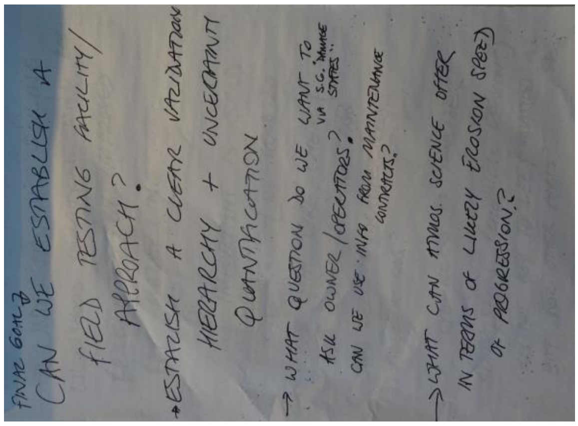


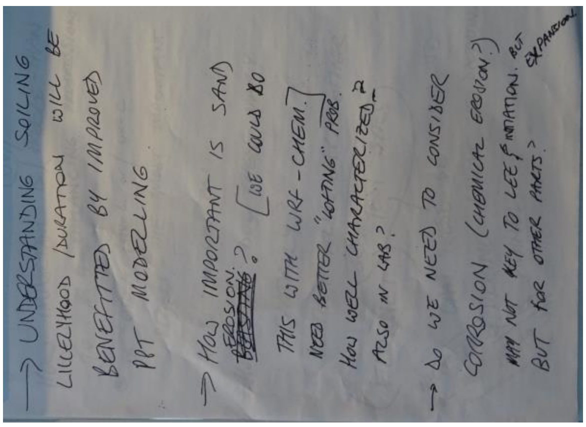
Effect of climate and particle aerodynamics moderated by Sara Pryor, Cornell University

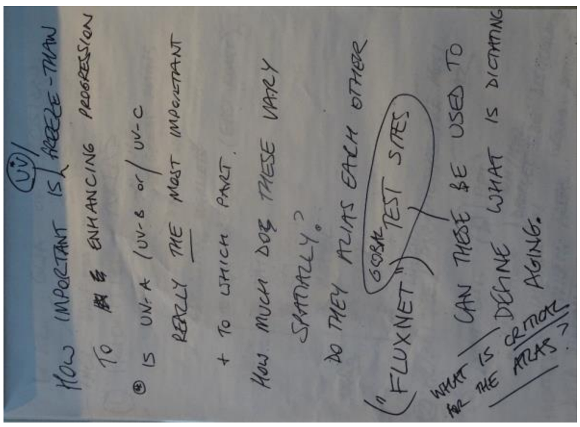












APPENDIX FIVE - IEA Agreement

International Energy Agency Agreement

Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems (IEA Wind)

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977 and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 26 contracting parties from 22 countries, the European Commission, and Wind Europe, participate in IEA Wind. Austria, Belgium, Canada, CWEA, Denmark, the European Commission, Finland, France, Germany, Greece, Ireland, Italy (two contracting parties), Japan, Republic of Korea, Mexico, Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, United Kingdom, the United States and WindEurope are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Three Subtasks

The task includes three subtasks.

The objective of the first subtask is to develop recommended practices (RP) in collaboration with the other IEA Tasks.

The objective of the second subtask is to conduct Topical Expert Meetings (TEM) in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, TEMs are arranged four times a year. Additional TEM types that would allow shorter reaction times, broader audience and augmented visibility are currently being researched.

The objective of the third subtask is to provide room for exchanges within the wind energy expert community. This is done through the IEA Wind platform with online communities.

Documentation

Since these activities were initiated in 1978, more than 90 volumes of proceedings have been published. In the series of Recommended Practices, 20 documents were published and six of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task. Some documents are publicly available one year after first publication.

Operating Agent

Planair SA
Rue Galilée 6
1400 Yverdon-les-Bains
Switzerland
Phone: +41 24 566 73 02
E-mail: ieawindtask11@planair.ch

COUNTRIES PRESENTLY PARTICIPATING IN TASK 11 (2020)	
COUNTRY	**INSTITUTION**
Belgium	Government of Belgium
Canada	Natural Resources Canada
Denmark	Danish Energy Authority
Finland	Business Finland
Germany	Federal Ministry for Economic Affairs and Energy (BMWi)
Ireland	Sustainable Energy Authority of Ireland (SEI)
Italy	Ricerca sul sistema energetico (RSE S.p.A.)
Japan	New Energy and Industrial Technology Development Organization (NEDO)
Mexico	Instituto de Investigaciones Electricas (IIE)
Netherlands	Ministry of Economic Affairs
Norway	The Norwegian Water Resources and Energy Directorate (NVE)
Republic of China	Chinese Wind Energy Association (CWEA)
Republic of Korea	Korea Institute of Energy Technology Evaluation and Planning (KETEP)
Spain	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas (CIEMAT)
Sweden	Energimyndigheten - Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy (SFOE)
United Kingdom	Offshore Renewable Energy CATAPULT
United States	The U.S Department of Energy (DOE)