IEA Wind Task 32 Workshop 11:

Windfield Reconstruction in the Induction Zone

14 January 2019
Hotel Ribera de Triana, Seville, Spain

About This Meeting

This meeting was held to discuss the results from a round robin to compare different approaches to reconstructing wind fields from measurements from a lidar in the induction zone of a wind turbine. More details of the round robin can be found on the IEA Wind Task 32 website.

This meeting was held as part of a series of related meetings in Seville in January 2019 and was organized in conjunction with the Power Curve Working Group (PCWG, www.pcwg.org). The meeting was organized and led by Nicolai Nygaard of Ørsted.

The Task 32 Operating Agent gratefully recognizes the support of EDPR in organizing this workshop and the enthusiastic participation of more than 40 people from across Asia, North America, and Europe. A list of attendees can be found at the end of this document.

Background

Nacelle-mounted lidars facing upstream of a wind turbine can measure the wind speed through the induction zone. Several nacelle lidar campaigns have indicated that the induction effect may be felt further upstream of the rotor than is commonly assumed in the design of power curve verification campaigns. To understand the magnitude of the induction effect, the freestream wind speed needs to be established. Since freestream velocity may only be reached beyond the measurement range of the nacelle lidar, an extrapolation based on the lidar measurements is necessary. A wind field model of the induction zone combined with the lidar line of sight wind speeds can be used to perform wind field reconstruction and derive not only the freestream wind speed, but also map the variation of the horizontal wind speed at different distances from the rotor.

Introductions

10:00	**Welcome** Housekeeping + Introduction Round (Nicolai Nygaard)
10:30	**IEA Wind Task 32 Introduction** Overview of Task 32 activities and plans (Andy Clifton)

Participants were welcomed and introduced themselves. A list of participants can be found at the end of this document.

A short introduction to Task 32 was provided. Slides can be found at the Task 32 website.

Round robin – background and execution

10:40	**Round Robin Background & introduction** (Nicolai Nygaard)

Nicolai Nygaard introduced the Round Robin and the results. More information can be found in the PDF from his talk.

Comments from participants:

- Should also note that the point is that we need to understand how to use measurements in the induction zone for whatever purpose, not just to estimate 2.5D
- Should remember that we can also enable measurements with convergent beam. This was widely agreed – Task 32 should be technology agnostic but also relate to current tech / approaches
- Would it be possible to add the round robin information and data set to the Workshop web page?
- Would it be possible to add related references to the Workshop web page?

Presentations by round robin contributors

11:00	**Presentations by Round Robin Contributors** ● 1-D model (Olivia Brisette, ENGIE) ● A CFD model (Paul Housley, SSE) ● IWES Fraunhofer approach (Alkistis Papetta, IWES) ● Vortex sheet theory model (Nicolai Nygaard, Ørsted)

Roughly four different types of model were used by participants in the Round Robin. Presentations were made by four different participants about their experience using one of those model types.

A 1-D Model (Olivia Brisette, ENGIE)

This group focussed on achieving something fast and light that could fit into other processes. They therefore chose to code a solution in python. Their approach was based on a paper by Borraccino et al[1]. and involved a reconstruction from LoS to horizontal / axial velocity, followed by a regression based on the Borraccino's paper (the Medici model[2]) to find the wind speed at the rotor plane and at infinity.

Comments

- This is an "inverse" process
- Using 2.5D as U_∞ could be a source of error. Might be more appropriate to use 4D.
- The lidar probe length may be a source of bias. A researcher noted that it was helpful to integrate the probe length for some devices, in that it reduced RMS error (but it was not clear if this is really "better"). It may also be important to recognize the relationship between pulse length and the gradient of wind speed introduced by induction.

CFD model (Paul Housley, SSE)

SSE developed a solution that used a RANS CFD (SST-RM turbulence model) in Ansys Windmodeller. Their approach would therefore be able to adjust to account for stability. The turbine is represented using an actuator disk. The approach was validated using pattern of production. Uses 5 turbines inline and constant wind direction. Data were modelled at 1-m/s intervals to 15 m/s. Confident that the model can capture thermal effects but these were not included in this case; would need temperature information to drive this. A neutral boundary layer was assumed. Did not include lidar tilt and roll. Reconstructed centreline wind speed from lidar LOS wind speeds. Then compared with CFD model. Assumed average of 10 calculated

[1] See https://doi.org/10.5194/wes-2-269-2017.
[2] See https://doi.org/10.1002/we.451

values of the yaw misalignment angle from the different ranges. The induction factor was calculated from the ratio of the CFD model wind speeds at 10D and at the rotor.

