Wind Energ. Sci. Discuss.,
https://doi.org/10.5194/wes-2020-82-RC1, 2020

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Open Access WIND ENERGY SCIENCE DISCUSSIONS

Interactive comment on "The most similar predictor – on selecting measurement locations for wind resource assessment" *by* Andreas Bechmann et al.

Anonymous Referee #1

Received and published: 1 July 2020

Thank you for the article, nice work. A few comments: l 21: delete "at" l 30: change: "its distant" to "its more distant" l 42: So is the first part of the equation from Clerck too? if so, write it :) l42: change "wind speed" to "wind speeds" l 53: i think it is d_i not d_iˆ2 that is the distance? l 55: change "mean decrease" to "mean decreases" l 109: missing a discussion of what the effect of the inevitable differences between the masts have on the final numbers. should they have been weighted according to some quality measure maybe? l118: but the maps could also be of varying quality? l126: find better reference, dont think T&P invented the Gamma function? l135: change "the paper focus" to "the paper focuses" and please donate 10kr to charity every time you make these errors :) l158: add text: compared to closest mast, and 7% compared to inverse

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Discussion paper

l161: "focuses" 10kr please Figure 4: Maybe a bit of a stretch to show the Gaussian distributions, they dont fit very well! Figure 5: Quite hard to see what message you are trying to convey here. l195: "decreases" 10kr please l204: any thoughts on applications in more complex terrain/bigger differences in RIX?

Interactive comment on Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-82, 2020.

Wind Energ. Sci. Discuss.,
https://doi.org/10.5194/wes-2020-82-AC1, 2020

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Interactive comment on "The most similar predictor – on selecting measurement locations for wind resource assessment" *by* Andreas Bechmann et al.

Andreas Bechmann et al.

andh@dtu.dk

Received and published: 6 July 2020

Thanks for the positive and constructive comments.

100 kroner has been sent to doctors without borders for the following errors: l21, l30, l42, l53, l55, l135, l161, l195.

L42: Only Equation 2 is from Clerc; this will be clarified in the manuscript.

L109: It is correct that the results for the different numbers of predictor masts are not directly comparable as they are based on different sites. The results section, therefore, normalise the "most similar" and the "inverse distance weighting" results with

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Discussion paper

the "closest mast" to make comparisons possible. The absolute values of the predictions are, however, kept in figure 5 and the appendix for reference. A small discussion/explanation on this should be added.

L118: The maps will be of varying quality, but the different strategies are using the same flow model results irrespectively. So non of the multi-mast strategies have any map-advantages.

l126: Thanks, T&P should not be referenced for the Gamma function, but only on how to apply the function for calculating the wind statistics.

L158: I agree

Figure 4: The fits are weak, but it is useful information that Gaussian distributions does not fit well. I would like to keep the distributions but write that we are aware of the poor fit.

Figure 5: The figure is an example/documentation of the absolute values. The figure is needed to prove that the achieved results are not due to the normalisation. The text needs clarification (also at L109) to highlight how we normalise and where to find the absolute values.

l204: I expect the improvements to be more substantial for more complex terrain, especially for flow models such as WAsP but also for CFD models. The reason for having relatively low dRIX sites in this paper is to not give "most similar" an unfair advantage. WAsP is known to have a bias for high dRIX values and "most similar" will by its nature find masts with low dRIX values (small speedups). Also, the uncertainty on wind speed prediction depends directly on the speedup. By reducing the speedup between predictor and prediction point, all else equal, the uncertainty should decrease.

Interactive comment on Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-82, 2020.

Wind Energ. Sci. Discuss.,
https://doi.org/10.5194/wes-2020-82-RC3, 2020

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Open Access WIND ENERGY SCIENCE DISCUSSIONS

Interactive comment on "The most similar predictor – on selecting measurement locations for wind resource assessment" *by* Andreas Bechmann et al.

Anonymous Referee #2

Received and published: 13 August 2020

General Comment: The overall structure and flow of this paper is very unconventional and makes it very hard to follow the logic of the paper. I suggest the sections be rewritten with more flow from topic to topic. The introductory material should be made more robust. Perhaps some more background information and references would make the author's thoughts clearer. The Conclusion section is very good, but it was not until the conclusion that the author's thoughts became clear to me. Overall, I think the content is good, but the presentation and writing needs some work.

Specific Comments:

-In the conclusion you acknowledge that this study benefited from having data from

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Discussion paper

existing met masts. In a real site placement exercise, what spatial resolution do you feel would be necessary to adequately classify a location as “most similar”, particularly with respect to terrain? Do you truly feel that WRF, without LES, would be an adequate model to use with spatial resolutions only down to $\sim$1km?

-Line 88: Define RIX, and how it is determined.

-Section 2.2: Give more details about the model setup. At what resolution are the topography maps? What source did they come from? Are the wind measurements you refer to the data from the 185 masts?

-Where did the met mast data come from? Industry partners? You do not need to specifically name companies, but some indication of the data source should be mentioned. Also, is there any information that can be shared about the anemometer types/ model numbers/ calibration status? Providing more information will speak to the reliability of the dataset used.

Interactive comment on Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-82, 2020.

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Discussion paper

Wind Energ. Sci. Discuss.,
https://doi.org/10.5194/wes-2020-82-AC2, 2020

WESD

Interactive comment on "The most similar predictor – on selecting measurement locations for wind resource assessment" *by* Andreas Bechmann et al.

Andreas Bechmann et al.

andh@dtu.dk

Received and published: 27 August 2020

Dear referee,

Thank you for the constructive feedback.

I understand the comments about the "flow" of the paper and making the introduction more robust. The introduction has been revisited and expanded with a paragraph that tries to link to the conclusion better. The conclusion has also been edited to try and establish a flow throughout the paper.

Regarding the specific comments:

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Discussion paper

Q: What spatial resolution would be necessary? A: To answer this question I think we need to clarify that we are operating with two different data sources and therefore two different resolutions: 1. the resolution of the met masts and WRF model results and 2. the resolution of the micro-scale model used to determine the most similar location. Met masts are placed with a spacing of a few km (3.1 km on average in this work); which is similar to the grid spacing of WRF simulations (1-5 km). The resolution of met masts and WRF grid points is therefore comparable. To determine the most similar predictor (mast location or WRF-point), we use a micro-scale flow model that operates with a much finer resolution (1-50 m). A small description is added to the conclusions of the manuscript to clarify this.

Q: Line 88: Define RIX, and how it is determined. A: RIX is defined by the percentage fraction of the terrain along the prevailing wind direction, which is over a critical slope of 0.3. The definition has been added to the manuscript.

