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Minutes
of the IEA WIND Task 32 Workshop #5 on
Elaboration of use cases in wake and complex flow measurements

Date: 19 and 20th June 2017

Workshop Venue: University of Glasgow, Room 257, Glasgow, Scotland

Workshop leader: Peter Clive, Wood Group

Minutes by Andy Clifton, David Schlipf

Agenda

Day one

9:00	Welcome and introduction round
9:30	Introduction to the workshop
9:45	Lidar use cases for assessing complex flow
10:00	Manufacturer's perspective: Paul Mazoyer, Scott Wylie
11:00	Coffee break
11:15	Case study: Nikola Vasiljevic
12:30	Lunch
13:30	Integration of measurements and models
14:30	Using lidar use cases to develop complete uncertainty models: Peter Clive
15:30	Coffee break
15:45	Group discussion
16:45	Summary and identification of next steps

Day two

9:00	Welcome and recap of day 1
9:15	Step 1: collating use cases
10:00	Step 2: what are the common aspects?
10:45	Coffee break
11:30	Wake measurement case studies: David Infield, Alexander Meyer Forsting
11:15	Discussion of lidar use cases for assessing wakes: Davide Trabucchi
12:30	Lunch
13:30	Discussion of wake measurement uncertainty models: Aiden Kean
15:00	Coffee break
15:15	Summary and identification of next steps
15:30	End of workshop

Minutes

Day 1

9:00	**Start of workshop – Introductions to Task 32 and workshop, introduction round**

- Welcome from David Schlipf
- Overview from Peter Clive about the challenge of representing reality using lidar measurements and the corresponding need to understand the uncertainty of a lidar measurement.
- Participants' introductions
  - Combination of lidar manufacturers, consultants, and data users.
  - General interest in knowing how to get the best information from lidar measurements
  - Would like to see best practices and community consensus documents
- Thanks to the University of Glasgow for hosting the workshop!

9:45	**Introduction to the workshop**

- What is a use case? A combination of three things:[1]
  - Data requirements (what do I want, *not* what can I do currently)
  - Measurement method (how do we do it)
    - First generation: data from met masts and vertical profilers ("easy to understand" data at one location) that are extrapolated.
    - Second generation: remote sensing measurements at multiple locations, but still radial components. This requires some assumption of flow characteristics to extract wind speed and direction, and thus has an interaction with the actual wind conditions.
    - Third generation: Measuring required wind speed and direction data everywhere simultaneously.
  - Situation
- Use cases are required to constrain the problem and allow comparability.
- Lack of progress may be linked to challenge in challenge in describing measurements situation, and how people use the data (e.g., use of turbulence intensity to describe turbulence, shear based on two measurements)
- Goal of workshop is to figure out starting point.

10:00	**Manufacturers' perspectives**

- ZephIR Ltd: Scott Wylie
  - LOS uncertainty versus moving belt. Errors arise from laser frequency and digital signal processing
  - Scan wedge measured directly, cone sensitivity checked against moving belt
  - Focus checked against belt at longer range
  - Accuracy and precision of one lidar were checked in wind tunnel
  - Conical scan can introduce differences versus point measurements. Can be mitigated using CFD to estimate upwind and downwind wind speeds versus wind speed directly above the

[1] See concept in www.nrel.gov/docs/fy16osti/64634.pdf

    - lidar to reference lidar back to point measurements. ZephIR consider this approach to be applicable to complex terrain.[2]
    - It is unrealistic to assign single uncertainty values because of the interaction of the lidar and atmosphere, the measurement tower and the atmosphere, and it may be time to have dynamic uncertainty.
    - Lidar could deliver more, if end users can gain confidence in it!
    - Research questions:
        - Would it be better to apply corrections to 1-second data?
        - How accurate are the CFD codes?
        - Is stability important?
- Leosphere: Paul Mazoyer
    - Have a standard DBS approach and a flow complexity recognition (FCR) mode
    - FCR mode for complex flow uses an embedded flow solver to compare all radial wind speeds to an incompressible flow model
    - FCR challenged when the model assumptions are violated
    - Summary of results available from EWEA 2011 poster[3]
    - Need to avoid double corrections
    - Series of case studies show FCR is challenged in some terrain conditions
    - Developing lidar campaign tool
- Discussion: Would ZephIR and Leosphere be willing to make some of the case studies public?
    - In general yes, but will require careful preparation

