Date October 26, 2020
Our reference WES-2020-80-RC1
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Subject Response to reviewers

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Reviewers
Wind Energy Science Discussions, EWEA

Dear reviewers,

The authors express their gratitude to the reviewers for their time and efforts spent on providing accurate and constructive feedback to the submitted manuscript. Their comments play a crucial role in further improving the scientific quality and relevance of this work. In accordance to the provided feedback, the article has been revised. The objective of the attached document is to respond to all concerns raised and to outline the changes made to the manuscript.

Yours sincerely,

Bart Doekemeijer

Enclosure(s):
Response to comments of Reviewer 1 (David Verelst)
Response to comments of Reviewer 2 (Anonymous)
Marked-up manuscript highlighting the changes made

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Response to Reviewer 1 (David Verelst)

Dear reviewer. Thank you for your valuable comments. They play a role in improving the scientific relevance and clarity of this manuscript. We have addressed both your major and specific remarks in the remainder of this document.

Major comments:

Q1. *Based on figure 8, the measurements show a relatively large difference between the baseline and optimized case (up to a 10% increase in power production with wake steering), while the modelling shows only a 1-2% increase. This seems to indicate that for this turbine (WTG26) the wake steering is having a clear effect. However, in figure 9, for WTG E5, this can not be replicated. Why is that?*

A1. We appreciate that the reviewer raises this concern and he is correct in his statement that the effects of yaw misalignment on WTG 26 are not reflected in WTG E5 when comparing figures 8 and 9 of the original manuscript. The authors would like to point out that the power production shown in Figures 8 and 9 are solely the power production of the single, yawed turbine being WTG 26 (Figure 8) or WTG E5 (Figure 9), respectively. Based on Appendix B, it appears that the GE 1.5s turbines in this farm show a slight power increase for (measured) negative yaw misalignment, which also holds for WTG 26 as seen in Figure 8. These effects do not seem to reflect onto WTG E5, perhaps because this is a GE 1.5sle wind turbine and therefore not the same type as WTG 26. Another explanation might be that the turbines, coincidentally, have different bias correction terms. Additionally, it may be that shear and veer effects in the wind farm give rise to different yaw-power behavior [Howland et al., 2020]. Though, this is only speculation, and the authors cannot give a definitive answer to why the yaw-power curve differs in the way that it does between WTG 26 and WTG E5. To explain this, the authors have added a comment in Section 5: "The authors speculate ... bias corrections." and also made a remark on the additional effects that shear and veer may have on the yaw-power curve.

Q2. *You acknowledge loads are important in one short sentence all at the end. If they are important (of which I am quite convinced they are), shouldn't you also mention this either in the abstract and the literature review? I think it is perfectly acceptable to limit the scope of this publication to study the effects on power production. However, assuming that the wake steering concept can not be considered in a real production environment without taking loads into account, it should take a more visible role in the evaluation of your experiment and publication (in my opinion at least).*

A2. The authors appreciate the reviewer's comment and agree with him that this discussion should be more transparent in the article. Consequently, remarks and additional citations have been added to the abstract, introduction and conclusion.

Q3. *Is there a specific reason why wake meandering is not discussed? I would expect wake meandering to be an important element in the context of wake steering, and it will have an impact on both power production and loads (considering partial wake conditions have a big impact on fatigue loads). How have you, or have others in the past, considered wake meandering when studying wake steering? Since the modelling you present is based on steady state wake deflections, how would you expect (qualitatively) wake meandering to impact the power production when compared to a steady state modelling approach? Could this be an important focus area for future work?*

A3. The reviewer is correct in stating that wake meandering is an important factor in wake steering. The current steady-state wind farm models attempt to predict a 5-minute-average power production based on the mean inflow conditions and turbine yaw misalignment. Since FLORIS is tuned to high-fidelity data that includes wake meandering, FLORIS also captures the mean (time-averaged) effects of wake meandering on the power production. Naturally, the model is a simplification, but it does include wake meandering, among other effects. To include the full dynamic spectrum of wake meandering in the model, one would need to migrate towards the usage of dynamic wind farm models for control. This is an active field of research. Accordingly, an explanation of this has been added to the section on FLORIS and the recommendations have been updated.