Q: Section 2.2: Give more details about the model setup. At what resolution are the topography maps? What source did they come from? Where did the met mast data come from? Providing more information will speak to the reliability of the dataset used. A: I fully understand and agree that transparency regarding the dataset is essential. Confidentiality constraints restrict us in some sense, but the large volume of data also makes it hard to describe it in detail as every wind farm site is different, including anemometer types/calibration and map resolutions. Vestas has provided both the wind and topography data, and we use it directly without corrections or quality control. However, as all data has previously been analysed and scrutinised in connection with wind farm development, we consider the data to have an industry-standard quality. This information is added to the manuscript.

Interactive comment on Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-82, 2020.

Wind Energ. Sci. Discuss.,
https://doi.org/10.5194/wes-2020-82-RC4, 2020

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Open Access WIND ENERGY SCIENCE DISCUSSIONS

Interactive comment on "The most similar predictor – on selecting measurement locations for wind resource assessment" *by* Andreas Bechmann et al.

Dariush Faghani (Referee)

dfaghani@pfdrive.com

Received and published: 18 August 2020

Thank you for your contribution. The approach is interesting and the results are promising. Please see below for a few hopefully constructive comments.

1. Have the paper reviewed by a technical writer to correct typos and improve fluency. 2. Lambda and L parameters have been set a priori based on Clerc et al., 2012. Are you suggesting they can be used universally for all sites and flow conditions? 3. Consider using a generic power curve to compare the performance of each approach. 4. The overall tone is very much oriented towards data analysis and processing. It would be good to add more wind resource assessment flavour to it. Especially in

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Discussion paper

Section 3.2 (Fig. 5) where you focus on just 2 sites. Adding more detail on actual terrain and flow conditions for those sites would be appreciated. 5. In the conclusion you state that your method is "expected to work well for weather models". What is the basis for this claim? If this is just a "teaser" for future work, rephrase appropriately.

Again, thank you for this research and interesting results.

Interactive comment on Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-82, 2020.

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Discussion paper

Wind Energ. Sci. Discuss.,
https://doi.org/10.5194/wes-2020-82-AC3, 2020

WESD

Interactive comment

Interactive comment on "The most similar predictor – on selecting measurement locations for wind resource assessment" *by* Andreas Bechmann et al.

Andreas Bechmann et al.

andh@dtu.dk

Received and published: 27 August 2020

Dear referee

Thank you for the comments; they help improve the manuscript, and I appreciate it highly.

Q: 1. Have the paper reviewed by a technical writer to correct typos and improve fluency

A: The fluency of the paper has been improved in the revised manuscript

Q: 2. Lambda and L parameters have been set a priori based on Clerc et al., 2012.

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Are you suggesting they can be used universally for all sites and flow conditions?

A: Lambda and L have not been re-calibrated in this work, but are kept to their original values. In Clerc et al., 2012, the expression is used for estimating energy yield uncertainty for which an accurate calibration may be necessary. For the application of determining the most similar predictor, I believe and suggest, that a precise calibration is less critical.

Q: 3. Consider using a generic power curve to compare the performance of each approach.

A: This is a good idea. However, as the prediction heights and wind speeds vary between the sites, choosing a single power curve representative for all sites is not trivial. The error on the predicted energy yield will depend significantly on the rated power and rated wind speed of the chosen generator.

Q: 4. The overall tone is very much oriented towards data analysis and processing. It would be good to add more wind resource assessment flavour to it. Especially in Section 3.2 (Fig. 5) where you focus on just 2 sites.

A: Fig 5 is the results of more than 33 million predictions, but the text is not very clear on this and has been revised. We are trying to keep the tone towards data analysis, to emphasis that the flow modelling and data is identical for all simulations. The paper attempts to demonstrate that it is a minimal change in the statistical post-processing of results that leads to considerable improvements.

Q: 5. In the conclusion, you state that your method is "expected to work well for weather models". What is the basis for this claim? If this is just a "teaser" for future work, rephrase appropriately.

A: The statement has been rephrased, also following referee #2. The statement was meant as a new hypothesis to prove; a challenge. Choosing the most similar mast location and choosing the most similar WRF result point seems quite comparable. When

downscaling WRF results and interpolating them from the WRF-calculation grid to a result-point, it is common to use the nearest WRF-point or to make a distance-weighted average using the four surrounding grid-points. This is very similar to how resource assessment is done with met masts. I would not be surprised if the "most similar" WRF point were a better approach.

Interactive comment on Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-82, 2020.

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Discussion paper

Summary of Comments on Marked-up Bechmann et al. - 2020 - The most similar predictor – on selecting measurem.pdf

Page: 1

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "conducting wind resource assessments with multiple wind measurements and for the optimal design of measurement campaigns."
[New]: "selecting optimal measurement positions for wind resource assessment."

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "location to a new"
[New]: "loca tion to a prediction"

Author: Text Inserted Subject: Text Date: Indeterminate
"micro-scale"

Author: Text Inserted Subject: Text Date: Indeterminate
"possible"

Author: Text Inserted Subject: Text Date: Indeterminate
"single"

Author: Text Inserted Subject: Text Date: Indeterminate
"Much research focuses on the development of improved micro-scale models; however, this work focus on optimal met masts positioning and on how this improves predictions irrespectively of the chosen micro-scale model. This introduction will first explain that met masts today are positioned to minimise the distance to wind turbine positions. We then present a hypothesis that states that met masts should instead be placed following the "similarity principle" and finally, 20 the section describes how the hypothesis will be tested. 1.1 The representativeness radius"

Page: 2

Author: Text Deleted Subject: Text Date: Indeterminate
"at"

Author: Text Inserted Subject: Text Date: Indeterminate
"more"

Page: 3

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "35 Instead of using distance as the parameter representing similarity, we propose to use the directional-averaged speedup uncer tainty, σ S :"
[New]: "parameter that represents similarity, we define the directional-averaged speedup uncertainty, σ S ,"

Font "NimbusSanL-Regu" changed to "NimbusRomNo9L-Regu".
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"where f j is the wind direction frequency at the met mast, N θ is the number of wind direction sectors and σ S 2 j is the speedup uncertainty of the micro-scale model. As an expression for the speedup uncertainty for a particular wind direction, we use the model by"

Author: Annotation Inserted Subject: Annotation Date: Indeterminate

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Author: Text Inserted Subject: Text Date: Indeterminate
"(2012):"

Author: Text Inserted Subject: Text Date: Indeterminate
"Clerc et al."