11:30	**Case study: Nikola Vasiljevic**

- Process of converting lidar measurements to wind fields
    - Challenge of comparing point and volumetric measurements
- Sources of uncertainty in scanning or multi-lidar systems[4]
    - Pointing accuracy (home position, pitch, roll, levelling etc.)
    - Use of multiple survey sticks around a circle, versus theodolite information, to give lidar orientation
    - Hard-target CNR can be smeared over multiple pixels because of backlash (encoder is on the motor side, not head side)
    - Some possibilities to reduce backlash through scanner design
    - Can also assess ranging accuracy using hard targets (probe is a Gaussian, hard target is a Dirac. Convolution gives a Gaussian with a peak at the location of the hard target).
    - Intersection angle is important for synchronized dual Doppler lidar
    - Created a simple uncertainty model. Rule of thumb is that intersecting angle should be greater than 30 degrees (N.B. [1/sin(alpha)] is the important term).
- Will be a further presentation at the Wind Energy Science Conference 2017 ("Learning from Mistakes: Designing Scanning Lidar Atmospheric Experiments").

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[2] See summary in *Post Conversion of lidar data on complex terrains.* S. Sanquer, A. Woodward, Wind Europe (2016)

[3] Sensitivity of the CFD based lidar correction. C. Bezault and M. Boquet, EWEA Annual Event, 2011

[4] N.B. Some participants refered to multi lidar methods as “convergent beam lidar”, to emphasize that these are synchronous measurements of the same point in space at the same time, and not asynchronous measurements.

- Comments from attendees:
  - Isn't it a bit simplistic to say that there is a rule of thumb?
    - Yes, but it's intended here as a demonstration of the effect of the wind direction compared to the observation angle
  - Need to embed this knowledge into tools so that people can assess their own systems / experiments
    - Yes, give me some time!
  - Quick recap of the benefits / issues associated with two or three lidars
  - What about other terms in the uncertainty?
  - Could be plugged in to the model over time
  - What about measurements of turbulence intensity?
    - Required for many wind energy applications, even if it's not a good description of turbulence
    - Need to consider bankability or effects of lidar measurements on LCOE
    - Need to validate measurements using Ti as well, but also need to look at (and present) different turbulence-related metrics (TKE, etc) that capture relevant information.
    - May be a good time to look at other ways of describing the sub 10-minute wind characteristics

12:30	**Lunch**

14:30	**Combining measurements and modeling**

- David Schlipf: Wind Field Reconstruction
  - Given knowledge of the lidar trajectory and measured LOS winds, can establish the wind field.
  - Applied by Antoine Borraccino to forward-looking lidar
  - Should be trying to model first, find the optimal, then go out and carry out the optimized process (e.g., start with wind field model and understanding of the process and capabilities of the equipment, and choose the optimal model
  - Could do pre simulations before going into the field
  - Comments: Simulation of a measurement effort is (currently) a huge effort; precludes the use of models for optimization
- Peter Clive
  - Can include models to adjust measurements back to "truth". This is a calibration process.
  - Several different types of calibration are recognized:
    - Black box; ignores the physics of the process and simply applies some kind of correction / calibration to remove biases
    - White box: model-based / full knowledge
  - Suggests there may be a place for a middle approach, a "glass box"
    - Combination of calibration / testing of lidar system components with use-case specific calibrations
    - Can plug models in to each term
    - Similar to GUM method of continuing to reduce the unknown term
  - Uncertainty framework would be helpful for allowing collaboration and further applications