Q4. *Have you considered any uncertainty (and/or a potential bias) in the wind direction measurement. If so, how would that affect the interpretation of figure B1 in particular, and the measurements in more general?*

A4. The reviewer points out an important factor in the controller design and data analysis. Currently, the wind direction is estimated by combining the local wind direction measurements from WTG 24 and WTG 25, considering WTG 26 is yawed and its wind direction measurement is less reliable. Note that the estimates from WTG 24 and WTG 25 are bias corrected by the internal GE algorithm. However, the workings and reliability of this bias correction algorithm are confidential, and the correctness of the assumption of using estimates of WTG 24 and WTG 25 for WTG 26 is uncertain. Indeed, Figure B1 suggests that WTG 26 may contain a bias in its wind direction measurement, and in that situation operates at a constant yaw misalignment when $\gamma = 0^\circ$ is assigned. This would explain the power increase we see in Figure 8 when yawing the turbine in a negative direction. This was not modeled inside FLORIS and if it was, the optimal yaw misalignment profile would look quite different, most probably shifting emphasis to generally smaller and negative yaw misalignment angles. In the field campaign, an incorrect wind direction estimate also leads to the usage of the wrong yaw angle database entries, which may be a source of performance losses. Though, in defense of the authors, the wind directions at which the largest measured power deficit occurred at the downstream turbines (due to the wakes of WTG 26 and E5) were periodically compared to what FLORIS (plus bias corrections) predicts, making sure they align. With the data available, the authors believe this is the best they can currently do. A statement has been added to the manuscript indicating the likeliness of bias on the wind direction measurement and how that partially explains Figures 8 and B1.

Q5. *If you where to re-plan the experiment again knowing what you know today, would you design it differently? Or in other words, based on your experience, how would you plan a follow-up experiment to address the challenges you have encountered?*

A5. The authors attempted to answer this question by listing a number of "lessons learned" in the conclusion. The authors now understand that this does not exactly answer the same question. To clarify, one large source of error was the wind direction uncertainty and the large discrepancy between the measured and modeled yaw-power curve of turbine WTG 26 (and possibly also WTG E5). This curve must be characterized accurately in the model before performing the yaw optimization. Additionally, in general, it would be greatly beneficial to tune the simplified wind farm model to SCADA data before implementing a wind farm control solution. Specifically, figures 9 and 10 showed large discrepancies between FLORIS and the measurements. One may want to perform simple and shorter wake steering tests to generate data for model tuning, such as keeping WTG 26 and a constant yaw misalignments of -20° to $+20^\circ$ in steps of 5° for periods at a time and under various wind shear and veer conditions [Howland et al., 2020]. However, this may go at the cost of the plant's energy production and therefore also depends on the willingness of the wind farm operator. Doing such a model calibration may also indicate weaknesses in the model, such as the absence of ground effects and variations in the surface level. Important for model tuning is an accurate characterization of the inflow conditions, both in front of turbine WTG 26 but also in front of WTG E5. Note that a difficult trade-off must be made between the value of additional/more accurate measurements, and the additional costs involved. Ideally, one would also measure the complete wakes downstream at a higher sampling rate, measure the fluid density and atmospheric temperature at various heights from the ground, and identify the incoming turbulence levels. Though, the authors cannot make a definitive conclusion on what equipment would provide most value and where it should be placed in a hypothetical future experiment. Rather, the scope of this article lies with the analysis of the experiment outcomes, rather than experiment design. The authors believe, to appropriately address this question, a study would be necessary that would make a publication by itself. In this manuscript, we have extended and reformulated the conclusion to better resemble the answer presented here.