Comments:

- Ørsted can reveal the data is from Burbo Bank offshore wind farm in the Irish Sea (25x 3.6 MW turbines). Turbine is on a corner and so may experience array effects; data have been filtered to exclude wake effects but may therefore include *array* effects.
- The round robin information pack will be updated with this information
- SSE's CFD calculations used similar turbine, but with a larger rotor diameter.
- There is a different wind speed recovery with distance to other models
- Could such an approach use thrust data or CT curves to improve induction estimates (constrain iterative solution?)
- It may be necessary to include dynamics in such a type of simulation
- A clear advantage of CFD is that it can quickly explore other configurations. This allows users to see different induction patterns depending on which turbines are operational in the area, or wind direction.
- The high wind speed reduction in induction zone could be evidence of high effect of induction versus blockage
- Should also remember that the power performance standard / resource assessment relates back to wind speed at the turbine location.
- It was noted that the round robin data was not separated into training and evaluation data sets. It was recommended that in future tests / round robins, the training and evaluation data sets should be separated and a blind comparison should be used.

SSE showed curves of wind speed versus distance for cases with a single WTG and a full wind farm. These induction curves had different shapes, with the full wind farm curve indicating a higher wind speed reduction. At short distances the two curves converged.

Comments:

- Do the convergence of the curves indicate that array effects are negligible at small distances? Is that a rationale for measuring the power curve closer to the rotor?

IWES Fraunhofer (Alkistis Papetta)

This group used a process comparable to the other participants. They considered whether to include tilt and roll and explored the impact; they saw a clear, systematic tilt response (linked to thrust) but less clear roll response. They then converted LOS to horizontal wind speed and yaw misalignment angle. They then fit the data to an induction model that including radial induction (from Troldborg and Meyer-Forsting[3]) and assumed a fixed shear exponent of 0.1. They tried two different fitting approaches, including fitting to all data and fitting to data "near" and "far" from the rotor separately. Fitting using only the farthest ranges misses the induction factor. They then decided to fit the closer ranges to get induction factor, and the furthest ranges to calculate the freestream wind speed.

Comments:

- Looks like a curve-fitting problem?
- The relatively poor fit suggests missing physics! Agreed!
- This could be a result of what data are fit at what point; would be helpful to store LoS data.
- Suggested to fit a model including "reconstruction" and induction at the same time
- The fitting model that was used assumes "stationary" induction, i.e. no variability with time
- brings us to the issue of data validation
- Was anyone able to look at effect of stability? No…

[3] See https://doi.org/10.1002/we.2137

- The results from this approach suggest ideas for successor studies, such as stability, cross-fold evaluation, complex terrain, 1-Hz / maximal resolution lidar data

Vortex Sheet Theory model (Nicolai Nygaard)

This was a different approach to the prior presentations. It is based on work by E. Branlard (2014)[4] and is driven by the vortex strength parameter. The turbine is represented as an actuator disk. A second "image" turbine is included to emulate ground effects. This creates a slip boundary, similarly to potential flow methods. Could include wave height, for example. This approach also allows inclusion of neighbours and simulation of wind farm effects; Nicolai has tried this out and it shows that increasing the number of turbines perpendicular to wind increases blockage.

Comments:

- What is the effect of roughness on this? The image turbine methods simulates a frictionless surface. Surface roughness needed to simulate a boundary layer. Suggests bigger impact with measurements on multiple heights, but these also offer the opportunity for more complex models.
- Q: Is there a need for inclusion of other effects, such as stability or Ti, shear, etc? A: Possibly, but that brings other complications...