4:00	**Group work: end-user focused Use Cases**

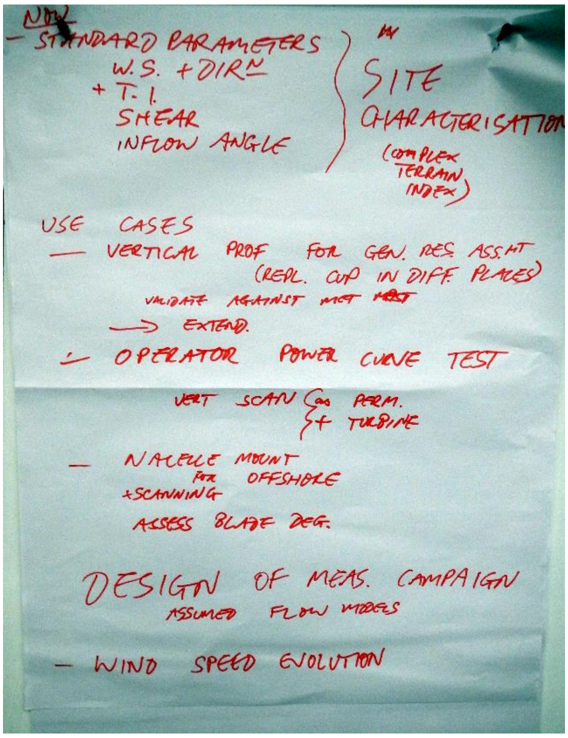
Group work:

- Step 1: identify end-user needs, and how do these translate into use cases?
- Step 2: what are the commonalities?

Two groups identified a range of use cases. Use case worksheets from each group are shown in Table 1 and Figure 1.

Table 1 Examples of Use Cases Developed by the Teams

Use Case	Data requirements	Situation	Measurement Method
Power performance testing	turbine inflow (wind speed)	Complex terrain	Nacelle-mounted lidar (forward looking conical or planar, also ground-mounted)
Resource assessment	Wind speed mapping for resource assessment	New site	Dual scanning lidar (to reduce uncertainty)



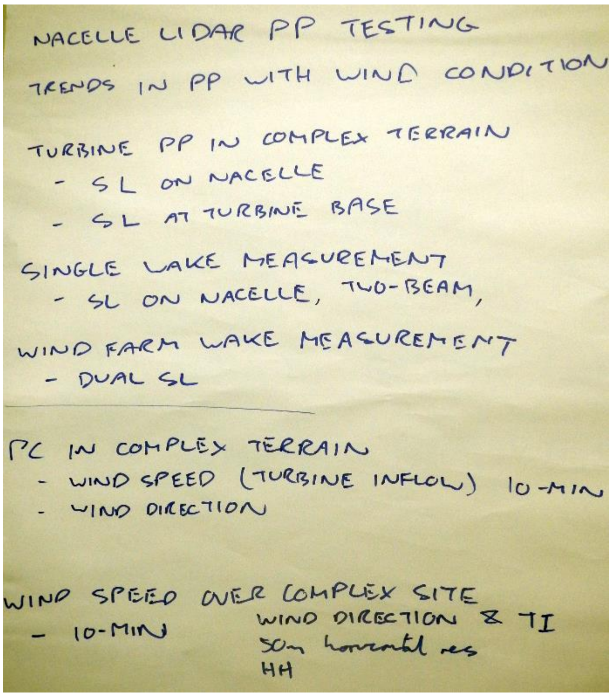


Figure 1 Use Case Worksheets Developed by the Teams

Day 1 of the workshop closed at 17:00.

Day 2

9:00	**Welcome and recap of Day 1**

- Welcome from Peter Clive
- What kind of document do we need?
  - Need referenceable documents that reflect the state of the art, with firm revision numbers
  - Would be interesting to have some form of "living document"

9:15	**Discussion of Use Cases**

- An expanded list of use cases developed by the attendees was presented. This is summarized in Table 2.
  - There is a need to agree on objective definitions of e.g. “simple terrain” and “complex terrain”, although this may be best left to the manufacturers as they know their equipment best.
  - This list is not exhaustive. There are many other possible use cases for lidar. The inclusion of a use case in this list does not imply acceptance or suitability for a particular purpose. Similarly, the exclusion of a use case does not imply that lidar cannot be used effectively for that purpose.
  - Different levels of complexity in the use cases were identified using the concept of first, second, and third generation measurements.
  - Also looked at the effect of moving from simple to complex flow conditions.
- Use cases require specificity so that it is possible to generate an uncertainty model for that use case (e.g. the use of remote sensing for power performance testing in simple terrain is a use case that is recognized by the new IEC 61400-12-1 power performance testing standard).

