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Interactive comment on "The Power Curve Working Group's Assessment of Wind Turbine Power Performance Prediction Methods" *by* Joseph C. Y. Lee et al.

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We thank the reader for conducting a comprehensive review to improve our manuscript. Specifically, we thank the reader for providing comments on some of our word choices, and the edits we made according to your comments notably improve the manuscript. The reader also recommended many additions to enhance the context of the manuscript, and we adapted a lot of your suggestions we find relevant.

In the following, the reviewer's comments are labeled by the line number in the original manuscript submission, followed by our comments beginning with "Response:".

Line 29: Maybe consider adding, already here, that the power curve does not depend only on the wind speed: *hub height* wind speed, and valid for a given air density, a range of turbulence intensities at hub height and a range power-law shear exponents across the rotor plane.

Response: Lines 28 to 30 now read:

"Current industry practices involve predicting power output using a power curve, which defines power production as a function of hub-height wind speed. Besides the traditional understanding of a power curve, wind power production also depends on other meteorological variables including air density, turbulence, and wind shear."

Line 40: , for a given wind speed distribution.

Response: The phrase "site-specific", used earlier in the sentence, already implies the test is performed for a specific wind-speed distribution.

Line 40: It is a bit unclear if the objective of the test is to compare AEPs, or binned power values. I believe it is both in the IEC61400-12, yet eventually the main output of the analysis is an AEP number + an uncertainty. In some (most?) TSAs the metric that is used is the AEP.

Response: In this sentence, we focus on the binned power values of the test. We believe that the AEP is ultimately more important, hence in this study, we focus on using NME instead of NMAE (Sect. 3.4). Lines 40 to 42 now read:

"The wind energy industry performs power performance tests on wind turbines to test the site-specific power production of wind turbines by calculating the difference between the power predicted by the reference power curve (often provided by the turbine manufacturers) and actual power production at different wind speeds."

Line 41: It could be interesting fpr the reader to refer to the IEC61400-12.

Response: We are discussing the standard in the next Section (Sect. 1.2) comprehen-

sively, and we want to focus on the challenge of the power curve herein.

Line 43: At this stage, it could have been nice for the reader to know than this range is defined by hub height TI and power-law shear exponent over the rotor.

Response: When we introduce the Inner Range and the Outer Range, we immediately add a sentence for the readers to refer to Sect. 3.1 in line 35: “The definitions are discussed in detail in Sect. 3.1.”. We choose not to discuss the full definitions in the Introduction because we want to highlight the power curve challenge in Sect. 1.1, and we are dedicating a full subsection for the Inner Range and Outer Range definitions in the manuscript.

Lines 44, 46, 105: Inner Range ?; lines 135 to 136: this is a bit unclear: do you refer to the power curve measured during prototype testing ? what is the reference power curve - the inner range power curve ?

Response: Thank you for asking for clarification. The reference power curve is not the Inner Range power curve, as discussed in Sect. 3.1 and 3.2. As suggested by another reviewer, lines 214 to 217 now read:

“Note that the Inner Range Power Curve is only valid for a subset of TI and wind shear conditions (Table 2), which resembles the premise of a typical reference power curve provided by turbine manufacturers. The Inner Range power curve is derived from the observed data, which differs from a reference power curve. We also do not use any reference power curves in this analysis because we do not require the participants of the Share-3 exercise to share them.”

When we first mention the reference power curve in the manuscript, we now introduce more details. Lines 40 to 42 now read:

“The wind energy industry performs power performance tests on wind turbines to test the site-specific power production of wind turbines by calculating the difference between the power predicted by the reference power curve (often provided by the turbine

manufacturers) and actual power production at different wind speeds.”

Line 55: This is a bit unclear to me, can you provide the definition of "Power Deviation" using a formula ?

Response: Power deviation = Observed power − Reference power (or Predicted power), and this is added in line 56.

Line 60: You mean that they are not known ?

Response: We are implying that data sharing is limited within the industry, hence the data are isolated within their own organizations. We edited the following from lines 62 to 63:

“Additionally, the data that could be most useful for improving power-curve modeling are typically isolated within the industry, they are not shared between organizations, and their usage is stymied by intellectual property agreements.”

Line 69: The reader may want to know whether these methods are normative or informative.

Response: Informative methods are implied here since we are referring to the IEC standard.

Line: 78: Maybe add a reference.

Response: We do not have a reference that specifically discusses the omission of the correction methods. Herein, we highlight the need of correction methods. Lines 80 to 81 now read:

“More importantly, given the inaccuracy of power curve models, not employing any corrections leads to increased scatter of production measurements of the power curve.”

Line 79: hub height

Response: We added that to the text.

Line 80: This may imply that it wasn't known prior to 2017, or 2005, while it has been known for longer time, see for instance https://www.osti.gov/servlets/purl/6348447 (1990) or https://backend.orbit.dtu.dk/ws/portalfiles/portal/55566391/ris_m_2632.pdf (1987)

Response: Thank you. Per your suggestion, the word "since" is removed.