Overview of all round robin results – similarities, differences and statistical analysis

13:30	**Overview of all results (Nicolai Nygaard)**

Nicolai provided an overview of the results. He noted that some simulations exceed the Betz limit, but this is not unrealistic; it can exceed it at lower wind speeds because of the effect of turbulence.
Comments:

- It would be helpful to provide more information for each result, without names
- The "high" induction near the rotor has implications for other models. Suggests that there may be array effects that are influencing the induction further from the rotor (i.e. the measurements from 0.5 to 2.5D are not just impacted by the induction of a single turbine).
- The results highlights need for better thrust data
- Some models (e.g. CFD) intrinsically link physics

Invited presentations

14:00	**Invited Presentations** ● Scanning lidar measurements of the induction zone (Peter Clive, Wood) ● Wind Farm Blockage (Taylor Geer, DNV GL) ● Global Blockage OWA project (Graham Hawkes, Frazer-Nash Consultants)

Scanning lidar measurements of induction zone (Peter Clive, Wood)

Peter introduced some results that have already been presented but are still relevant. They are from a one-year campaign of measurements at Alpha Ventus 2013 using a nacelle-mounted scanning lidar staring along the rotational axis of the turbine. The results from that study suggest the induction zone extends out to at least 3.5D while 10D is clearly in the "free stream", i.e. no change in wind speed with distance. There was up to 3% difference between U_∞ and $U_{2.5D}$ at lower wind speeds. At low wind speeds there were structures (bands) in the induction zone.

[4] See https://doi.org/10.1002/we.1800.

Peter noted that the current approaches are predominantly driven by met-mast derived data, and as a result wind lidar are forced to conform to / emulate those data.

Wind Farm Blockage (Taylor Geer, DNV GL)

Wind farm and wind turbine blockage is probably leading to an observable impact on AEP estimates. Currently done estimates for the fleet but need to get this to be project specific. Blockage was acknowledged in 2008 as a missing part of the problem, but no industry consensus could be reached.

DNV GL understands from OEMs that the warranted power curve is specified at freestream. (One person disagreed with this, stating that the sales power curve is based on models validated on data measured under conditions more in between freestream and induction affected). DNV's approach is therefore to use isolated turbine simulations to estimate induction effect and replaced the measured wind speed in the power curve table with the (higher) free-stream wind speeds, as follows:

1. Convert measured power curve to what we would measure if test was for a turbine in isolation
2. Correct for effect of induction for isolated turbine

The total power curve correction depends on the test configuration. Average correction translates to 1% on AEP (calculated by CFD). Based on PCV not at the site, but at a test site.

More details can be found in a peer-reviewed paper in *Energies* (J. Bleeg et al., 2018[5]).

Comments:

- How can we deal with a PCV contractual test after commercial operation date? How to work it into the turbine supply agreement?
- Array effect and induction both happen, but based on the results presented here and seen elsewhere, they dominate at different distances from the rotor; up to approx. 1D the induction is strongest, beyond that the freestream and blockage effect are important
- We should use different tests (or different data from the same campaign) for different applications
- What about downstream effects? Sometimes see downwind acceleration.
- It is good to see this effect being recognised, but also need site-specific data. Should not be applying a straight haircut.
- Comment: could also define a u-infinity power curve for wind turbines, which would be in line with turbulence, shear, and other normalizations

Global Blockage OWA project (Graham Hawkes, Frazer-Nash Consultants)

Graham reviewed the state of understanding of global blockage effects and introduced a recent Offshore Wind Accelerator (OWA) project to explore the issue. It appears that models are useful but lacking in validation. Can imagine an induction model/wake coupled model run front to back (model wakes) and back to front (modelling induction given modelled wake wind speeds).

There was an appeal for interested parties to contact Graham with ideas; there are some opportunities for collaboration and cooperation.

Comments

- It is important to quantify the impact that justifies the research
- It would be good to find out where the missing effects in the models are. What effects are important? Is a combined model needed?
- It would be very helpful if the OWA and others could make historical PCV measurement information available.