Q6. *You briefly mention the measurements are in complex terrain. Could you elaborate further on why this might be very challenging in a validation measurement campaign?*

A6. We thank the reviewer for attending us to the lack of clarity on this matter in the draft manuscript. Section 2.2 contains a list of challenges specific to this field experiment, among which the terrain complexity is mentioned. Specifically, this wind farm is situated in hilly area, where the turbines are positioned between 400 and 450 m above sea level. Such variations are likely to give variations in the ambient wind speed and wind direction between different upstream wind turbines. However, FLORIS assumes a uniform (homogeneous) ambient inflow, where each upstream turbine experiences the same wind speed, wind direction and turbulence intensity. Specifically, variations in the ambient wind direction have a large influence on wakes, and thereby on the wake steering campaign. Inclusion of such topology effects are an important challenge to tackle in future work. Additionally, as can be seen in Figure 1, various types of vegetation are present on the ground. The surface roughness varies with the type of vegetation, which in turn impacts the level of turbulence and thereby wake recovery. Such effects are not included in FLORIS and are speculated to play a role in the mismatch between the measurements and FLORIS for the downstream wind turbines. For clarification, this explanation has been summarized and included in Section 2.2.

Specific remarks:

SR1. *Lines 49-50: Sounds contradictory. I think it is quite clear why wake steering is not likely to affect the net energy production of wind farms in general. Howland et al (2019) for example summarize this quite well in their abstract/introduction. I understand that for certain cases (specific layout at a specific wind speed and wind direction) a dramatic power output can be obtained when employing wake steering and evaluating the effect on power production with a steady state wake deflection model. I also believe it is important to study that. However, I don't think it is correct to claim at this point in time that wake steering has a real potential to increase the net energy production of wind farms in general.*

A1. The authors appreciate the reviewer's comment, especially in relationship to the results of Howland et al. (2019). In the authors' eyes, wind farm control does still have real potential to increase the power production of wind farms on an annual basis. The authors believe that the measured increases for specific wake-loss-heavy situations may currently be outweighed by losses for other situations due to incorrect yaw misalignment. Namely, all persistent power losses can in theory be avoided by simply only yawing the turbines when an increase in power production can be guaranteed. The results in this publication support the notion that the current wind farm controllers do not suffice yet. An interesting observation supporting our opinion is that Siemens-Gamesa recently released their wind farm control solution "WakeAdapt", in which wake steering is sold as a service to wind farm operators to increase their annual power production. However, as the reviewer rightfully points out, this is not something we can guarantee. Therefore, we have softened the statement on lines 49-50.

SR2. *Lines 79-81: A minor detail of course, but I think you can leave this statement out as it is not relevant for the paper. It also sounds like a snippet from the companies advertisement brochure ("global leader", "forefront").*

A2. This statement has been removed from the manuscript.

SR3. *Figure 2: based on the [-] unit I assume data size is normalized in order to avoid disclosing too much sensitive information? Or is that referring to number of 10 minute averages (so unit is number of samples)?*

A3. We thank the reviewer for his detailed remarks, and have updated Figure 4 and Figure 7 accordingly. Indeed, the unit is the number of samples.

SR4. *Lines 102-104: The surrogate model is based on a physical model I assume? One element is what the physical model can capture, the other how well the surrogate can re-capture the underlying data. To what is this statement referring to? This only becomes clear on line 155, maybe here you could refer to section 3.2 for more details on the surrogate model?*

A4. We appreciate the suggestion made by the reviewer and have added the reference to Section 3.2 accordingly.

SR5. *Line 112: Completely agree, but as you already point out, a high quality reference measurement for wind speed, turbulence intensity and wind direction is required in a validation study context.*

A5. We thank the reviewer for his comment. We have addressed this issue previously with answering the major remark Q5 and the modifications made to the manuscript based on that comment.