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "speed respectively. σ S combines into one expression, the uncertainty associated with both extrapolation distance and speedup."
[New]: "speeds respectively. L 1 and λ have not been re-calibrated in this work, but are kept to their original values. σ S combines into one expression, the uncertainty associated with both extrapolation distance and the wind speed difference. 50"

Author: Text Inserted Subject: Text Date: Indeterminate
"micro-scale"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "decrease"
[New]: "decreases"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "inverse distance weighting is not the optimal way of performing resource assessments. Instead, we suggest to follow the similarity principle and determine the "most similar" mast location (not"
[New]: "met masts should be placed following the "similarity principle" instead of reducing extrapo65 lation distance. The hypothesis is verified by showing that the "most similar" predictor gives lower prediction errors than the"

Page: 4

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "the nearest mast). To validate 60 this approach, we conduct a large number of predictions, test the different multi-mast strategies and compare the results to measurements. We test the following multi-mast strategies:"
[New]: "closest predictor and inverse distance weighting. In the following, we conduct a large number of predictions using the following multi-mast strategies and compare the results to measurements: "

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "method,"
[New]: "predictor,"

Author: Text Inserted Subject: Text Date: Indeterminate
"wind"

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[Old]: "70 1."
[New]: "1. Wind"

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Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "Wind"
[New]: "Prediction"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "model setup"
[New]: "flow model setups"

Author: Text Inserted Subject: Text Date: Indeterminate
"wind"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "75 2.1 Measurements A dataset has been collected to validate the multi-mast strategies. The dataset consists of measurements from sites with three or more met masts. By having at least three masts, each mast"
[New]: "2.1 Wind measurements The datasets used in this work has been collected specifically to validate multi-mast strategies. It is obtained through wind project developers worldwide and is considered to cover the full spectrum of the conditions experienced in wind projects. The dataset consists of wind measurements from sites with three or more met masts. By having at least three masts, each mast 85"

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Font-size "8.51801" changed to "9.9626".

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "power"
[New]: "project"

Page: 5

Author: Text Deleted Subject: Text Date: Indeterminate
"for this study"

Author: Text Inserted Subject: Text Date: Indeterminate
"where RIX is defined by the percentage fraction of the terrain along the prevailing wind direction, which is over a critical slope of 0.3"

Page: 6

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "sites"
[New]: "predictions"

Author: Text Inserted Subject: Text Date: Indeterminate
"million different predictions with 6 predictor masts. The many combinations are primarily possible due to the site that has 25 met masts."

Author: Text Inserted Subject: Text Date: Indeterminate
"The results for different numbers of predictor masts are not directly comparable since they are based on different sites."

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "Figure 3. Mast height and distance to the closest neighbouring mast for all 185 met. masts."
[New]: "and the "inverse distance weighting" results with the "closest mast" to make comparisons of the multi-mast strategies possible."

Font "NimbusRomNo9L-Medi" changed to "NimbusRomNo9L-Regu".
Font-size "8.9664" changed to "9.9626".

Author: Text Inserted Subject: Text Date: Indeterminate
"The results section will, therefore, normalise the "most similar""

Page: 7

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "The table illustrates the number of predictions possible for combinations of sites with specific number of predictors."
[New]: "Number of predictions possible for different numbers of predictors"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "Mast combinations"
[New]: "Predictions"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "million different predictions with 6 predictor masts. The many combinations are primarily possible due to the site that has 25 met masts. The results section show how the multi-mast strategies perform with these combinations of multi-mast sites. 2.2 Flow model 110 The"
[New]: "120 2.2 Flow model The micro-scale"

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Font-size "9.9626" changed to "8.51801".

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "The topography maps and wind measurements needed were provided to the authors and used directly without conducting any corrections. Also, no ΔRIX-or other corrections have been made to the model 115 results, and no tuning of model parameters to improve results was performed. This study represents a statistical analysis of multi-mast strategies. All simulations are based on identical model setups and using the digitised maps, mast locations, anemometer heights and wind data provided to the authors; only the method used to calculate the"
[New]: "No ΔRIX-or other corrections have been made to the model 125 results, and no tuning of model parameters to improve results was performed. The topography maps used for the flow model were provided to the authors and used directly without corrections or quality control. As all data has previously been analysed to be used for wind farm development, and scrutinized by third party companies, the data are considered to have an industry standard quality. The current work is a statistical analysis of the multi- mast strategies. All simulations are based on identical model setups and using the digitised maps, mast locations, anemometer 130 heights and wind measurements provided to the authors; only the method used to calculate the predicted"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "Wind statistics 120"
[New]: "Predicted wind statistics"

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Author: Annotation Inserted Subject: Annotation Date: Indeterminate

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "by:"
[New]: "following"

Author: Text Inserted Subject: Text Date: Indeterminate
"(1989):"

Author: Text Inserted Subject: Text Date: Indeterminate
"Troen and Petersen"

Author: Text Deleted Subject: Text Date: Indeterminate
"(Troen and Petersen,"

Author: Annotation Deleted Subject: Annotation Date: Indeterminate

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Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "gamma function"
[New]: "Gamma function."

Page: 8

Author: Text Inserted Subject: Text Date: Indeterminate
"It was also considered to apply a generic wind turbine power curve to allow calculation of energy yield predictions. However, as the prediction heights and wind speeds vary 145 between the sites, using a single power curve for all predictions was not pursued."

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "focus"
[New]: "focuses"

Author: Text Attributes Changed Subject: Text Date: Indeterminate
Font-style changed.

Author: Text Attributes Changed Subject: Text Date: Indeterminate
Font-style changed.

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "All"
[New]: "Original"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "the histograms, and 150"
[New]: "the histograms (despite the poor fit), and"

Page: 10

Author: Text Inserted Subject: Text Date: Indeterminate
"Histograms of the absolute wind speed (left) and power density (right) error for different combinations of prediction location and 6 predictor masts using the three different multi-mast strategies. Each histogram consists of more than 33 million predictions. 165"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "location instead of the closest location, the mean prediction error is significantly reduced (22% for power density)."
[New]: "location, the mean power density error is reduced by 22% compared to closest mast, and 7% compared to inverse distance weighting."

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "Dependence on predictors 160"
[New]: "New predictor combinations 175"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "focus"
[New]: "focuses"

Author: Text Inserted Subject: Text Date: Indeterminate
"new"

Author: Text Inserted Subject: Text Date: Indeterminate
"As an example of the absolute prediction errors,"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "the"
[New]: "a"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "the combinations of 165 sites that have seven met masts (6 predictors for each prediction)."
[New]: "predictions that uses 6 predictors. The available dataset allow 33 million different combinations of a prediction location and 6 predictor masts."

Author: Text Deleted Subject: Text Date: Indeterminate
"(13%)"

Author: Text Deleted Subject: Text Date: Indeterminate
"(34%)"

Page: 11

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "site-combinations"
[New]: "predictor-combinations"

Author: Text Inserted Subject: Text Date: Indeterminate
"normalised"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "are the same for sites with only one predictor. The figure"
[New]: "give 190 identical results for predictions with only one predictor. Figure"

Author: Annotation Inserted Subject: Annotation Date: Indeterminate

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "180 large improvements could be"
[New]: "significant improvements are"

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Font-size "8.51801" changed to "9.9626".

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "was used for deciding the location of met masts for resource assessment."
[New]: "is followed for placement of met masts, especially for single met mast campaigns."

Author: Text Inserted Subject: Text Date: Indeterminate
"This proves the hypothesis that met masts should be positioned according to the "similarity principle" instead of reducing the distance to the wind turbines."

