Power Curve Working Group Agenda

Impact of 'non-standard' inflow

4th Meeting Minutes, Thursday 19th September 2013, Vestas R&D, Aarhus, Denmark

Theme: The 1st meeting gave a clear statement of the problem. The 2nd meeting examined possible solutions. The 3rd meeting put some of those solutions into practice. The 4th meeting consolidated the learning to date by examining new datasets.

Attending: Andrew Tindal (GL DNV), Erik Tuxen (GL DNV), Richard Whiting (GL DNV), Anna Marsh (GL DNV), Rozenn Wagner (DTU), Oisin Brady (Natural Power), Ralph Torr (Sgurr), Michael Pram Nielsen (Vestas), Yavor V. Hristov (Vestas), Thomas Blodau (Repower), Daniel Bendel (Repower), Daniel Stevens (SSE), Peter Stuart (RES), Alan Derrick (RES), Anabel Gammidge (RWE), Axel Albers (Wind Guard), Jørgen Højstrup (Højstrup Wind Energy), Jared Kassebaum (EDF), Lasse Svenningsen (EMD), Samuel Davoust (Leosphere), Stuart Baylis (Prevailing), Diego Azofra (Barlovento), Jean-Marc Thevenoud (Leosphere) and Herbert Schwartz (Anemos-Jacob).

Key Outcomes:

- **The working group has demonstrated that it can consistently apply the rotor equivalent wind speed method.**
- **Further work is required to build consensus on how to apply the turbulence renormalisation method.**
- **Both the time series and binned/frequency distribution approaches have been shown to give consistent results for both the equivalent wind speed and turbulence renormalisation methods.**
- **The rotor equivalent wind speed and turbulence renormalisation methods have been demonstrated to combine linearly and hence can be applied independently.**
- **The working group plans to work towards publishing a consensus analysis of the round robin datasets.**
- **The working group plans to focus on validating the rotor equivalent wind speed and turbulence renormalisation methods. Securing appropriate validation datasets is critical.**
- **The working group plans to work towards publishing a statement on the benefits of the inner/outer range proposal.**

Presentations:

- “01 Review of Previous Meetings” Daniel Stevens SSE
- “02 Round Robin Results Overview” Peter Stuart (RES)
- “03 Round Robin Impact of High Wind Shear Introduction” Anna Marsh (GL DNV)
- “04 Round Robin Impact of Turbulence Introduction” Anabel Gammidge (RWE)
- “05 Numerical Modeling ” Peter Stuart (RES)
- “06 Extended RR2 Analysis” Axel Albers (Wind Guard)
- “07a The role CFD Modelling” , Oisin Brady (Natural Power)
- “07b The role CFD Modelling” , Yavor V. Hristov (Vestas)
- “07c The role CFD Modelling” , Richard Whiting (GL DNV)

Minutes of Discussion

Round Robin Exercise 2: Dataset Overview

Three datasets were provided each consisting of a co-located mast and LiDAR:

- Dataset 1: Cold climate moderately complex forested site with moderate tree height.
- Dataset 2: Flat terrain site (no forestry).
- Dataset 3: Densely Forested site

In a change from the first round robin all datasets were pre-filtered to eliminate discrepancies between participant results due to filtering strategies. Participants were also asked to calculate the ‘Specific Energy Production’ (SEP) i.e. the energy production for the specific time periods provided. Hence gap-filling and annualisation were unnecessary which eliminated additional sources of discrepancy. These simplifications allowed participants to focus solely on the methodologies of primary interest to the working group.

Round Robin Exercise 2.1: Wind Shear (Rotor Equivalent Wind Speed)

The first exercise was to calculate the SEP of each of the three datasets considering rotor equivalent wind speed. An introduction to the exercise was presented by Anna Marsh of GL DNV (see *'03 Round Robin: Impact of High Wind Shear Introduction'* for further details) who contrasted the wind shear behaviour across the three sites. A comparison of the results of the participants was presented (relative to a base case of a hub height wind speed assessment) as shown in Figures 1a-c. The results showed good agreement in the majority of cases with some outliers. Dataset 1 was analysed with both time series and frequency distribution methods which also showed good agreement.