[5] See https://doi.org/10.3390/en11061609

- This suggests that it would be a good idea to repeat this round robin with wind farm information and data, remembering to hold back some data for validation (either different range gates or entire records).
- We need open source reference models or a consensus for testing them (i.e. validation metrics)
- We need better definitions and vocabulary. We need to use the same language.[6]
- Q: Does it matter if there are two or hundreds of wind turbines for modelling the wind farm blockage? A: would like to take holistic approach where it does not matter. Induction should be modelled together with wakes.
- It is important to test the hypothesis that array effects are less relevant closer to the turbine. This should be tested in another version of the round robin.
- Another / a future round robin should use a lidar data set with a central beam.
- How can yaw be calculated with accuracy?
- We should push for clear definition of wind speeds in power curve from OEMs. Start with guidelines then move to standards (after choosing best model). Interfacing with the Power Curve Working Group will be important.
- From commercial perspective 2.5D cannot be considered freestream.
- Industry parties should agree on common understanding of a sales power curve.
- In the Danish UniTTe project, measurements at close range were used to estimate wind speed at 2.5D. The results from that project could be useful for PCV.

[6] Task 32 has started work on a glossary. More details will be announced in 2019.

Workshop

15:30	**Workshop** • Breakout sessions • Presentation of findings

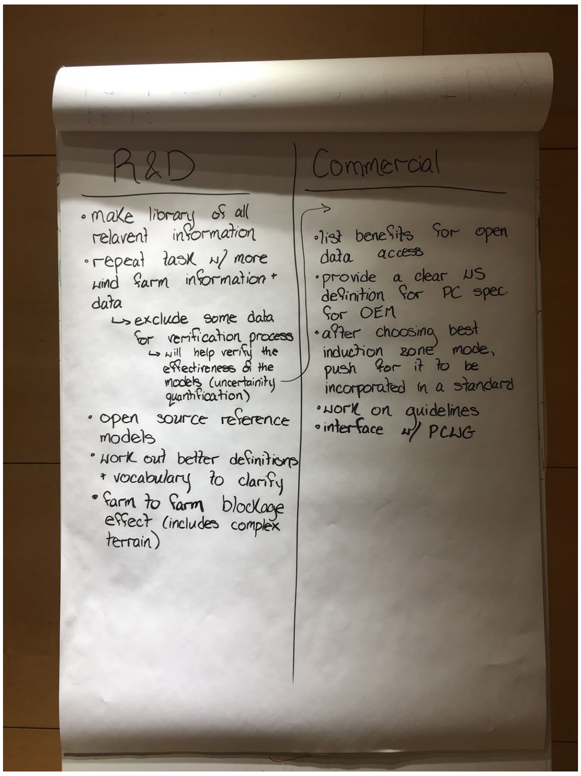
The participants were split randomly into groups to consider the following questions:

- How can we progress research and achieve consensus?
- What is the significance for power curves?
- What is the significance for production estimates

The groups were asked to identify questions and issues that needed to be addressed by the R&D community, and those that might be more commercial in nature.

Photos of the posters from the groups are included below with notes from the discussions. The groups are not shown in a particular order.

Group 1



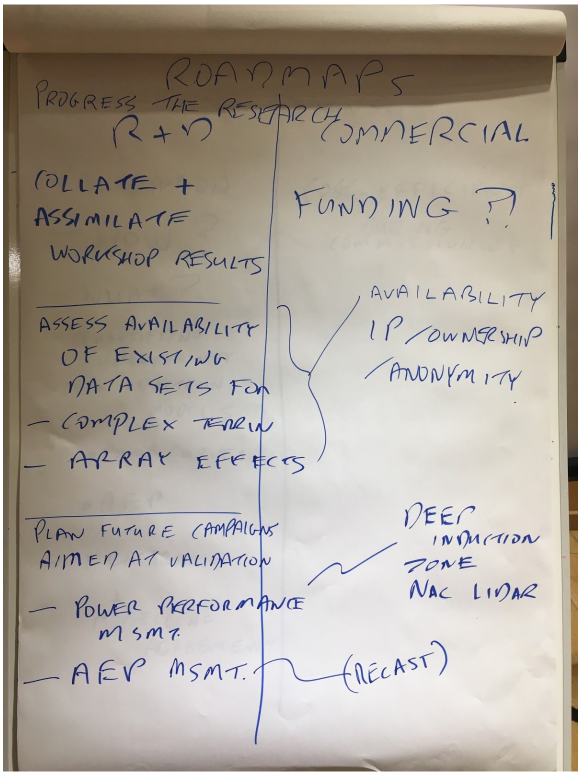
R&D issues

- Make a library of relevant papers and information.
- Repeat the round robin with more wind farm data & information.
- Exclude some data for validation
- Consider creating open-source reference models
- Investigate better definitions or vocabulary to clarify what's being seen
- Explore farm-to-farm blockage effect