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "Figure 6. Reduction of the standard deviation of wind speed (left) and power density (right) error as function of predictor masts when using inverse-distance weighting and most similar predictor compared to closest mast 190 even larger error reductions are possible if resource measurement campaigns are designed from the start using the most similar methodology. Designing an optimal measurement campaign using the most similar methodology requires a"
[New]: "even larger error reductions are possible if resource measurement campaigns are designed from the start using the most similar methodology, especially for single met mast campaigns. Designing an optimal measurement campaign using the most similar 210 methodology requires a micro-scale"

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Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "decrease"
[New]: "decreases"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "time"
[New]: "period"

Author: Text Deleted Subject: Text Date: Indeterminate
"also"

Author: Text Inserted Subject: Text Date: Indeterminate
"optimally"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "The "most-similar" method is expected to work well for"
[New]: "The "most similar" predictor is a practical alternative. 220 The "most similar" method could also work well for numerical"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "interpolated from a"
[New]: "downscaled and interpolated from the"

Author: Text Replaced Subject: Text Date: Indeterminate
[Old]: "However, this is a topic for future research."
[New]: "The resolution of WRF calculation grids (1-5km) are of comparable magnitude to that of met masts, and a micro-scale flow model could determine the most similar WRF predictor. It is today standard practice to choose the nearest WRF grid-point or to make distance-weighted averages using the four surrounding grid-points. However, we expect the most similar approach to also 225 work well for this application, especially in complex terrain."

The most similar predictor - on selecting measurement locations for wind resource assessment

Andreas Bechmann[1], Juan Pablo M. Leon[1], Bjarke T. Olsen[1], and Yavor V. Hristov[2]
[1]DTU Wind Energy, Denmark
[2]Vestas Wind Systems A/S, Denmark
Correspondence: Andreas Bechmann (andh@dtu.dk)

Abstract. We present the "most similar"-method for selecting optimal measurement positions for wind resource assessment.

Wind resource assessment is generally done by extrapolating a measured and long-term corrected wind climate at one location to a prediction location using a micro-scale flow model. If several measurement locations are available, standard industry practice is to make a weighted average of all the possible predictions using inverse-distance weighting. The "most similar"-method challenges this practice. Instead of weighting several predictions, the method only selects the single measurement location evaluated "most similar".

We validate the new approach by comparing against measurements from 185 met masts from 40 wind farm sites and show improvements compared to inverse-distance weighting. Compared to using the closest measurement location, the error of power density predictions is reduced by 13 % using inverse-distance weighting and 34 % using the "most similar"-method.

1 Introduction

When assessing the energy potential of a new wind farm, a crucial step is to predict the mean wind climate at each wind turbine position. The conventional approach for predicting the wind climate is to erect a meteorological mast (met mast) at a nearby location and extrapolate the measured wind climate to every wind turbine position using a micro-scale flow model (MEASNET, 2016). The flow model estimates how the surrounding topography perturbs the wind and can thereby predict the wind climate at each wind turbine position. Much research focuses on the development of improved micro-scale models; however, this work focus on optimal met masts positioning and on how this improves predictions irrespectively of the chosen micro-scale model.

This introduction will first explain that met masts today are positioned to minimise the distance to wind turbine positions. We then present a hypothesis that states that met masts should instead be placed following the "similarity principle" and finally, the section describes how the hypothesis will be tested.

1.1 The representativeness radius

The distance between the measurement and prediction location is traditionally used as an indicator of model uncertainty, and measurement campaigns are often planned to minimize the extrapolation distance. MEASNET (2016) defines a "representa-

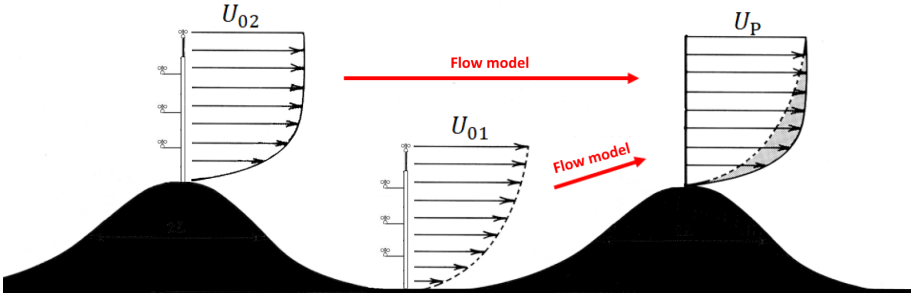

Figure 1. The figure illustrates how a measured wind climate can be extrapolated to a prediction site using a flow model. Following the "representativeness radius", the model error is reduced when the distance between met mast and prediction location is minimized; accordingly met mast 1 (U_{01}) is the preferred predictor. Following "the similarity principle" model errors are reduced when the wind conditions at the met mast and the predicted location are similar; accordingly met mast 2 (U_{02}) is preferable despite its more distant location

tiveness radius" as the distance from a met mast to the furthest location that can be extrapolated with tolerable uncertainty. The representativeness radius depends on the complexity of the terrain, where complex terrain is characterized by having terrain slopes greater than 0.3. Figure 1 illustrates two met masts located in complex terrain. Following the recommendations of MEASNET (2016), the measurements taken in the valley, U_{01}, are preferable for predicting U_P as the distance is small.

1.2 The similarity principle

According to Landberg et al. (2003), errors related to flow modelling are minimized when the predictor site (the met mast location) and the predicted site (the wind turbine location) are as "similar" as possible regarding factors like regional wind climate, roughness, orography and obstacles. Landberg et al. (2003) refers to this this as the "similarity principle". The underlying assumption is that no matter how advanced a flow model, it always produces errors, and they scale with the forcing applied. Figure 1 illustrates the similarity principle. The wind conditions in the valley, U_{01}, differ substantially from the conditions at the prediction site, U_P, and a better predictor (according to the similarity principle) is, therefore, the hilltop met mast, U_{02}, despite its more distant location.

1.3 The most similar predictor

Experienced wind and site engineers determine suitable locations for met masts based on the representativeness radius and their judgment. They intuitively understand that distance is not the only parameter that should be evaluated; however, since no algorithmic method for similarity exists, the industry standard is to minimize the extrapolation distance.

To make a parameter that represents similarity, we define the directional-averaged speedup uncertainty, σ_S,

$$\sigma_S^2 = \sum_{j=1}^{N_\theta} f_j \sigma_{Sj}^2 \tag{1}$$

where f_j is the wind direction frequency at the met mast, N_θ is the number of wind direction sectors and σ_{Sj}^2 is the speedup uncertainty of the micro-scale model. As an expression for the speedup uncertainty for a particular wind direction, we use the model by Clerc et al. (2012):

$$\sigma_{Sj}^2 = \left(\lambda\left[1 - exp\left(\frac{-d}{L_1}\right)\right]\right)^2 + \left|\frac{S_j - 1}{S_j + 1}\right|^2 \tag{2}$$

where d is the extrapolation distance, $L_1 = 1\,\mathrm{km}$ and $\lambda = 0.1$ are empirically calibrated constants (Clerc et al., 2012), $S_j = U_{Pj}/U_{0j}$ is the speedup where U_0 and U_p are the measured and predicted mean wind speeds respectively. L_1 and λ have not been re-calibrated in this work, but are kept to their original values.