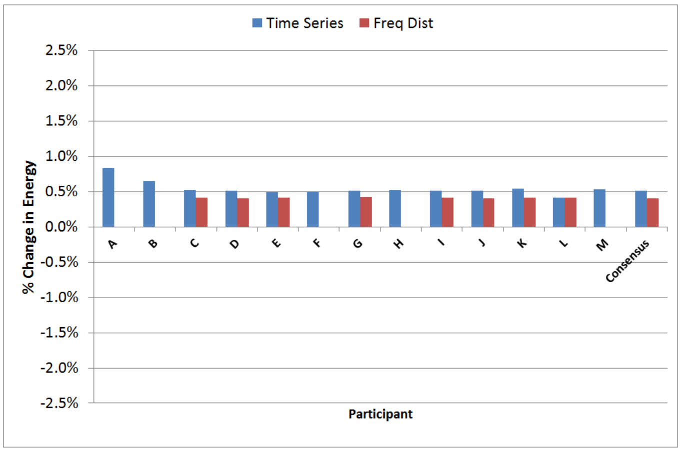

Figure 1a. Comparison of participant results for Exercise 2.1 - Dataset 1

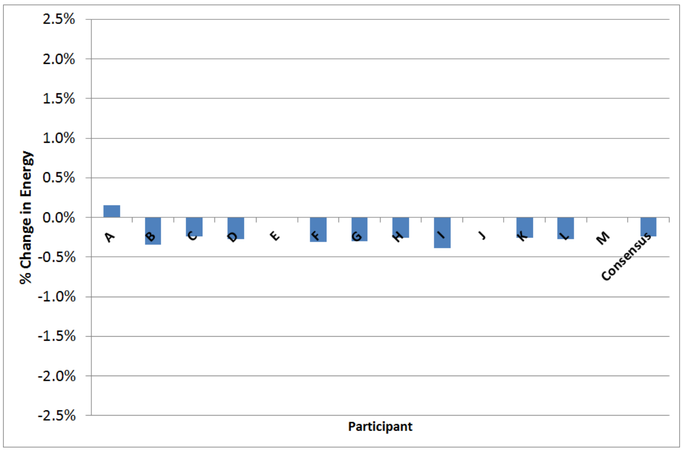

Figure 1b. Comparison of participant results for Exercise 2.1 - Dataset 2

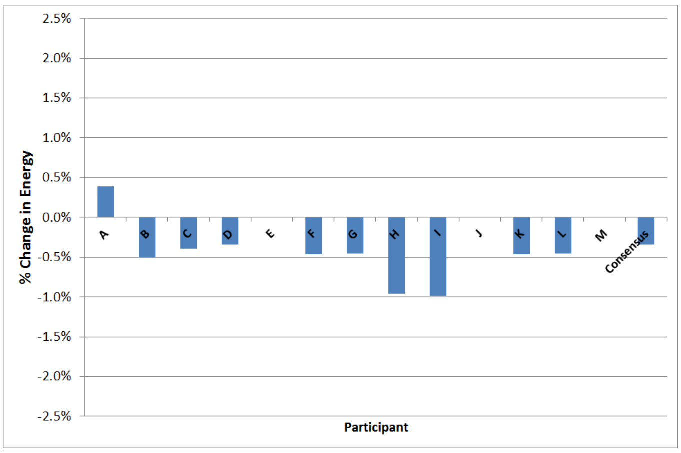

Figure 1c. Comparison of participant results for Exercise 2.1 - Dataset 3

Round Robin Exercise 2.2: Turbulence

The second exercise was to calculate the SEP of each of the three datasets considering the turbulence re-normalisation scheme proposed as an informative in the draft IEC power performance standard. An introduction to the exercise was presented by Anabel Gammidge of RWE (see *'04 Round Robin: Impact of Turbulence Introduction'* for further details). A comparison of the results of the participants was presented (relative to a base case of no adjustment for turbulence) as shown in Figures 2a-c. The results showed less consistent agreement than those for Exercise 2.1 suggesting that the group found the turbulence renormalisation method more difficult to understand and apply than the rotor equivalent wind speed method.