SR6. *Lines 117-118: Could you elaborate a little bit more what the context of these simulations are (model type, etc)?*

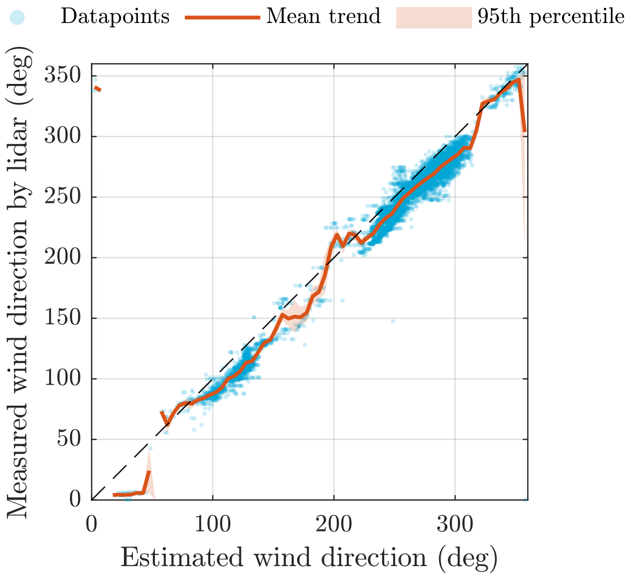
A6. The authors assume that the reviewer is talking about the simulations shown in Figure 3. To clarity, the simulations are done with the same model parameters as used to generate the LUT, which are taken from the Renewable Energy publication of Doekemeijer et al. (2020). The turbulence intensity is 5% and the wind speed is 8.0 m/s. We understand that this level of turbulence intensity is not particularly realistic for this site, but Figure 3 should serve to explain how the turbine scheduling works in the work at hand, rather than give an accurate representation of the wake length and depth. A remark is added to the caption of Figure 3 to explain this.

SR7. *Lines 139-142: To my knowledge, the biggest hurdle would be certification, is that correct? I completely agree with the authors that a closed loop controller would be much more complex, however, technically it would not be prohibitively complex.*
I would imagine a wind turbine manufacturer will not open the controller up to its customers to perform these types of experiments. Knowing that the load certification process heavily relies on a well tuned controller, this is a reasonable precaution from the manufacturer side.

A7. The authors agree with the reviewer in that the main challenge currently lies with certification. While the loads can be kept under control by setting limits on the assigned yaw angles, other factors such as controller stability further complicate things. Moreover, very few closed-loop wind farm control solutions have been developed and tested in realistic (time-varying) simulations, and thus confidence levels for such solutions are still low.

SR8. *Figure 4: Is each data point the 1 minute averaged wind speed? Can you show a similar plot for the turbulence intensity and the wind direction? Assuming you have access to the MET mast data, does it illustrate that, as you write on lines 120-125, it is simply too far away to be used reliably as an indication of free stream wind direction and speed? Do you expect that this validation/correlation curve is independent of wind direction?*

A8. These are indeed the 1-minute averaged data points for the wind speed. The lidar system also provides wind direction measurements, with which we can make a similar comparison as for the wind speed:



When we look at this figure, we can see an offset in which the lidar-estimated wind direction is consistently lower than the turbine-estimated wind direction. However, we cannot know whether one or both of the estimates is wrong, and by how much. Instead, we opted to correct the turbine-estimated wind direction by comparing the situations of largest wake loss, as also answered in our response to major remark Q4. To the authors, this seems the most sensible way to tune the model, since this is concerned with the relative position of the wakes rather than the absolute values of wind direction estimates.

Moreover, unfortunately, the dataset does not include lidar estimates of the turbulence intensity, nor does it include measurements from the measurement tower. However, again, if the turbine-based wind estimates would not align with the measurements from the measurement tower, this would not imply that the turbine-based estimates are faulty, nor would it allow us to decide which of the two measurements is more reliable. The comparison shown in the publication provides supporting evidence that the wind speed (and with the figure here: wind direction) is roughly correct, though the conclusions we can draw from the data are limited.

Finally, the wind speed correlation curve (Figure 4) is not expected to be independent of the wind direction. Namely, ground effects can give rise to consistent higher/lower wind speeds in front of a turbine. The lidar system measures the inflow at a distance upstream of the rotor, while the turbine-based estimates are derived from the flow at the rotor plane. Therefore, a persistent difference between the estimates may arise for particular wind directions. Though, it is uncertain to the authors how large this effect would be.