σ_S combines into one expression, the uncertainty associated with both extrapolation distance and the wind speed difference. Small values of σ_S signify that predictor and prediction conditions are "similar". The inclusion of speedup in the expression ensures that any difference between predictor and prediction site included in the micro-scale flow model is evaluated (roughness, orography, obstacles, measurement height, etc.). The speedup uncertainty is, therefore, expected to be a more accurate "measure-of-similarity" than distance, and we define the "most similar" predictor to be the location with the smallest σ_S-value.

1.4 Multi-mast strategies

For large wind farms with several met masts, a standard practice when making predictions is to either select the closest available predictor or to make a weighted average of multiple predictions using "inverse distance weighting". As an example, the inverse distance weighted mean wind speed, U_P, can be determined as,

$$U_P = \frac{\sum_{i=1}^{N_M} W_i U_{Pi}}{\sum_{i=1}^{N_M} W_i} \tag{3}$$

where U_{Pi} is the predicted mean wind speed, $W_i = d_i^{-2}$ is the predictor weight, d_i is the extrapolation distance, and N_M is the number of predictors on a particular site. The underlying reason for using inverse distance weighting is that the standard error of a weighted mean decreases with the number of independent predictions. However, for this to be valid, the predictions are assumed independent (model errors should be random), and extrapolation distance is assumed to be the parameter that correlates the strongest with model error.

This paper aims to show that met masts should be placed following the "similarity principle" instead of reducing extrapolation distance. The hypothesis is verified by showing that the "most similar" predictor gives lower prediction errors than the

closest predictor and inverse distance weighting. In the following, we conduct a large number of predictions using the following multi-mast strategies and compare the results to measurements:

Closest predictor:
$$W_i = \begin{cases} 1 & \text{if } d_i = \min(d) \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

Inv. dist. weighting:
$$W_i = d_i^{-2} \tag{5}$$

Most similar predictor:
$$W_i = \begin{cases} 1 & \text{if } \sigma_{Si} = \min(\sigma_S) \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

2 Validation Method

To validate the usefulness of the "most similar" predictor, we compare the performance of the three multi-mast strategies against wind measurements. Sites with at least three met masts are used in the comparison. The multi-mast sites allow for predictions with multiple predictors and provide an objective way to evaluate the strategies. The validation method consists of three steps described in detail in the following sections:

1. **Wind Measurements:** Preparation of the wind data for the flow model.
2. **Flow model:** Prediction of all mast locations using every other mast as a predictor.
3. **Prediction statistics:** Calculation of mean wind speed and power density using each multi-mast strategy.

The wind measurements and flow model setups are identical for each multi-mast strategy; only the mast weights, W_i, used for calculating the wind statistics are different to allow for a simple and objective evaluation.

2.1 Wind measurements

The datasets used in this work has been collected specifically to validate multi-mast strategies. It is obtained through wind project developers worldwide and is considered to cover the full spectrum of the conditions experienced in wind projects. The dataset consists of wind measurements from sites with three or more met masts. By having at least three masts, each mast location can be predicted using at least two predictors, and results can be compared against the measurements taken at the predicted mast.

The dataset consists of wind speed and wind direction measured from the top anemometer of each met mast, already screened and long-term corrected by wind project developers. The data is grouped into 36 10-degree wind direction sectors, and have

Weibull distributions fitted to the wind speed histogram. Wind statistics from a total of 210 met masts were provided for the study. The only additional screening that has been conducted is the removal of four sites (25 met masts) from the dataset. These sites were removed since mast-to-mast predictions of wind speed, and power density led to substantial errors ($> 3\sigma$) for four of the met masts. We did not investigate the reason for the significant errors but removed the sites from the investigation. Table 1 shows a summary of the sites and met masts used. As seen, the screened data consist of 185 met masts distributed over 40 wind turbine sites.

Table 1. Number of met masts used for the study.

Masts per site	Sites	Masts	Cumulative sum
25	1	25	25
7	4	28	53
6	3	18	71
5	5	25	96
4	8	32	128
3	19	57	185

The data comes from met masts located near potential wind energy installations, and the 185 mast locations represent varied site conditions from all over the world. Figure 2 illustrates the complexity of the sites using the RIX (left) and ΔRIX (right) measure where RIX is defined by the percentage fraction of the terrain along the prevailing wind direction, which is over a critical slope of 0.3 (Bowen and Mortensen, 2004). The mean RIX value is 7.0%, which can be considered moderately complex terrain. Compared to the closest neighbouring mast, 84 masts have $|\Delta\mathrm{RIX}|$ values of less than 1% and 164 masts have $|\Delta\mathrm{RIX}|$ below 5%. Most of the met masts are therefore placed in similar, well-exposed hills and ridges.

Figure 3 shows the height of the masts (right) and the distance to their closest neighbour (left). The distance is up to $10\,\mathrm{km}$, but on average the distance is $3.1\,\mathrm{km}$. As seen, the masts do not have the same height but vary from 20 meters to 120 meters, and half of the sites have height variations within them. These sites often have combinations of short and tall masts e.g. of 40/80 meters, 60/80 meters or 60/100 meter masts. The wind statistics have not been corrected or "sheared up" to unify the heights differences. Instead, the flow model has been used directly to estimate the wind statistics at the prediction height using the statistics at the predictor height. The "most similar" method have an advantage compared to the other multi-mast strategies for sites with different mast heights as there will be a speedup between masts of different heights and the will therefore not be valued as similar. In the current analysis, this is however of minor importance as the results, particular in Section 3.2, depend mainly on a single site with 25 met masts that are all 80 meters tall.