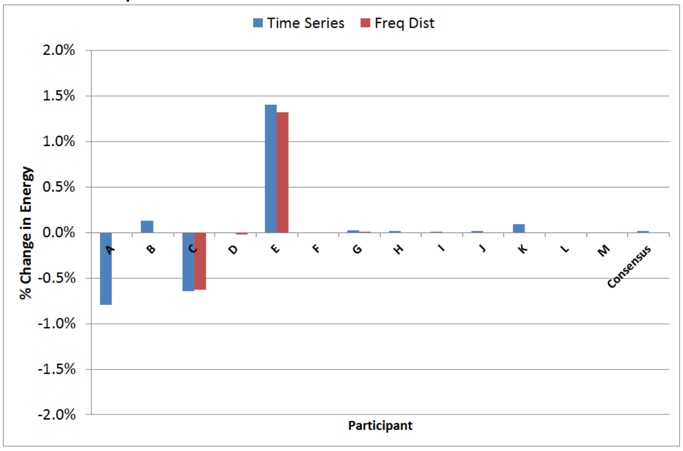

Figure 2a. Comparison of participant results for Exercise 2.2 - Dataset 1

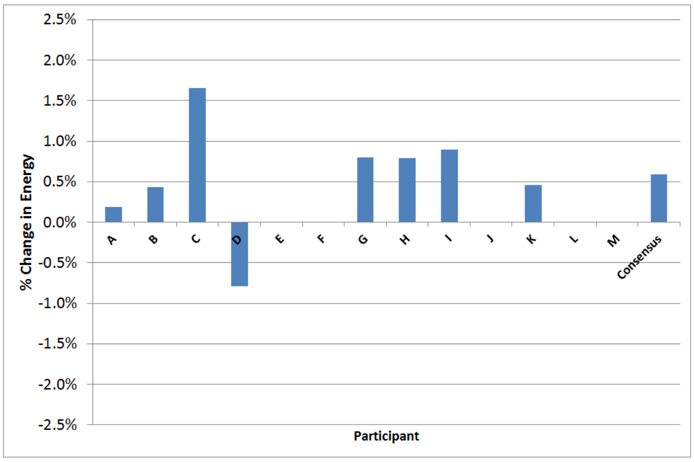

Figure 2b. Comparison of participant results for Exercise 2.2 - Dataset 2

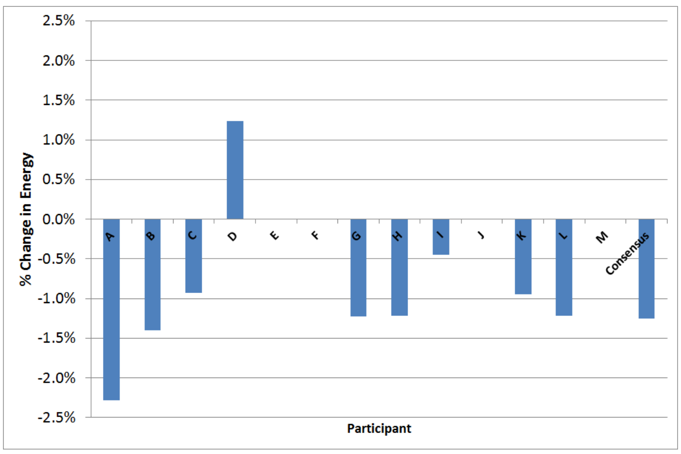

Figure 2c. Comparison of participant results for Exercise 2.2 - Dataset 3

Round Robin Exercise 2.3: Wind Shear and Turbulence

The third exercise was to calculate the SEP of each of the three datasets considering both the rotor equivalent wind speed and turbulence re-normalisation methods. A comparison of the results of the participants was presented (relative to a base case of no adjustment for turbulence) as shown in Figures 3a-c.

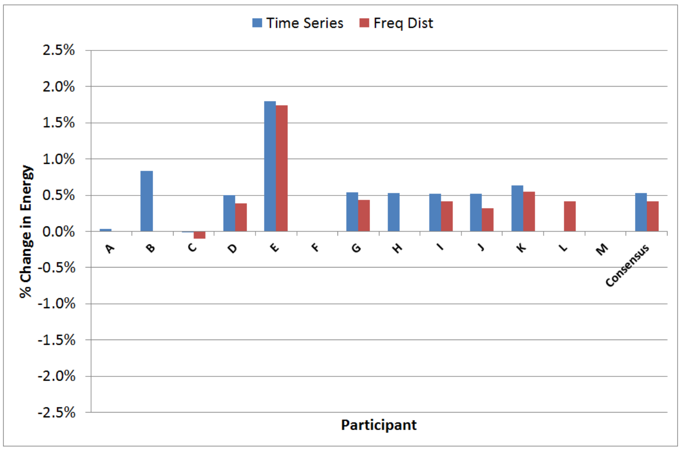

Figure 3a. Comparison of participant results for Exercise 2.3 - Dataset 1

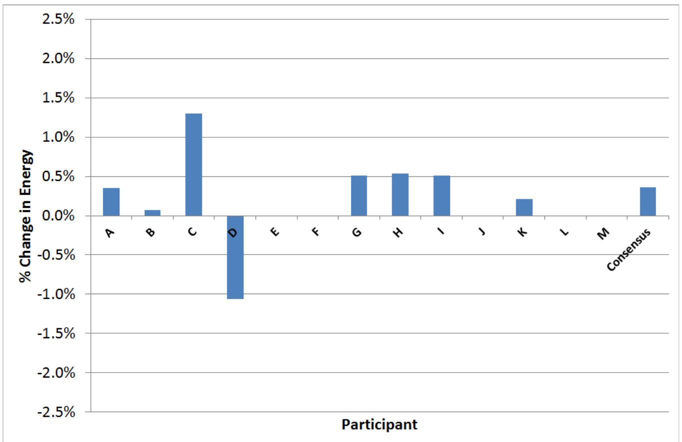

Figure 3b. Comparison of participant results for Exercise 2.3 - Dataset 2

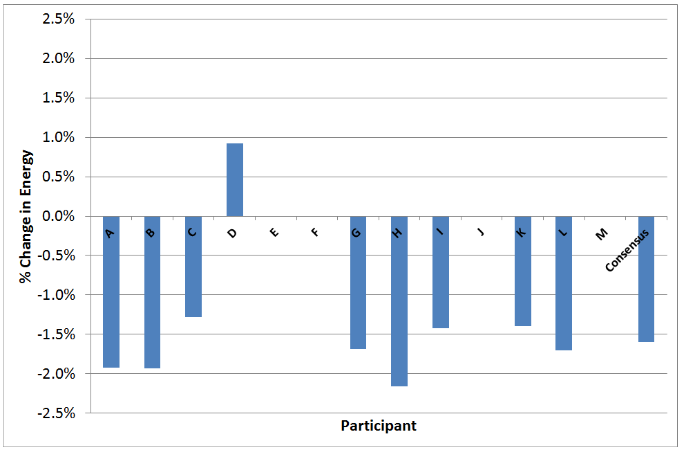

Figure 3c. Comparison of participant results for Exercise 2.3 - Dataset 3

Supplemental Comparison: Rotor Levels used for Exercise 2.1 (Rotor Equivalent Wind Speed)