Line 81: Maybe add that this reference used model data (i.e. no measurements).

Response: Lines 84 to 85 now read:

"Clifton et al. (2013) demonstrated that simulated wind shear and TI impacted power performance with respect to the manufacturer's power curve in a clear and systematic way."

Line 85: It is unclear which of these references deal with power and loads, or just power, or just loads.

Response: We combined the references in one sentence, because herein we simply want to demonstrate that meteorological variables other than wind speed also affect wind energy production.

Line 88: What does "modern" mean in this context ?

Response: "Modern" means new data and techniques, such as remote sensing data and machine learning models, which are discussed in the following sentences.

Line 89: Maybe add a reference.

Response: This is the topic sentence of the paragraph, and the references are listed in subsequent sentences in the same paragraph.

Line 95: Maybe worth explaining what this means.

Response: This sentence summarizes the work from others, so specifying the variables may cause more confusion. It should be understood that the multidimensional

model includes other meteorological variables than wind speed, as discussed in this Sect. 1.2. We adjusted this sentence, and lines 101 to 103 now read:

"Recently, machine learning and neural networks that derive multidimensional power curve models involving many meteorological variables have grown in popularity."

Line 95: Do you mean these have been adopted by the industry ?

Response: Not necessarily, and we do not have the evidence to either support or deny a widespread adoption in the industry. Herein, we imply that these techniques have been popular topics for research.

Line 108: in the Outer Range.

Response: We do not limit our purpose to only Outer Range conditions, because the Outer Range changes with Inner Range conditions. In general, the Power Curve Working Group wants to benchmark the model effectiveness in all conditions, and mostly focuses on the Outer Range in this share initiative.

Line 122: It is not very clear what these data are, I assume these are datasets that fullfil the requirements of the IEC61400-12 for power performance testing. Also, it is not clear whether the datasets have been shared with a common, trusted third party, or if the data remained with the data owner and only the results were shared.

Response: These data sets were submitted for previous share initiatives from our participants, they should fulfill the IEC requirements, and they are owned by different organizations. Line 128 now reads:

"âIJŞ indicates method included in trial with at least 30 applicable summary statistics data sets submitted by the participants."

Line 134: can it be thought of differently ?

Response: "Thought of" is now changed to "interpreted".

Line 138: Isn't it contractual (i.e. a risk-mitigation measure for the manufacturer) ?

Response: It is possible. Herein, we are introducing Inner Range and Outer Range as a part of our research methodology, which is proposed by the Power Curve Working Group.

Line 141: You mean, by averaging a number of outerange AEP results from different test locations, or at the same site using different outer range datasets ? What I focused only a a subset of the outer range leading to larger AEP ? This statement is a bit unclear.

Response: For a wind turbine, its resultant AEP would fall below its capacity when one accounts for all the Outer Range conditions it experiences. This is a key distinction between Inner Range and Outer Range, which is explained in this paragraph. It is possible that if one only focuses on a subset of Outer Range conditions, the "AEP" could theoretically be larger than that predicted by a reference power curve.

Line 145: power-law wind shear exponent

Response: Lines 156 to 158 now read:

"The PCWG differentiates Inner Range and Outer Range data based on the wind shear and TI. Wind shear, represented by the power law exponent, is calculated using the wind speeds between the lower blade tip and hub height, and the TI at hub height (Power Curve Working Group, 2018)."

Line 151: maybe worth explaining what this means in this context

Response: To be more specific, "under ideal conditions" is now changed to "in a controlled environment defined in the IEC standard".

Line 152: You may want to provide some explanation about the limitation of using a power-law shear measured between blade top and bottom tips. Maybe could you refer to some ABL meteorology works in flat terrain, like the ones of Alfredo Peña ? In partic-

ular, it could be interesting for the reader to understand how the wind speed profiles is characterised in the surface layer (MOST) and above (not only MOST), how the height of the surface layer changes with stability and therefore how the power-law may or may not represent well the wind profile. See examples in slides 12 and 13 of [C2W19]: deriving a power-law shear value computed only using the highest and lowest tip heights wind speeds would not represent accurately the wind speed profile over the rotor. The errors are, in absolute terms larger in stable conditions, but in relative terms the errors are also large in unstable conditions. This is, important to mention when dealing with tests that have been carried out using different rotor spans. Also, it is important to explain the link between wind shear and turbulence intensity, that is: the influence of the roughness and orography (mechanical turbulence) and the stabiity (thermal turbulence), so the reader know these are linked, but that this link is site-specific. For instance, large turbulence may still exist in stable conditions, because of an obstacle upstream, so the link is not a simple as "stable -> small TI/large shear". [C2W19]: http://c2wind.com/f/content/windeurope_wra_workshop_20190627_c2w_rev4.pdf

Response: Thank you for your comment. Similarly, one could argue our use of TI, or even AEP, omits their own limitations. We understand that representing the wind shear with the shear exponent can be inadequate in different ways, while discussing its imperfection herein is marginally relevant. This is a study about data sharing and data science on power curve modeling, rather than a discussion on meteorological variables and calculations. In this section, we emphasize on differentiating the Inner Range and the Outer Range, we explain our analysis methodologies extensively in Sect. 3 and Appendix C, and we also discuss the constraints of our methodology throughout the manuscript, especially in Appendix A and B.