The dataset (Table 1) allows for a total of 185 possible predictions with two or more predictor masts. The results section analyse how the different multi-mast strategies perform with this specific mix of multi-mast sites. Also, other combinations of multi-mast sites from the same data-pool have been made, to analyse how the multi-mast strategies perform on sites with a

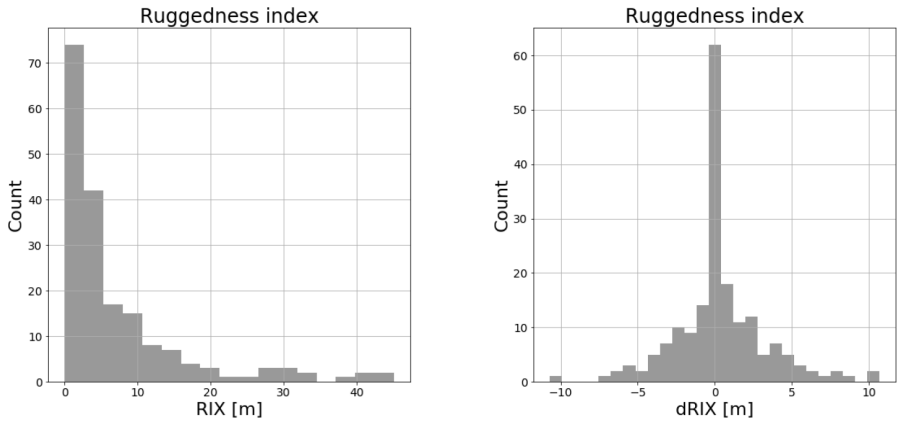

Figure 2. RIX and $|\Delta \mathrm{RIX}|$ for all 185 met. masts. $|\Delta \mathrm{RIX}|$ is calculated using the closest neighbouring mast.

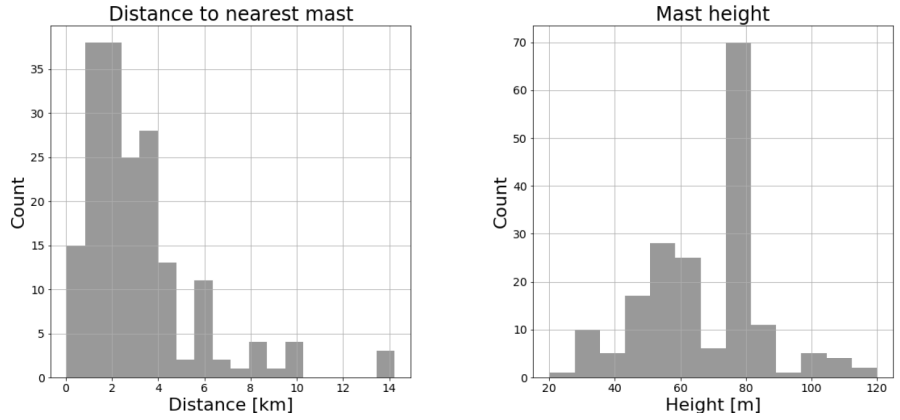

Figure 3. Mast height and distance to the closest neighbouring mast for all 185 met. masts.

specific number of predictor masts. As an illustration of how other multi-mast combinations can be made from the same data, we can imagine that a single site with 3 met masts can also be viewed as 3 different sites with 2 met masts. Table 2 shows the many combinations of predictions possible with 1, 2, 3, 4, 5 or 6 predictor masts. As seen, it is possible to make more than 33 million different predictions with 6 predictor masts. The many combinations are primarily possible due to the site that has 25 met masts. The results for different numbers of predictor masts are not directly comparable since they are based on different sites. The results section will, therefore, normalise the "most similar" and the "inverse distance weighting" results with the "closest mast" to make comparisons of the multi-mast strategies possible.

Table 2. Number of predictions possible for different numbers of predictors

Predictors	1	2	3	4	5	6
Predictions	1168	7803	51472	266185	1062786	33644928

2.2 Flow model

The micro-scale flow model WAsP 12.3 (Troen and Petersen, 1989) has been used to make all wind climate predictions in this study. Since every mast location needs to be predicted using every possible predictor mast, there is a total of 1168 mast-to-mast predictions. A database and an automatic model script (PyWAsP) was made to conduct all the simulations, and every simulation was run with the standard WAsP 12.3 parameters. No ΔRIX- or other corrections have been made to the model results, and no tuning of model parameters to improve results was performed.

The topography maps used for the flow model were provided to the authors and used directly without corrections or quality control. As all data has previously been analysed to be used for wind farm development, and scrutinized by third party companies, the data are considered to have an industry standard quality. The current work is a statistical analysis of the multi-mast strategies. All simulations are based on identical model setups and using the digitised maps, mast locations, anemometer heights and wind measurements provided to the authors; only the method used to calculate the predicted wind statistics is different between the 3 multi-mast strategies.

2.3 Predicted wind statistics

Wind statistics are calculated at each prediction location to validate the performance of the multi-mast strategies. Specifically, the predicted mean wind speed, U_P (ms^{-1}), and mean power density, E_P (Wm^{-2}), is compared to the measured values (U_0 and E_0). Since the measured wind data and the wind climate predictions are given in terms of the Weibull parameters A and k, the mean wind speed and mean power density is calculated following Troen and Petersen (1989):

$$U_i = \sum_{j=1}^{N_\theta} f_j A_{ij} \Gamma\left(1 + \frac{1}{k_{ij}}\right) \tag{7}$$

$$E_i = \frac{1}{2}\rho \sum_{j=1}^{N_\theta} f_j A_{ij}^3 \Gamma\left(1 + \frac{3}{k_{ij}}\right) \tag{8}$$

where ρ is air density (1.225 kg m^{-3}) and Γ is the Gamma function. Having calculated the wind speed and power density for every possible single-mast prediction, the multi-mast strategies was applied to calculate the final predicted wind statistics:

$$U_P = \frac{\sum_{i=1}^{N_M} W_i U_{Pi}}{\sum_{i=1}^{N_M} W_i} \tag{9}$$

$$E_P = \frac{\sum_{i=1}^{N_M} W_i E_{Pi}}{\sum_{i=1}^{N_M} W_i} \tag{10}$$

where W_i is the mast weight that depends on the chosen strategy (Sec.1.4). It was also considered to apply a generic wind turbine power curve to allow calculation of energy yield predictions. However, as the prediction heights and wind speeds vary between the sites, using a single power curve for all predictions was not pursued.

2.4 Evaluation method

To evaluate the multi-mast strategies, we compare the measured and predicted wind statistics at each mast position and calculate the average error of all predictions. The "closest mast" results are used as a baseline. The paper does not analyse the baseline error in any detail; instead, the paper focuses on how the multi-mast strategies improve the baseline. The data and model setup used for the "closest mast", "inverse distance weighting" and "most similar" methods are identical, to make an objective comparison of the multi-mast strategies. For each multi-mast strategy, the absolute error of each mast prediction is given by

$$X_i = X_P - X_0 \tag{11}$$

where X_P is either the predicted mean wind speed (U_P) or power density (E_P) and X_0 is the measured value (U_0 or E_0). The mean error of a strategy is calculated by

$$\mu = \frac{\sum_{i=1}^{n} X_i}{n} \tag{12}$$

where n is the number of mast predictions. Finally, the standard deviation of the error is given by

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \mu)^2}{n-1}} \tag{13}$$

The results shown in the following indicates the mean error, μ, the standard deviation of the errors, σ, and the number of predictions used to calculate the statistics, n.