In an attempt to understand the possible reasons for the disparity in the results for Exercise 2.1 participants were asked to provide details of the rotor levels used in their calculations. Comparisons of the rotor levels and associated SEP results are made in Figures 4a-4c. It can be seen that the choice of rotor levels for participant A and I do not explain why their results differ from the other participants. Hence while in principle the choice of rotor levels could explain some of the disparity between the participants it does not seem to be the primary reason.

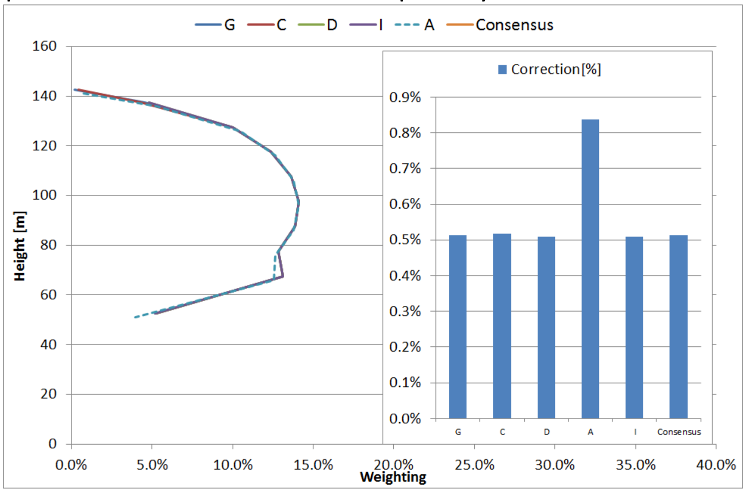

Figure 4a. Comparison of rotor levels used for Exercise 2.2 - Dataset 1 (with results inset)

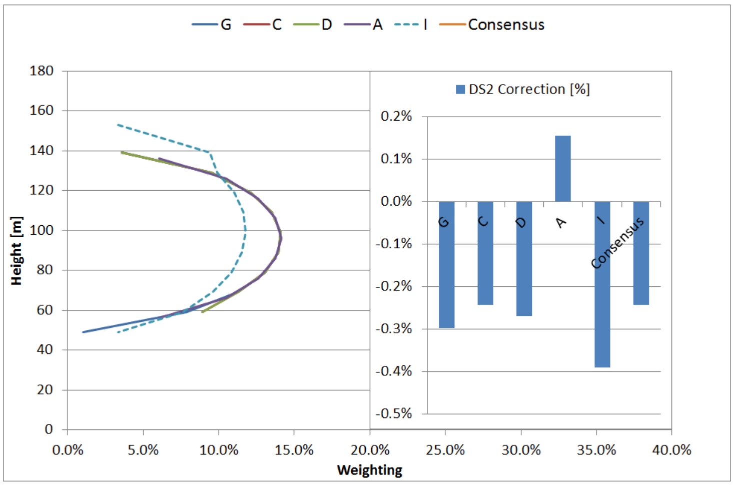

Figure 4b. Comparison of rotor levels used for Exercise 2.2 - Dataset 2 (with results inset)

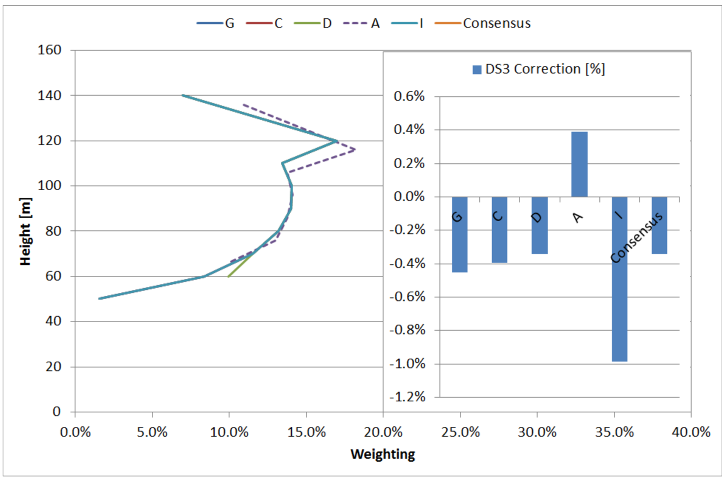

Figure 4c. Comparison of rotor levels used for Exercise 2.2 - Dataset 3 (with results inset)