Commercial issues

- List benefits for open data access
- OEMs should provide a clear definition of the wind speed used for power curves
- Definitions should be captured in standards
- There is a need to integrate with the Power Curve Working Group

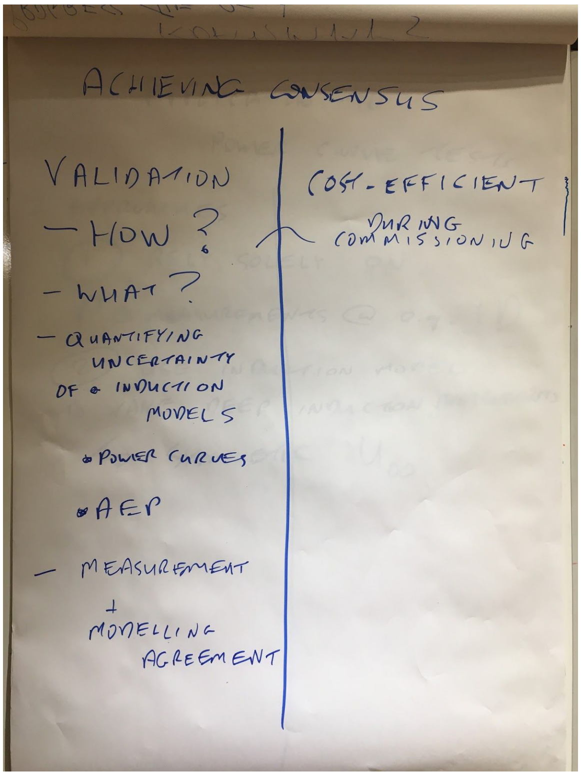
Group 2



Roadmap for making progress

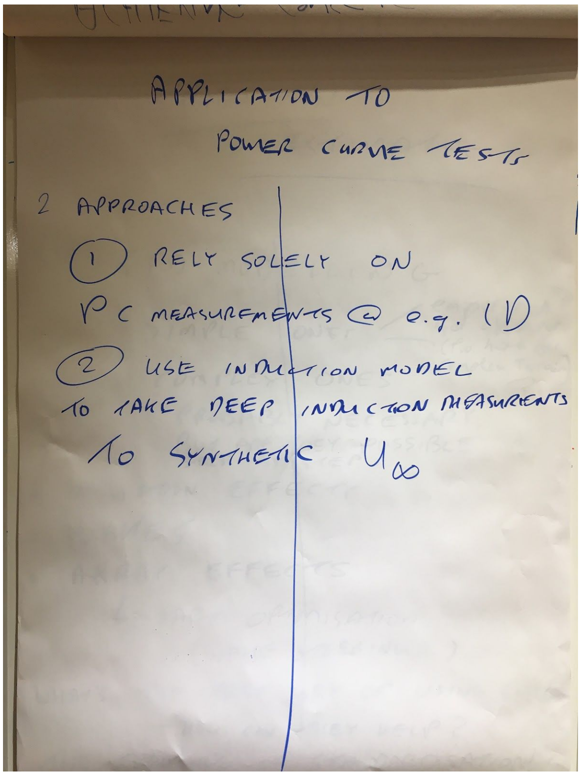
R&D activities:

- Collate the workshop results
- Assess availability of existing data in complex terrain and that might show array effects. This will have implications for IP / ownership and anonymity
- Plan future campaigns that are aimed at validation and align them with other groups, e.g…
    - for power performance measured deep in the induction zone by nacelle lidar
    - for AEP measurements, e.g. in collaboration with the RECAST project



How to achieve consensus

Most of the activities required here were R&D-related. The key was felt to be validation of models so that the uncertainty of any models was known. This would include models of the induction zone but also their implication for power curves and AEP. It was noted that this validation effort would need significant commercial support.