Line 166: Are meta-data shared as well (rotor span for instance) ?

Response: Some of the submissions include their metadata including the rotor span, yet not all of them do.

Line 213: median ?

Response: That is correct, as pointed out by another reviewer. Lines 237 to 239 now read:

“Generally, NME represents the average bias on power production of the correction method. Such bias on power-curve modeling affects the long term P50, which is the median expected AEP over many years of production and is used to inform investment decisions.”

Line 218: subsetting the overall dataset of 10-minute samples? "slicing the 10-minute data" may lead to thinking you are using sub-10minute time series.

Response: Thank you, and the phrase now reads: “slicing all the 10-minute data of each submission in several ways”

Line 231 to 239: Do you provide statistics about how much data is found in each category, for instance: for more than 80% of the tests, less than 30% of the data are in the inner range... or something like this, which could help visualise the populations ?

Response: Sect. 4.1, including Fig. 4 and Fig. 5, is dedicated to discussing the metadata distributions.

Line 240: What does it mean in this context ?

Response: The word “broadly” is unnecessary and thus removed.

Line 283: Could you also provide explanations about the wind measurements ? How did you derive the power-law shear across the rotor is only met mast at hub heights are used ? Same question for TI (lidar TI?) ?

Response: The participants do not only use wind speeds at hub height in the PCWG analysis tool, where wind shear “is calculated using the wind speeds between the lower blade tip and hub height, and the TI at hub height (Power Curve Working Group, 2018).” (lines 157 to 158).

Line 288: What does it mean in this context ?

Response: The word “modern” here means that the data we have indicate wind turbines of modern models, because most of the tests results are recorded after 2013.

Line 291: There are different meteorogical conditions and sites in each of these countries, maybe could the users have reported "regions" instead of countries ?

Response: Unfortunately, only a subset of the submissions indicate their region or country of origin, so we cannot fully disclose the geographical metadata.

Line 316: in the control region I (optimal TSR)

Response: Lines 351 to 352 now read:

“This feature fits our expectation because of the cubic relationship between wind speed and power, when the hub-height wind speed is between cut-in wind speed and rated wind speed.”

Line 331: Are these the ones discussed in Section 4.1 ?

Response: Yes, the phrase is updated to “only 48 of the 55 submissions. . .”

Line 346: can you explain where these results are in Figure 8a (row, column) ?

Response: This is explaining the “ITI-OS”, which is Inner Range TI and Outer Range shear, and it is the 5th row from the top.

Line 353: I read this paper quickly, sorry for the silly question, but: shouldn’t this value be zero ?

Response: Thank you for raising this question. You are correct, and these numbers are very close to zero, which are less than or close to 0.01%. These numbers are not absolute zeros because the trial methods and the interpolation method (Appendix A) minimize the prediction error in the Inner Range, while the residual errors are not necessarily equal to zeros. Thanks to your comment, we added lines 387 to 388:

“Ideally, the Inner-Range errors would be zero, yet the trial methods and the interpolation method (Appendix A) minimize the prediction errors and do not necessarily result in zero residual errors in the Inner Range (second-last row in Fig. 8).”

Line 368: What does this mean, in this context ?

Response: The word “broadly” is unnecessary and hence removed. The key message here is that for some submissions, the data set itself influences how effective a trial method is.

Line 386: What does this mean in this context ?

Response: For the submissions we have on hand, we do not find the meaningful correlations between turbine characteristics and trial method effectiveness. However, we do not have all the metadata for all the data sets, hence we can only conclude this in a general sense.

Line 387: Still, i think it could be interesting to show the correlations plots.

Response: We decide not to display in this manuscript because of the lack of strong correlations. Mentioning this finding in the text sufficiently serves the purpose.

Line 456: is it probability density (unitless) ?

Response: The probability density here represents the probability per file count. The units of probability density is usually implied. Per your comment, we added the explanation in the caption for Fig. 12 and Fig. C2.

Lines 485 to 486: What does this mean, specifically ?

Response: It means the current set of power deviation matrices is not derived from a broad selection of data sets. This is the topic sentence of the paragraph, and the explanation is provided in the subsequent sentences.

Lines 505 to 506: Key message.

Response: Hence we put it in this section.

References

Clifton, A., Kilcher, L., Lundquist, J. K. and Fleming, P.: Using machine learning to predict wind turbine power output, Environ. Res. Lett., 8(2), 024009, doi:10.1088/1748-9326/8/2/024009, 2013. Power Curve Working Group: PCWG 3rd Intelligence Sharing Initiative Definition Document. [online] Available from: https://pcwg.org/PCWG-Share-03/PCWG-Share-03-Definition-Document.pdf, 2018.

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