Supplemental Comparison: Zero Turbulence Power Curves used for Exercise 2.3 (Turbulence)

In an attempt to understand the possible reasons for the disparity in the results for Exercise 2.2 participants were asked to provide their zero turbulence power curves. Comparisons of the zero turbulence curves and associated SEP results are made in Figures 4a-4c. It can be seen that the disparity in the zero turbulence curve for participant C could explain why their results differ from the other participants. The zero turbulence curves for the remaining participants showed good agreement. It was noted by the group that some participants had forced their zero turbulence curves to stay below rated while others allowed their zero turbulence curves to exceed rated. It was noted that the draft standard implies that the zero turbulence curve can exceed rated. Hence while in principle the calculation of the zero turbulence curve could explain some of the disparity between the participants it does not seem to be the sole reason.

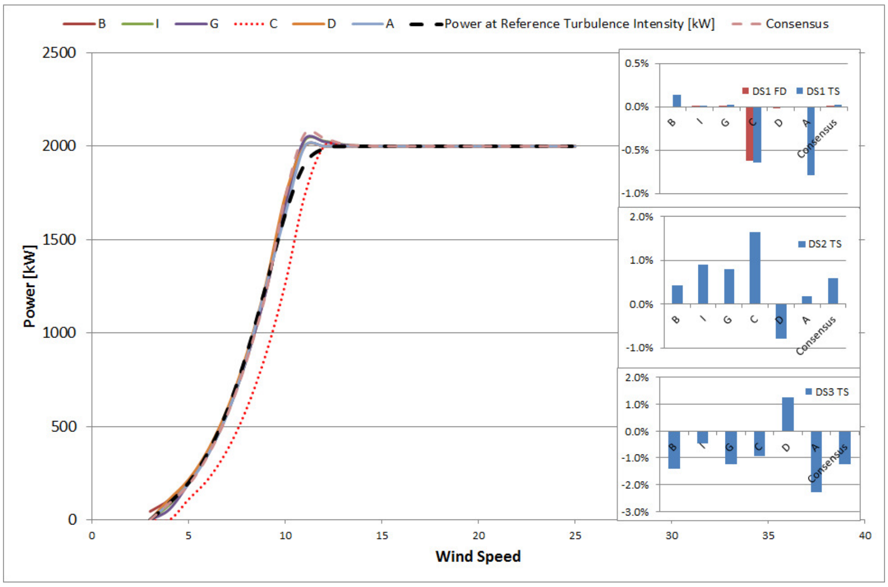

Figure 5. Comparison of participant zero turbulence power curves (with turbulence results inset)

Supplemental Comparison: Linearity of Methods

The participant results were tested to see if it is possible to apply the rotor equivalent wind speed and turbulence renormalisation methods independently. Figure 6 indicates that there is almost no difference in the results if the corrections are applied independently and then combined (Exercise 2.1 * Exercise 2.2) compared to if they are calculated at the same time (Exercise 2.3).

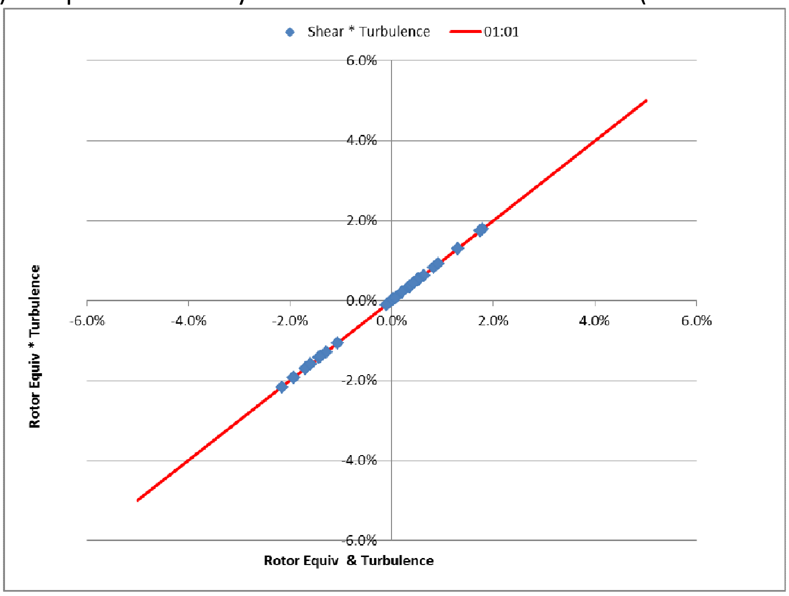

Figure 6. Test of linearity of results i.e. Exercises 2.2 * 2.1 (y-axis) vs. Exercise 2.3 (x-axis)

Supplemental Comparison: Time-series vs. Frequency Distribution

The participant results were tested to see if the time series and frequency distribution methods give similar values. Figure 7 indicates that there is very good agreement between time series and frequency distribution methods across the participants.