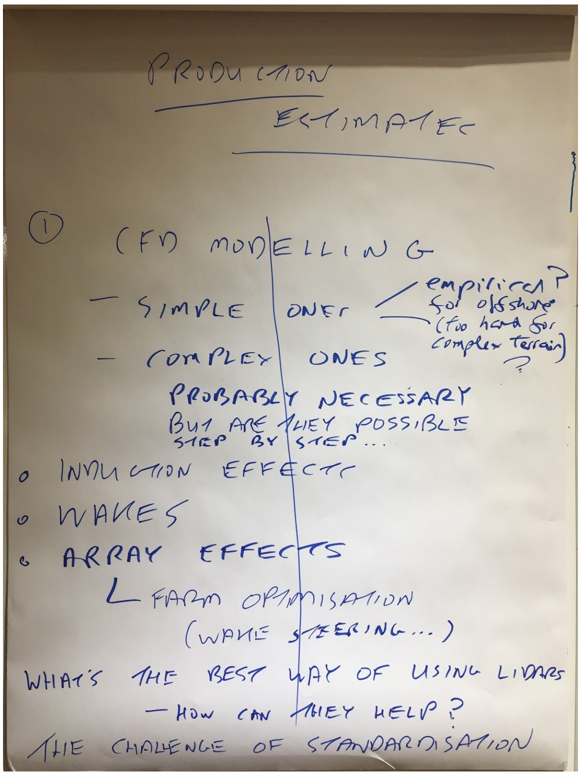


Application to power curve tests

This group felt that there appear to be two approaches:

1. Rely solely on power curve measurements made at a specific distance, e.g. 1D, or
2. Use an induction zone model to estimate a synthetic U_∞ from measurements made within the induction zone.

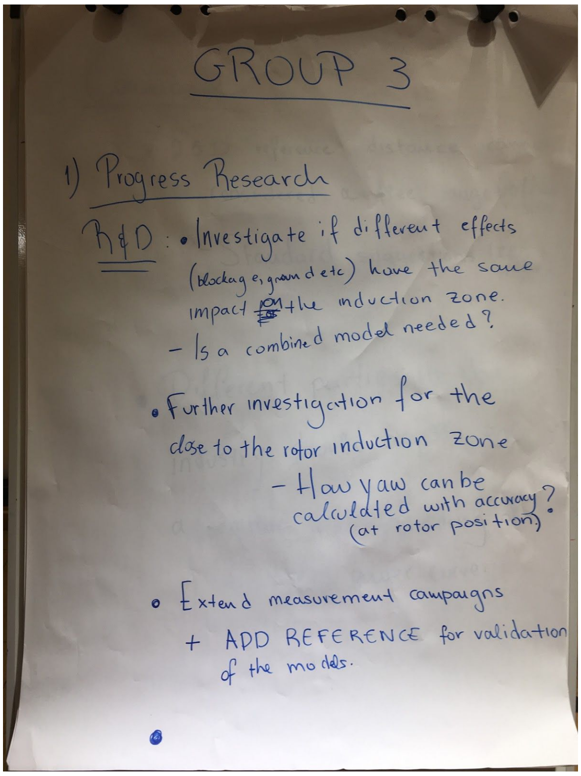
It was noted that (1) would make it extremely challenging to use the resulting power curves for resource assessment, while (2) might be more generally applicable - but requires validated models.



Application to production estimates

This group thought that there were several possible approaches to accounting for the induction zone in production estimates; CFD based or model based. CFD tools would have an advantage through being able to capture mutiple physics-based effects simultaneously, if they were included in the CFD tool. Alternatively, induction and blockage effects could be added to the loss budget of a wind plant. The group also identified that it was not clear how lidar would help at this stage of a project, or how such approaches would be included in standards.