Table 2 Example Use Cases, Sorted by Generation

#	Data Requirements	Situation	Measurement method	Generation
1	Wind speed distribution: wind speed measurement over period of time (10 min, several months) to use in MCP, at turbine height ->hub height 10 min wind speed	Simple terrain	Profiling lidar • DBS • VAD • Multi lidar All methods are feasible	1
2	Hub height, 10 min wind speed at turbine location and reference location for Power Curve Test	Onshore complex terrain	2 x ground based vertically scanning lidar	1
3	Estimation of wake characteristics (e.g. wake centre) in downstream direction	Simple terrain, complex windfarm layouts	Scanning lidar	2
4	WIND DATA: 10-minute wind speed, wind direction CFD DATA REQ: Terrain data, Land coverage and roughness data	CFD compensation for VAD lidar in complex terrain. Non-homogenous flow situation as a result of complex terrain.	Ground-based vertically-scanning lidar	2
5	Hub height wind speed, shear, Ti for pre-construction load assessment and component failure root cause analysis	Onshore complex terrain + Forestry	Ground based vertically scanning lidar	2

6	2D or 3D flow detection in wind farms at hub height	simple terrain, complex windfarm layouts	Multi lidar	3
7	Convergent beam lidar[4] for vector field measurement at a single point, requiring motion stabilisation for handling high sea states	Offshore wind measurement including quantifying turbulence intensity for suitable wind turbine selection	Convergent beam lidar can be preferred for measuring turbulence intensity in a point-like (small) sampling region so as to minimise error due to spatial extent of sampling volume; one or many buoys can be employed	3
8	Wind vector field map across whole rotor using converging beams in order to give warning/alarm for elevated loads in any part of the turbine structure and therefore allow control system to take protective action	Any terrain onshore or offshore during operational phase of turbines	convergent beam lidar, can be CW or pulsed, probably but not necessarily a scanning system in order to sample many positions	3

10:00	**Using Use Cases to Support Uncertainty Evaluation**

- Formulate use case
- Identify required output
  - Single value
  - Spatial/ Map
  - Dynamic
- Introduction to the concept of an uncertainty model for lidar
  - Lidar measurements and data analysis are extremely complex
  - Careful and specific definition of a use case (e.g. profiling lidar in simple terrain, measuring wind speed at hub height) allows confident transfer of results from one measurement campaign to another
  - If the sources of uncertainty and how they propagate through the measurement chain (for example due to the interaction of the measurement device, lidar, environment, and the data analysis process are not well known) an effective uncertainty estimate cannot be made

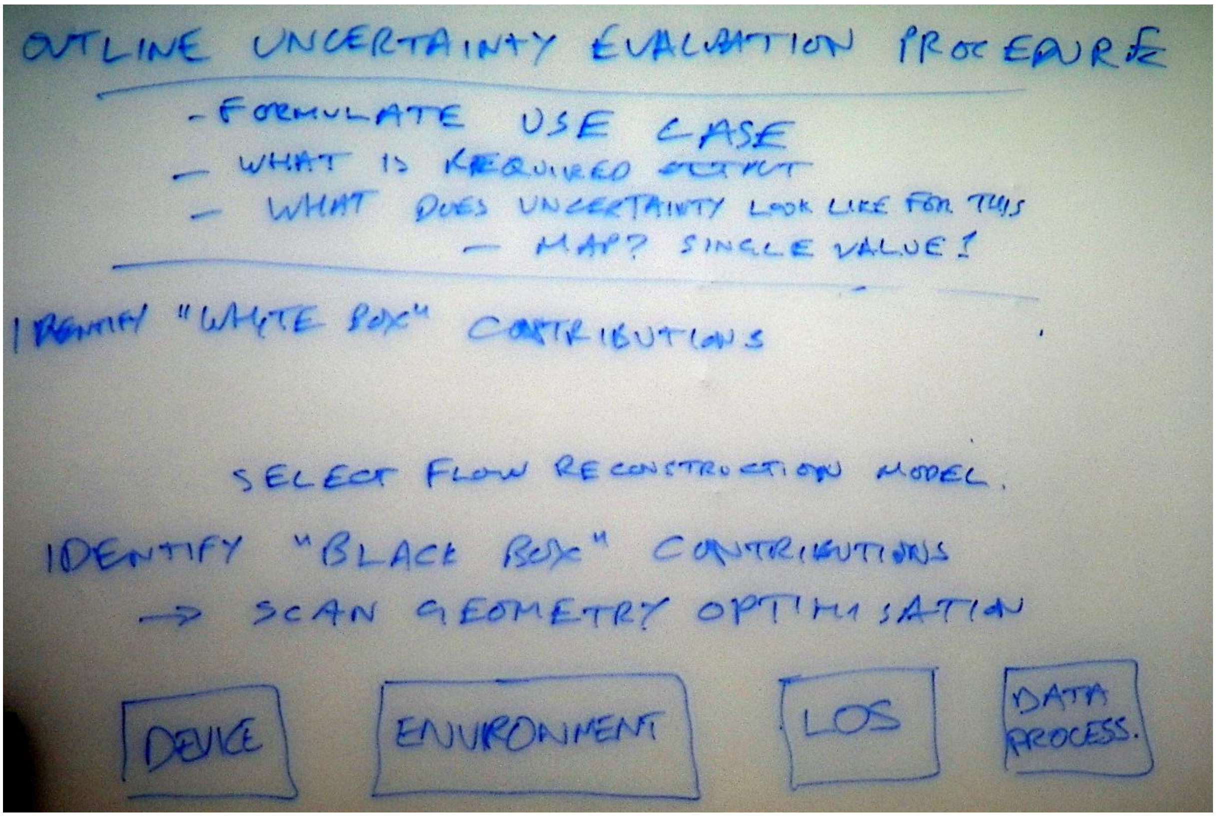
11:00	**Presentations: Wake measurement and analysis**