Based on the reviewer's comment and our explanation here, we have updated Figure 4 and expanded the explanation in Section 2.3 on how the turbine-based estimates are calibrated.

SR9. *Lines 175-176: I understand it is out of scope for this publication, but is it possible to add one or two sentences how different the "underlying equations" between the FLORIS and FarmFlow solvers are?*

A9. We appreciate the reviewer's comment. Though, the authors refer readers that are interested in the model differences to the corresponding literature, rather than repeating such information in this article.

SR10. *Lines 176-177: For someone who is not a wind farm flow modeller expert this statement might not be obvious. Are there any references to back this statement? Or is it based on the author's general experiences as users and/or expert modellers?*

A10. We appreciate the reviewer's comment in improving the clarity and contributions of this manuscript. The authors assume that the reviewer's comment is concerned with the statement that FarmFlow has a common trend of predicting lower gains than FLORIS. This is indeed based on experience of the modellers/users of each model, which are co-authors on this publication. We understand that this statement can cause confusion and have therefore added that this is empirically motivated.

SR11. *lines 197-199: Wouldn't this still result in a relatively broad range of operating an inflow conditions? I would be worried that all that averaging and aggregation will make it very difficult to make any clear conclusions since it won't be clear what exactly happens at which conditions. How do the results compare for much more limited datasets? For example, for a given sector/wind speed bin/turbulence intensity bin for which you have a fair amount of measurement samples? That could illustrate in a more detailed manner how the wake steering is visible in the measurements.*

A11. We understand the concern of the reviewer and it is a valid one. Essentially, by clubbing different turbulence intensity and wind speed measurements together in a single bin, how can one assure that the reported gains are accurate? The authors believe that value remains in the averaged values reported from the bins. Due to the limited number of measurements, it is difficult to limit the bins to narrow ranges of turbulence intensity and wind speed. Rather, the turbulence intensity range has been limited to a range of 12% to 18%, rather than from 0% to 18%. Additionally, by normalizing the power production measurements to a reference turbine's power measurement (WTG 25), we largely remove dependency of power measurements on the freestream wind speed. Then, narrowing the number of samples would give more reliable results (reducing spread), but the limited number of samples may instead led to an increase in spread/uncertainty. Therefore, the authors iteratively found a relatively narrow range which produced narrow confidence bounds in the final plot. Individual values for very specific bins and ranges can provide more positive results than what was shown here, but would not be necessarily more accurate or representative of what can be gained with wake steering. The authors believe that the approach described in the manuscript shows a more realistic and representative picture of the potential of wake steering. In response to the reviewer's comment, a note has been added to Section 4 motivating the choice for the wind speed and turbulence intensity ranges.

SR12. *Lines 200-205: Based on figure 3, I can see that WTG 10 and 11 are downstream turbines. I am confused with what this means for your measurements? If the turbine is being curtailed, I would expect that it would be less affected by the wakes upstream, is that correct? Are you at liberty to share to what exactly the curtailed operation refers to (in terms of different pitch and RPM strategy)?*

A12. The reviewer is correct in stating that a downstream turbine will be less affected by an upstream turbine when curtailed *in terms of the power production*. Effectively, the freestream-equivalent wind speed at the downstream turbine is unchanged. Therefore, using estimates of the freestream-equivalent wind speed of the downstream curtailed turbines provides a very comparable measure to using the power production in noncurtailed operation. The word "freestream-equivalent" has been added in Section 4 to further clarify this. Also, unfortunately the authors cannot share how the turbines are curtailed for confidentiality reasons.

SR13. *Figure 8: How many data samples do you have in each bin, I assume that varies per bin? Is the range of turbulence intensities and wind speeds similar across the bins? How does the yaw measurement uncertainty compares to the applied yaw error?*

A13. The reviewer is correct in stating that the number of samples vary per bin, and that this does have a large effect on the statistical uncertainty of the reported outcomes in the manscript. To prevent repetition of plots, the authors decided to show the number of samples previously in Figure 7. Initially, the bins varying across wind directions do not contain an even distribution over turbulence intensities and wind speeds, as the reviewer rightfully points out. This was addressed by balancing the bins as stated in bulletpoint 7 of Section 4. For clarify, a reference to Figure 7 has been added to Figures 8-11.