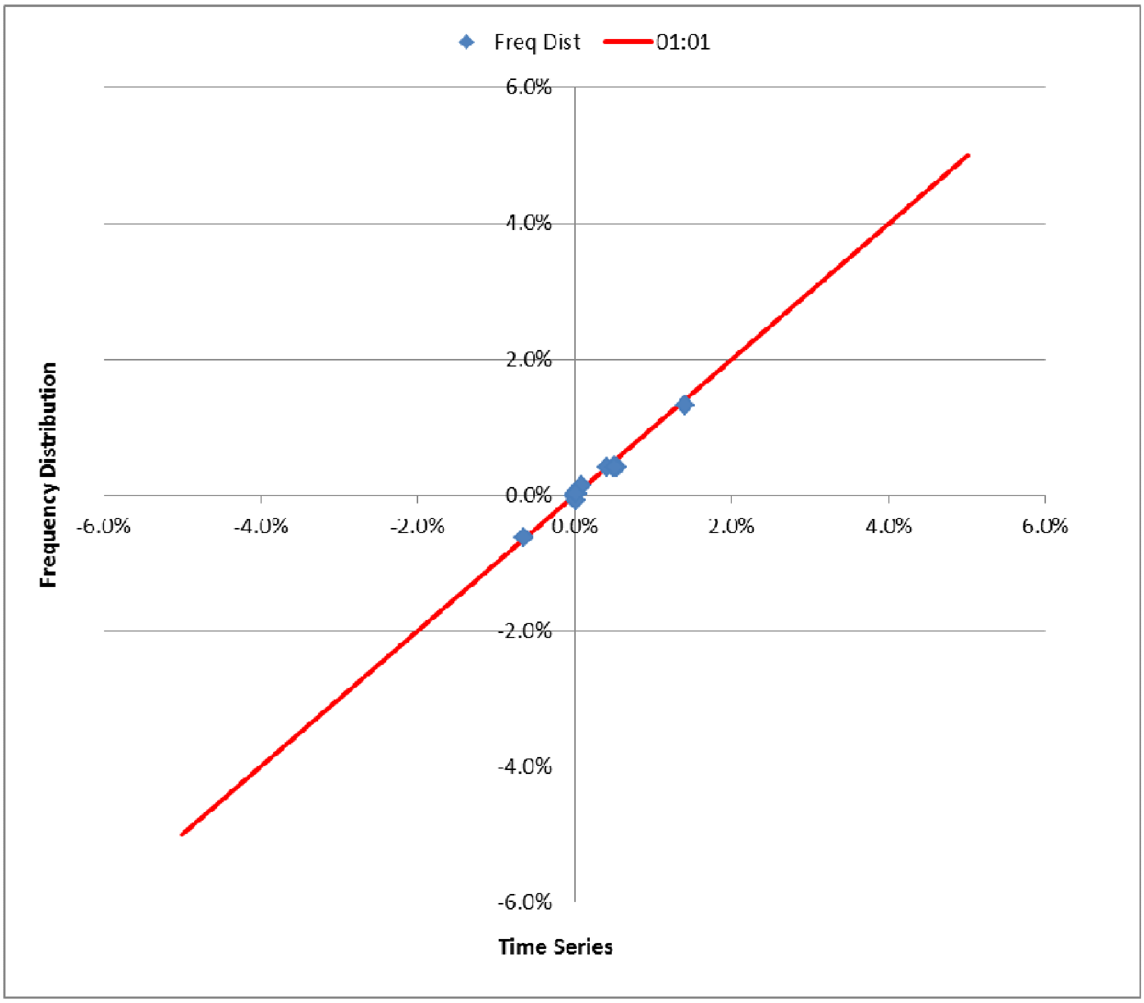

Figure 7. Comparison of Time Series (x-axis) and Frequency Distribution (y-axis) Methods. Each blue dot represents a set of participant results submitted for both time series and frequency distribution.

Morning Presentation Session

After the comparison of round robin results the group had a presentation session:

- Peter Stuart presented the results from a numerical modelling study (see *'05 Numerical Modeling*' for further details). The study combined the numerical results of the turbulence renormalisation method with an empirical observation of the relationship between shear, turbulence and rotor equivalent wind speed. The model demonstrates how performance degradation associated with turbulence renormalisation and shear relaxation (rotor equivalent wind speed less than hub wind speed) can be coincident. The results were compared qualitatively with power performance data.

- Axel Albers presented the some additional results using the round robin datasets (see ' 06 Extended RR2 Analysis' for further details). The results indicate that in all cases time series and frequency distribution methods give very similar results. The results also support the conclusion that the rotor equivalent wind speed and turbulence renormalisation methods are highly linear and can be applied independently.

- Two brief presentations were made on the role of CFD modelling in correcting power curves for non-standard conditions:

  - "07a The role CFD Modelling" , Oisin Brady (Natural Power)
  - "07b The role CFD Modelling" , Yavor V. Hristov (Vestas)
  - "07c The role CFD Modelling" , Richard Whiting (GL DNV)

Morning Discussion Session

A comparison between the inner/outer range concept and the round robin results was presented. It was agreed that the comparison was not helpful as it was not comparing like for like.