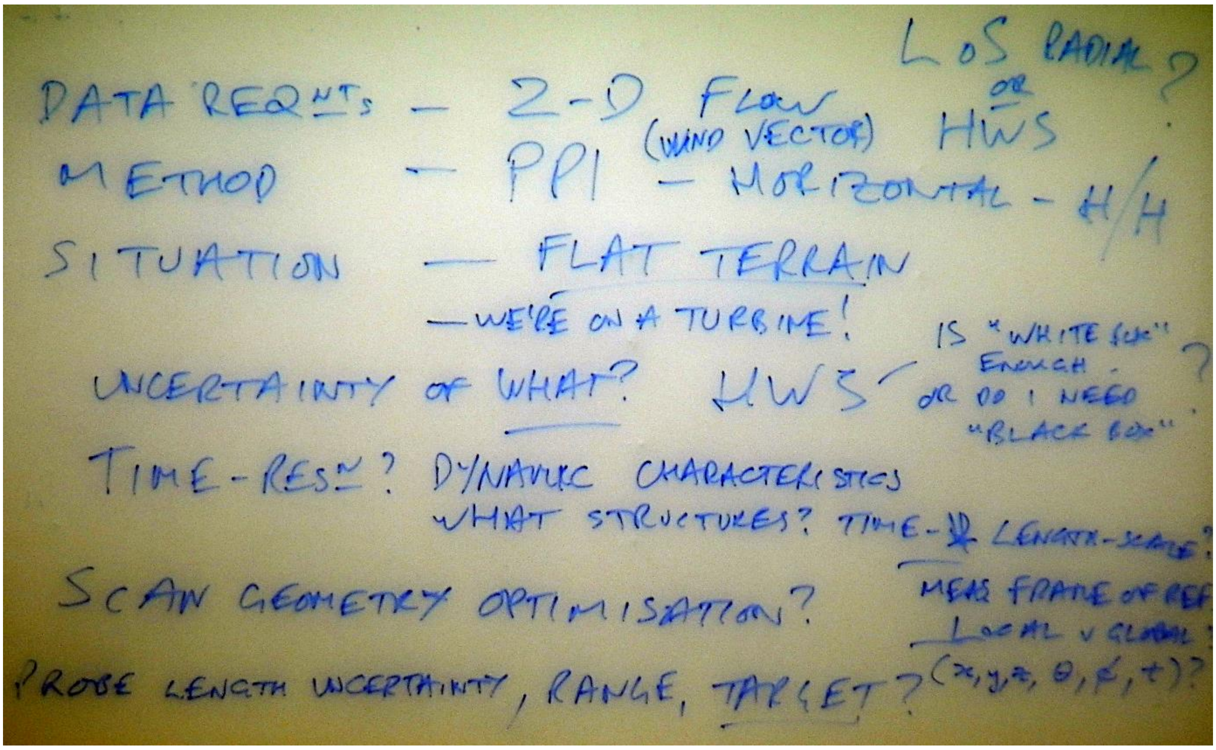
- Presentations:
  - David Infield, University of Strathclyde, impact of atmospheric stability on wake development
  - Alex Meyer Forsting, DTU, A Probabilistic Approach to CFD Model Validation with Field
    - Fair comparison between lidar and CFD by matching the boundary conditions
    - Incorporating measurement uncertainty helps the comparison and validates model
  - Paul Mazoyer, Leosphere, Wake tracking and wake interaction analysis through an extensive field campaign with a scanning lidar system
  - Aiden Kean, Wood Group, Lidar WTG Wake Analysis
  - David Schlipf, SWE, Wake Redirecting Using Lidar