3 Results

3.1 Original sites

The top row of figure 4 shows histograms of the absolute error of wind speed (left) and power density (right) for each of the 185 mast predictions using "closets mast" as a multi-mast strategy. Gaussian distributions are shown on the histograms (despite the poor fit), and the mean error and standard deviation of wind speed ($\mu = 0.11, \sigma = 0.63$) and power density ($\mu = 36.3, \sigma = 149$)

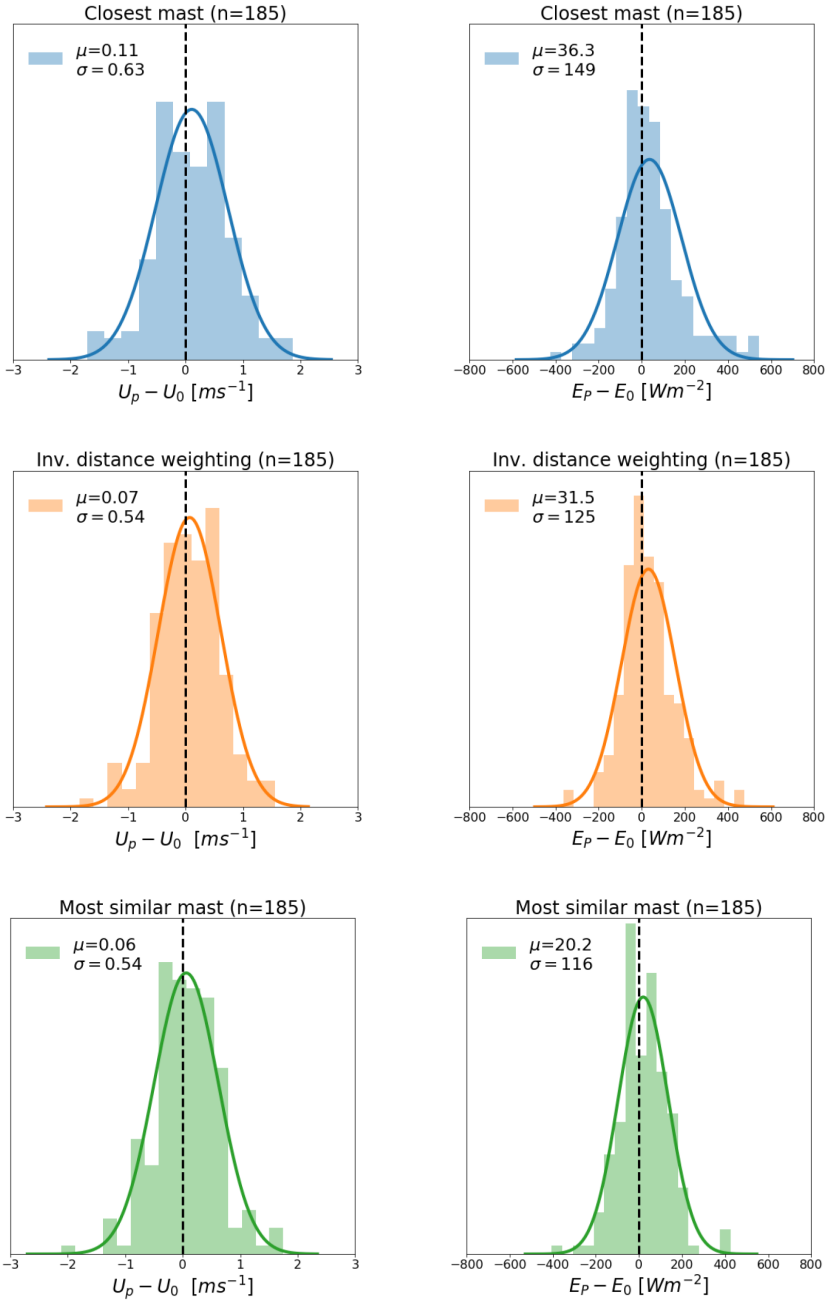

Figure 4. Histograms of the absolute wind speed (left) and power density (right) error when using the closest mast (top), inverse distance weighting (middle) and most similar (bottom) strategies. The mean bias and standard deviations are given in the legend. All 185 mast positions have been predicted to make this figure.

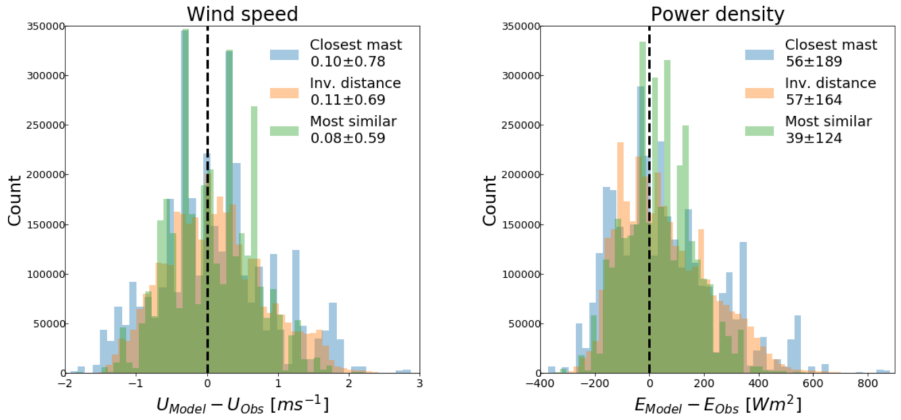

Figure 5. Histograms of the absolute wind speed (left) and power density (right) error for different combinations of prediction location and 6 predictor masts using the three different multi-mast strategies. Each histogram consists of more than 33 million predictions.

are given in the legends. The observed mean wind speed and power density of the 185 masts are 7.36 ms^{-1} and 460.7 Wm^{-2} respectively.

The results for "inverse distance weighting" and "most similar" predictor are shown in the middle and bottom row of figure 4. The left column shows that both multi-mast strategies significantly reduce both the mean wind speed error and the standard deviation compared to "closest mast". The standard deviation of the wind speed error is seen to decrease from 0.63 ms^{-1} to 0.54 ms^{-1} for both methods. The right column of the figure shows even more substantial error reductions for power density. The standard deviation of power density decreases from 149 Wm^{-2} to 125 Wm^{-2} for "inverse distance weighting" and from 149 Wm^{-2} to 116 Wm^{-2} for "most similar" mast. Therefore, by selecting the most similar location, the mean power density error is reduced by 22% compared to closest mast, and 7% compared to inverse distance weighting.

3.2 New predictor combinations

To clarify the difference between strategies that rely on the representativeness radius (closest mast and inverse distance weighting) and the similarity principle (most similar predictor), this section focuses on sites with a specific number of predictor masts. By combining the available dataset, it is possible to generate new combinations of sites with 1, 2, 3, 4, 5 or 6 predictors (see Table 2).