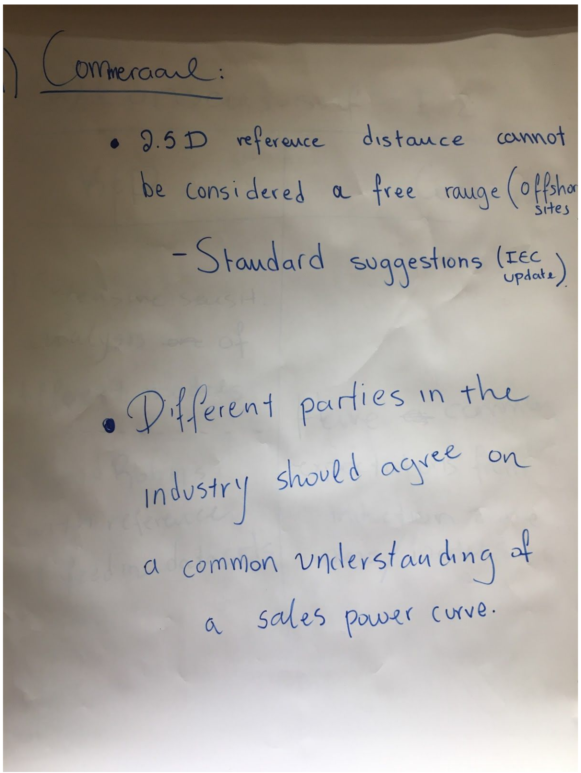
Group 3



How to progress research

R&D issues

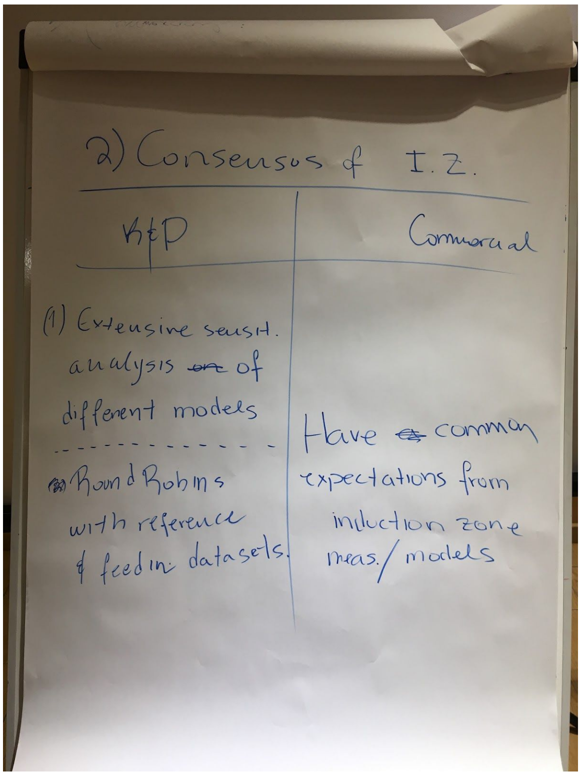
- Investigate if different effects (blockage, ground, etc) have the same impact on the induction zone; is a combined model needed?
- Further investigations about the use of lidar close to the induction zone. e.g. how can yaw can be calculated with accuracy?
- There's a need for more, and longer, measurement campaigns that include one or more reference points that can be used for model validation



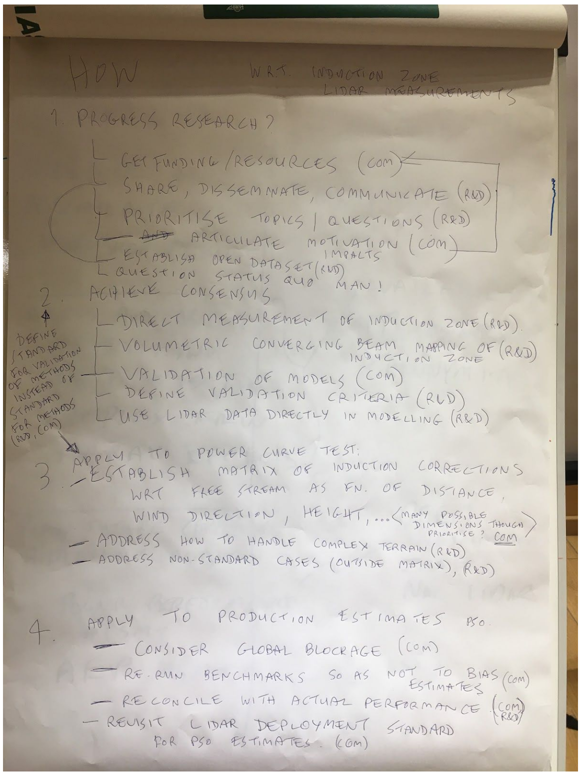
Commercial issues

- It appears that 2.5D cannot be considered to be in the free stream.
- This may need to be included in an update to standards
- There appear to be several different definitions of wind speed and power in use in a wind turbine's sales power curve. It would be helpful for the terms to be clearly defined.