SR14. *Figure 10: The model predicts a very small difference (baseline vs optimized), while the measurements show a very different picture. Further, the difference between the models seems to be smaller than the 95% confidence of the measurements.*

A14. The reviewer is correct in his observations. The authors agree that the surrogate model is not particularly accurate in predicting the wake losses at WTG-10, 11, 12 and 31. This is discussed in the text, for example, "However, FLORIS overestimates ... accurate terrain model." and "Also, FLORIS predicts ... accounted for in FLORIS." The fact that the confidence bounds seem larger than the potential gains predicted by FLORIS are more to blame on FLORIS rather than on the measurements. We have emphasized this in the text corresponding to Figure 10.

SR15. *Figure 11: could you also indicate the average net gain (simple average over the considered directions, not including probability of occurrence)? It seems to be positive, is that correct?*

A15. The average net gain when weighing each wind direction bin equally would be **1.7%**, which indeed is positive. However, the authors would like to refrain from such statements in the article, as it might be misleading and is not representative of the potential gain due to wake steering in this wind farm experiment.

SR16. *Lines 285-287: I am puzzled by this statement and it contradicts the general understanding I have of wind turbines. Wind turbines operating under a yaw error will have by definition less power output and are subject to higher fatigue loads. So how can it be beneficial to operate a turbine with a constant yaw error? I can understand the statement when assuming there is a bias in the wind direction measurements, or that the complex terrain results in a flow field that is very complex and produces counter-intuitive results. However, I don't see such a discussion here.*

A16. We appreciate the reviewer's comment and agree with his statement that nonzero yaw misalignment should generally lead to power losses instead of power gains. This is what the authors also intended with this message, but in retrospect was poorly formulated. This phenomenon is likely due to a poorly calibrated wind vane sensor, rather than a true property of the wind turbine. We have added clarifications in the results section for WTG 26 and in the conclusion.

SR17. *Line 289: You place "free" between quotes, but what about loads?*

A17. We have rephrased this statement to better represent the discussions on the yaw-power curve relationship and on the loads previously discussed in major remark Q2.

SR18. *Lines 290-291: If there are large discrepancies between the measurements and the model, how can you conclude the surrogate model is able to predict the dominant wake interaction trends? I understand that the model is intended to do so (and effectively does in other cases), but that doesn't mean it is true for your specific case.*

A18. We appreciate the reviewer's comment and agree that the results make it seem like the reliability of the entire FLORIS model is questionable. What we attempt to convey with our statement is that FLORIS is accurate in predicting at what wind directions the wake losses will be largest. Considering in this aspect the FLORIS model is accurate, then one could reason that FLORIS more or less accurately predicts where the mean position of the wake is as a function of wind direction. The actual depth of the wake is not estimated accurately, but perhaps this is secondary. If the position of the wake would be estimated incorrectly, that could lead to situations in which turbines are erroneously yawed and thereby perhaps accidentally steering a wake back onto a downstream turbine. If the error instead lies with the depth of the wake (as is the case in this manuscript), the result is a too large/small yaw angle, which typically has a much smaller effect on the success of the algorithm. We have attempted to clarify this in the manuscript, both in the Results section and the Conclusions.

SR19. *Line 313: Agreed. I would suggest to split the conclusions chapter into 2: "conclusions" and "future work". In the "Future Work" section you could consider being more specific about what you suggest should be done to resolve specifically the shortcomings you've seen in your experiment. This could be valuable for future validation campaigns of the wake steering concept.*

A19. The authors appreciate the reviewer's comment and the corresponding major comment Q5. The conclusions have been extended to include a more detailed overview of recommendations for future experiments. Furthermore, the authors would like to refrain from introducing subsections in the conclusion. Namely, the conclusions section, as it is written now, would have to be split up into a *conclusions*, *recommendations*, and *wrap-up* subsection. The authors believe this would worsen the manuscript's readability.