        - Lidar systems can help to track the wake and assist redirecting
        - Wake tracking works well with the model-fitting approach even on high temporal resolution
    - Davide Trabucchi, U. Oldenburg
        - Balance between more elevation angles and time required for the scan. Extra data does not always provide a benefit
        - Avoided the need for a third lidar as vertical component not important

14:45	**Summary and Next Steps**

- Looking for some way to continue the case studies after this workshop
- Worked example: PPI lidar (simple, well-known application)
    - Use case
        - Data required: 2D flow "map" of radial velocity with possible conversion to planar display of 2-D wind vectors. Snapshots to allow dynamic characteristics
        - Method: Single lidar PPI with 0 elevation, at hub-height
        - Situation: Flat terrain
    - Goal: uncertainty of …?
        - Need to carefully define the thing we are trying to measure
        - Highlights that the use case needs to be better defined!
    - Use case refined to establish u and v components
    - Basic model – black box
        - Comparison of lidar-derived wind vector with a single met mast in the domain
    - Higher resolution
        - Adding details to the uncertainty: effect of range, etc.
        - Need to calibrate model to maintain overall level of uncertainty (experience)
- Possible workshop outcome
    - Definitions of concepts
        - Use case
        - Black box versus white case
    - Worked example of use cases, different ways of defining uncertainty models, enables end users and technology developers to define and refine use cases


OUTLINE UNCERTAINTY EVALUATION PROCEDURE
- FORMULATE USE CASE
- WHAT IS REQUIRED OUTPUT
- WHAT DOES UNCERTAINTY LOOK LIKE FOR THIS
- MAP? SINGLE VALUE?
IDENTIFY "WHITE BOX" CONTRIBUTIONS
SELECT FLOW RECONSTRUCTION MODEL.
IDENTIFY "BLACK BOX" CONTRIBUTIONS
→ SCAN GEOMETRY OPTIMISATION
DEVICE
ENVIRONMENT
LOS
DATA PROCESS.


LOS RADIAL?
DATA REQ^NTs — 2-D FLOW (WIND VECTOR) OR HWS
METHOD — PPI — HORIZONTAL — H/H
SITUATION — FLAT TERRAIN
— WE'RE ON A TURBINE!
UNCERTAINTY OF WHAT? HWS
IS "WHITE BOX" ENOUGH OR DO I NEED "BLACK BOX"?
TIME-RES^N? DYNAMIC CHARACTERISTICS
WHAT STRUCTURES? TIME- & LENGTH-SCALE?
SCAN GEOMETRY OPTIMISATION?
MEAS FRAME OF REF
LOCAL v GLOBAL?
PROBE LENGTH UNCERTAINTY, RANGE, TARGET?
(x, y, z, θ, φ, t)?

Participants

Name	Country	Institution
Alexander Raul Meyer Forsting	Denmark	DTU Wind Energy
Andrew Clifton	Germany	Windfors
David Böckler	Germany	Enercon
David Infield	UK	University of Strathclyde
David McCracken	UK	SSE
David Schlipf	Germany	SWE University Stuttgart
Davide Trabucchi	Germany	University of Oldenburg
Demetrios Zigras	UK	Nordex
Hong Yue	UK	University of Strathclyde
Hugo Herrmann	UK	EDF Energy
Inga Reinwardt	Germany	HAW Hamburg
James Arnott	UK	Texo Drone Survey and Inspection
Jie Bao	UK	University of Strathclyde
Julian Feuchtwang	UK	University of Strathclyde
Martin Hendry	UK	University of Glasgow
Nikola Vasiljevic	Denmark	DTU Wind Energy
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