The group discussed what actions would help consolidate the progress to date related to common understanding of the rotor equivalent wind speed and turbulence renormalisation correction methods. It was agreed that the datasets should be extended to include a standardised calculation of mast hub height wind speed and turbulence intensity. One group member said that they believed there was an issue in terms of standardising language e.g. the terms 'shear correction' and 'profile correction' are used by some interchangeably and could be open to different interpretations.

Rotor Equivalent Wind Speed

The rotor equivalent wind speed method was discussed by the group. It was agreed that the round robin results demonstrate the ability of the group to apply this method consistently. The group discussed the concept of creating a 'consensus analysis' for the round robin exercises i.e. an open set of analysis that could be reviewed/agreed by the entire working group. The group agreed to prepare a consensus analysis for the rotor equivalent wind speed method[1].

Turbulence Renormalisation

The turbulence renormalisation method was discussed by the group. In contrast to the rotor equivalent wind speed method the turbulence renormalisation results show a relatively large level of disagreement. It was agreed that the round robin results demonstrate that the group needs to further develop its ability to apply this method consistently[2]. The group agreed that the calculation of the zero turbulence power was one potential source of discrepancy. It was also agreed that including a standardised calculation of hub height turbulence in the dataset would help improve agreement[3]. One consultant commented that there are several sub-steps to the calculation; calculation of power at zero turbulence, calculation at site specific turbulence, power curve interpolation etc. It was noted by the group that the formulas in the draft power performance standard (Annex M) need to be modified slightly (change of signs) so that they can be applied in the resource assessment context (see slide 3 of '06 Extended RR2 Analysis' for further details). One consultant commented that the choice of bin size is very important in the integration across the Gaussian distribution and that a maximum bin size of 0.1m/s should still be used (which is still quite a large step for low turbulence intensity values).

Time Series vs. Frequency Distribution

The group noted the impressive level of agreement between the time series and binned/frequency distribution approaches. It was commented that this is encouraging as the frequency distribution methods are potentially easier to apply in practice. One consultant said that in general it should be sufficient to a apply rotor equivalent wind speed distribution (as a function of wind speed) to a site specific power curve power curve which has been adjusted for site specific turbulence and shear (as a function of wind speed). The same consultant then expanded on the details of the specific shear adjustment (see slide 10 of '06 Extended RR2 Analysis' for further details). The consultant commented that the round robin exercises has been defined in such a way that the shear renormalisation is not required i.e. participants have been told to assume that the same power curve is valid for both hub height and rotor equivalent wind speed ($f_{r,ref}$=1).

<u>Afternoon Discussion Session</u>

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[1] Subsequent to the September meeting the rotor equivalent wind speed consensus analysis has been agreed by the group. A comparison with the consensus analysis and round robin results has been included in the preceding sections.

[2] In a subsequent working group conference call it was agreed to extend the consensus analysis to the turbulence renormalisation methods. The turbulence renormalisation consensus analysis has been completed and is currently being reviewed by the working group. A comparison with the consensus analysis and round robin results has been included in the preceding sections.

[3] A standardised calculation of turbulence intensity at hub height has now been included in the datasets in DropBox.

Validation

The group agreed that having built consensus around how to apply the rotor equivalent wind speed and turbulence renormalisation methods the next key step is validating these methods. One consultant commented that although the effects are relatively small this shouldn't mean that they cannot be separated out and verified. One manufacturer said that validation is also important to establish the limitations of the corrections i.e. to determine where 'Type B effects' start to occur. One developer commented that the focus of the validation needs to remain the resource assessment context (as opposed to the power performance context). The group discussed the ideal dataset for a validating the methods. It was agreed that concurrent mast, tip-height (e.g. LiDAR) and power measurements would be most suitable. One developer said that he felt that this measurement set up would be common in the future, but is probably in short supply now. The group identified the following potential datasets:

- The current round robin dataset 1 already includes mast, LiDAR and power data. Although already available to the group, it was agreed that this dataset should be packaged up in a more convenient form to facilitate validation.

- Several other developers said that they may have concurrent mast, LiDAR and power datasets in the near future and would investigate.

The different levels of access were briefly discussed:

- Full access to all data (e.g. Dataset 1).

- Access to screened data.

- No direct access to data, but presentation of results within the working group.