It was noted that there are supporting activities taking place in the Power Curve Working Group

 	**What would help make consensus?** R&D activities: ● Extensive sensitivity study of different models ● Round-robins with separate training and testing data sets Commercial activities: ● Having common expectations for induction zone measurements and models

Group 4



How can we progress research?

- Commercial groups have to help researchers understand the need and impacts, and provide / help access funding
- R&D community needs to prioritise research into impactful questions
- R&D needs to share, disseminate, and communicate
- Open data sets would help both sides

How can we achieve consensus?

- Direct measurement of the shape and extent of the induction zone (e.g. using masts, drones, or convergent-beam lidar) would provide evidence and data for model validation
- Need to agree validation criteria
- Define standards for method validation, not standards for methods.

How can we apply this to power curves tests?

- Establish a matrix of corrections to power curve met tower data, based on distance, direction, etc.
- Address how to handle complex terrain and conditions that are not captured in the matrix

How can these be used for performance estimates?

We should consider blockage effects
Blockage effects should be included in benchmarking effects as they may introduce bias
Blockage effects may also be important for observed performance
Standards should be revisited as current measurement methods may place towers and or lidar in the induction zone for some wind directions

Comments from IEA Wind Task 32

This workshop illuminated several issues:

1. That there is a need to repeat this round robin, possibly using the same data or a new data set. Ideally such a data set should include some reference data set. Task 32 will gladly support such an initiative.
2. Because of the range of possible methods and the many different ways that they could be used, it seems unrealistic to develop standards for methods that account for the effect of the induction zone or of wind plant blockage. Instead it appears that it is more sensible to look for ways to demonstrate that the methods have been validated.
3. There is a need for an up-to-date community glossary or dictionary of terms. Task 32 would be happy to host such a document or tool, but would need input to do so. Also, it is clear that all members of the community - consultants, researchers, OEMs - should provide detailed information about the definition of the wind speed data that they are using.

Close

17:00	**Close**

The workshop closed at approximately 18:00. The organizers and participants were thanked for their hard work.

Participant List

1	Alix Pradel	Engie Green
2	Alkistis Papetta	IWES Fraunhofer
3	Andy Clifton	Stuttgart Wind Energy at Institute of Aircraft Design, U. Stuttgart
4	Camille Dubreuil	Equinor
5	Chris Slinger	ZX Lidars
6	Christophe Lepaysan	EPSILINE
7	Claude Abiven	natural power
8	Daniel Cabezon	EDPR
9	David Schlipf	Flensburg University of Applied Sciences
10	Demetrios Zigras	Nordex Group
11	Frank Klintø	Suzlon
12	Gibson Kersting	E.ON Climate & Renewables
13	Graham Hawkes	Frazer-Nash
14	Greg Poulos	ArcVera
15	Iñaki Lezaun Mas	SGRE
16	Jason Fields	NREL National Wind Technology Center
17	Jochen Cleve	Ørsted
18	Julien Tissot	Leosphere
19	Márcio Ferreira	ENERCON GmbH
20	Martin Koch	sowento
21	Martin Strack	Deutsche WindGuard Consulting
22	Nicolai Gayle Nygaard	Ørsted
23	Olivia Brissette	ENGIE Laborelec
24	Paul Housley	SSE
25	Pedro Jorge	GE
26	Peter Clive	Wood - Clean Energy
27	Rebeca Rivera Lamata	Ørsted
28	Stefan Goossens	Vattenfall
29	Taylor Geer	DNV GL
30	Theo Holtom	Wind Farm Analytics
31	Vishwanath Hange	Enel Green Power India Pvt Ltd