As an example of the absolute prediction errors, Figure 5 shows a histogram of the absolute error of wind speed (left) and power density (right) for predictions that uses 6 predictors. The available dataset allow 33 million different combinations of a prediction location and 6 predictor masts. The histograms of the strategies have different colours, and the legends indicate the mean error and the standard deviation of each. Compared to the "closest mast", the standard deviation of power density decreases from 189 Wm^{-2} to 164 Wm^{-2} for "inverse distance weighting" and from 189 Wm^{-2} to 124 Wm^{-2} for "most similar" mast.

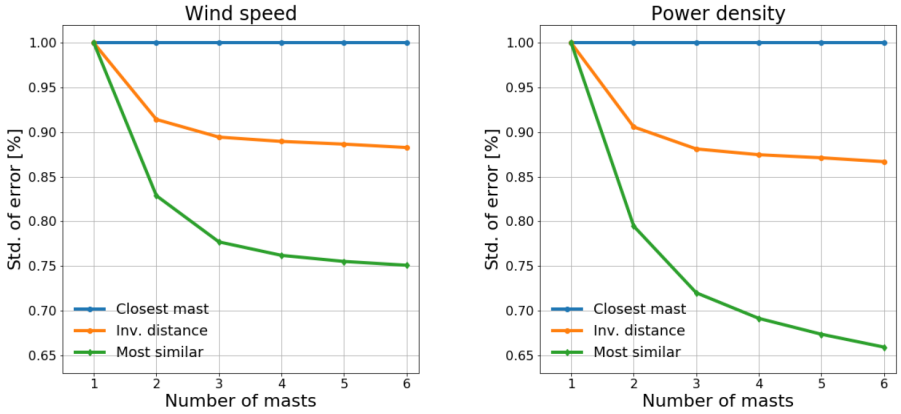

Figure 6. Reduction of the standard deviation of wind speed (left) and power density (right) error as function of predictor masts when using inverse-distance weighting and most similar predictor compared to closest mast

The mean absolute error and the standard deviation for predictor-combinations with 1, 2, 3, 4, 5 and 6 predictor masts are given in Table A1 and Table A2 (Appendix); however, the results are not directly comparable since they are based on different sites. To make a more valid comparison, we normalise all the results with the results of the "closest mast". Figure 6 shows the normalised average reduction in the standard deviation of wind speed error (left) and power density error (right) for inverse distance weighting and the most similar predictor compared to the closest mast. Note that the multi-mast strategies give identical results for predictions with only one predictor.

Figure 6 shows that both inverse distance weighting and most similar predictor significantly reduce the average prediction error compared to the closest mast. While inverse distance weighting reduces the error significantly with two predictors compared to one, the added improvement of using three or more predictor masts is much smaller. The most similar strategy has achieved 34% reduction of the standard deviation of power density error with 6 predictor masts, and it appears that the error would keep decreasing with additional predictor masts. It should be noted that the most similar strategy only uses a single predictor mast, but having more options to choose from decreases the error. This indicates that significant improvements are gained if the "most similar" strategy is followed for placement of met masts, especially for single met mast campaigns.

4 Conclusions

We have presented a novel method for determining the "most similar" measurement location for wind resource assessment using an expression of the directional-averaged speedup uncertainty. Based on measurements from 185 met masts the "most similar" met mast is on average a better predictor than the "closest mast" and "inverse distance weighting". This proves the hypothesis that met masts should be positioned according to the "similarity principle" instead of reducing the distance to the wind turbines.

The met masts used in this study have all been positioned by experienced wind and site engineers on well-exposed ridges, and 164 of the 185 met masts have $|\Delta \mathrm{RIX}|$ values below 5%. In the traditional view, this would mean that the closest predictor and the predicted location on average should have similar wind conditions. Despite this, substantial improvements (36% uncertainty reduction on power density predictions) was found by selecting the most similar predictor. This also indicates that even larger error reductions are possible if resource measurement campaigns are designed from the start using the most similar methodology, especially for single met mast campaigns. Designing an optimal measurement campaign using the most similar methodology requires a micro-scale flow model, a wind turbine layout and an indication of the main wind directions. With these tools, the directional-averaged speedup uncertainty for all wind turbine positions can be calculated and minimised.

The current industry standard is to use inverse distance weighting for resource assessment; the underlying reason is that the standard error of a weighted mean decreases with the number of independent predictions. Troen and Hansen (2015) demonstrates that the average of two independent flow models does decrease the uncertainty; however, predictions that use the same flow model and measurements from the same period are not independent. The reason why inverse distance weighting improves compared to "closest mast" is probably that it "repairs" a poor choice of predictor mast. Weighted results using inverse "directional-averaged speedup uncertainty" as predictor weight has also been tried (not shown); however, results do not improve compared the most similar predictor. To optimally combine the solution from several masts, it is necessary to consider the correlation of the errors (Clerc et al., 2012), which is not trivial. The "most similar" predictor is a practical alternative.

The "most similar" method could also work well for numerical weather models, like the Weather Research and Forecasting (WRF) model, where results have to be downscaled and interpolated from the calculation grid to the result-point. The resolution of WRF calculation grids (1-5 km) are of comparable magnitude to that of met masts, and a micro-scale flow model could determine the most similar WRF predictor. It is today standard practice to choose the nearest WRF grid-point or to make distance-weighted averages using the four surrounding grid-points. However, we expect the most similar approach to also work well for this application, especially in complex terrain.

Appendix A

Table A1. Wind speed error (mean and standard deviation) depending on the number of predictor masts and selected strategies.

Masts	1	2	3	4	5	6
Closest mast	0.09 ± 0.83	0.09 ± 0.87	0.09 ± 0.86	0.09 ± 0.83	0.10 ± 0.80	0.10 ± 0.78
Inv. distance	0.09 ± 0.83	0.10 ± 0.80	0.10 ± 0.77	0.11 ± 0.73	0.11 ± 0.71	0.11 ± 0.69
Most similar	0.09 ± 0.83	0.06 ± 0.72	0.06 ± 0.66	0.07 ± 0.63	0.07 ± 0.60	0.08 ± 0.59

Table A2. Power density error (mean and standard deviation) depending on the number of predictor masts and selected strategies.

Masts	1	2	3	4	5	6
Closest mast	46 ± 194	55 ± 208	55 ± 206	55 ± 199	55 ± 193	56 ± 189
Inv. distance	46 ± 194	56 ± 188	58 ± 181	58 ± 174	58 ± 168	57 ± 164
Most similar	46 ± 194	40 ± 165	38 ± 148	39 ± 138	39 ± 130	39 ± 124

Data availability. The data that support the finding of this research is not publicly available due to confidentiality constraints.

Author contributions. A. Bechmann analysis; J. P. Murcia Leon analysis asistance; B. T. Olsen paper corrections; Y. V. Hristov wind data and paper corrections.

Competing interests. A. Bechmann and B. T. Olsen work in the section at DTU Wind Energy that develop the WAsP software.

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