Type A vs. Type B

The issue of Type A (available energy) vs. Type B (conversion efficiency) corrections was discussed by the group. One manufacturer commented that there may be Type B effects at low air density and also potentially at very low and very high turbulence. Another manufacturer mentioned a potential issue with cut-in and cut-out whereby if a turbine is controlled with a nacelle anemometer it may not cut in at low wind speed, even though the rotor equivalent wind speed would say there is sufficient wind to do so. One manufacturer commented that they believed that Type A effects dominate. One consultant said that he believed that Type B effects cannot be discounted. Another consultant said that they believe Type B effects can only be identified after Type B effects have been removed. Another consultant commented that validation may demonstrate that some empirical factor applied to the correction methods may give the best result. One consultant commented that Type B effects could be examined using aero-elastic models i.e. modelling the power using more detailed aero-elastic models and then comparing to simpler models (e.g. rotor equivalent wind speed and turbulence renormalisation). One manufacturer questioned the value of such an approach and commented that Type A effects are machine independent while Type B effects are machine specific. It was agreed that gathering validation datasets was key to progressing the 'Type A vs. Type B' issue.

Working Group Stakeholder Engagement

The issue of active participation in the working group was raised. One developer commented that active engagement was required from all stakeholders in order to make meaningful progress on the issue. The same developer added that things are moving a certain way and expected developers and consultants to act unilaterally in the absence of participation from the remaining stakeholders.

Proxy Methods

The concept of 'proxy methods' was discussed by the group i.e. how to account for the shear/profile correction in the absence of tip-height (e.g. LiDAR) data. One consultant commented that there is a large body of concurrent power and mast data (in contrast to the small volume of available LiDAR data). The same consultant added that the advantage of the proxy methods is that they make use of this large volume of data e.g. by building a matrix of power deviations as a function of shear, turbulence etc. It was commented that several consultants have already established different proxy methods and have identified many of the same 'shapes and trends'. One manufacturer commented that plotting power deviations as a function of turbulence and wind speed (for different shear ranges) was a useful diagnostic. One consultant commented that when the matrices were established in the right way it was surprising to see the level of commonality between markets and that the real difference was the frequency of the difference matrix bins. One developer said that if a proxy can be determined for rotor equivalent wind speed (e.g. rotor equivalent wind speed as a function of turbulence) then it would be possible to use the same methods (rotor equivalent wind speed and turbulence renormalisation) regardless of the data that's available. The group agreed that further work was required to determine the most effective proxy method and that the validation datasets would be critical in doing so.

Inflow Angle and Complex Terrain

The current focus of the group on shear and turbulence was contested. Some members of the group felt that this was inappropriate as other effects may be more significant in certain circumstances (e.g. large inflow angles associated with complex terrain). It was commented that the current round robin datasets are in non-complex terrain and that there is a general issue with obtaining reliable LiDAR data in complex terrain. One consultant commented that in order to make progress in the short term it made sense to use datasets with lower measurement uncertainty. One manufacturer said the group should move to examining complex terrain over time. One developer said that it should be noted that simple terrain sites are still very common and important to get right. The group agreed to keep the focus on shear and turbulence for now and to revisit the issue of inflow angle (and complex terrain) in 2014.

Inner/Outer Range Proposal

The manufacturers were asked to give their thoughts on the Inner/Outer range proposal (introduced in previous meetings). One manufacturer said that they hadn't discussed it in detail internally, but liked the pragmatism of this approach. Another manufacturer added that it was simple to apply and well suited to defining the warranty. One manufacturer commented that detailed matrices of performance deviations were not practical for warranties and their role was more for resource assessment calculations i.e. the inner/outer range is a more appropriate concept for warranties. One manufacturer commented that the current contractual cover is often very limited and that the inner/outer range proposal could extend this by either broadening the definition of the inner range (i.e. extending the power performance filters) or offering a reduced guarantee in the outer range. This would have the secondary benefit leading to a faster power performance test i.e. as less data would be rejected the data capture thresholds would be reached sooner. One developer asked if the inner range definition would be machine independent to which a manufacturer replied that it was always likely to be machine dependent. One developer commented that a strength of the inner/outer range proposal was its relative simplicity and that it could be easily understood by non-technical people involved in the contractual arrangements. The group agreed that the main application for the inner/outer range concept was as a warranty tool (as opposed to calculating the most accurate energy yield). One consultant commented that it would be good to reach out to manufacturers not involved with the group regarding this concept. The group agreed to publically issue a document (2-3 pages) explaining the inner/outer range concept and the benefits. Feedback will be sought from all manufacturers (including those not currently involved with the working group).

Rotor Equivalent Wind Speed and Veer

The group briefly discussed that the round robin exercises did not consider the vertical veer when calculating the rotor equivalent wind speed. It was agreed that this would need to be addressed in future, but that it should not hold up the validation.

AWEA Conference Presentation

The group was informed that Andy Clifton[4] of NREL had been asked by AWEA to give a presentation at their annual conference in Las Vegas. The presentation will cover the progress of the working group (analogous to presentation at Dublin EWEA Workshop by Peter Stuart). The group agreed that Andy should accept the invitation to speak.

Next Meeting

It was agreed that the next meeting would be hosted by SSE on the 4th of December 2013 (date changed to avoid clash with AWEA). It was agreed that the theme of the December meeting would be validation.

DTU offered to host a working group meeting in 2014. It was agreed that one of the 2014 meetings would be held in London.

[4] Subsequent to the working group meeting the speaker was changed to Jason Fields of NREL.