SR20. *Figure 1B: Is this a reasonable or comparable power-yaw curve when compared to other experiments, for example when looking at the data from Danaero, MEXICO, MexNext, etc? How have you verified the presented result is not due to a bias in the yaw inflow measurement?*

A20. We thank the reviewer for his comment, and he is very right in pointing out that the presented bias may very well be due to a poor yaw inflow measurement rather than a physical property of the turbine. Additionally, wind shear and veer have been reported to effect the yaw-power curve of commercial wind turbines [Howland et al., 2020]. The authors have previously addressed this in their response to major remark Q4. In the revised manuscript, the authors explain that they cannot verify whether the power-yaw curve is due to this bias in the yaw inflow measurement with the data available, but that it is a likely assumption. Literature suggests a yaw bias is common in operational wind turbines [e.g., Fleming et al., 2014, Scholbrock et al., 2015, Kragh and Hansen, 2015]. The authors attempted to mitigate this bias by comparing at what wind direction the largest wake losses are at downstream turbines compared to the actually measured losses and wind directions. Though, it is not unreasonable to assume that this was insufficient. In addition to the adjustments made in response to Q4, remarks have been added in the results section and the appendix to further clarify this issue, including a reference to the literature mentioned in this response.

Response to Reviewer 2 (Anonymous)

Dear reviewer, thank you for your compliments, for reviewing the revised manuscript and for providing us with useful suggestions to improve this manuscript. We have split up your commentary in parts, attempting to address each of your concerns with care.

Q1. Dear Authors, your paper presents results from a wake steering experiment considering three-turbine interactions in complex terrain. It is well written and organized. The paper contains a unique wind farm control experiment and the work presented is very important for the wind energy research community. Thanks for working on it! It nicely confirms that there is a large potential for wind farm control, but also still more research is necessary to understand all effects. In general, the paper could focus more on these effects which are not fully understood. For example in Section 5, line 221, the authors try to interpret the effect, although the uncertainty of the data is very high: you write: ". . .while negative yaw misalignment angles even lead to a slight increase in the power production. . .". However, the difference between both curves for 255-295 deg is similar to the difference between both curves below 230 deg, where both lines should be equal, since WTG 26 is not misaligned. Therefore, the conclusion "that upstream turbines may benefit from nonzero yaw misalignment, already leading to an effective increase in power production at these turbines without considering the phenomenon of wake steering downstream" is hard to follow. Further, it might be that the upstream wind turbine already had a static yaw misalignment and a demanded nonzero yaw misalignment unintendedly aligned the turbine into the wind and thus increased the power.

A1. We thank the reviewer for his/her insightful comment. Namely, the reviewer addresses an important point that was also addressed by reviewer 1: a relatively large uncertainty remains in the power production for the baseline and optimized dataset shown in Figure 8 and, based on the general understanding of wind turbines, a nonzero yaw angle leading to a consistent increase in power production is counter intuitive and rather points towards an issue with the baseline wind direction estimate and yaw controller. The text in Section 5, Section 6 and Appendix B have been updated to further highlight the possibility is these phenomena being due to a bias in the wind direction estimates. Supporting literature for this claim has also been included in the manuscript.

Q2. Another example is that for Figure 10, you write "the predictions (no losses due to wake steering for downwind turbines) are largely reflected", but for a quite a large are, there are losses for WTG 11 and 12. Focusing on these effects might help more to improve further wind testing campaigns compared to highlighting (sometimes uncertain) positive effects."

A2. We appreciate the reviewer's comment and agree with him/her that he cited statement is incorrect. What the authors intended to convey is that FLORIS does a reasonable job in predicting where the largest losses will be (i.e., when we wake will have the largest overlap with a downstream turbine). However, indeed, FLORIS does not accurately predict losses at downstream turbines compared to baseline operation. This statement has been adjusted and Section 5 of the manuscript has been updated according to the explanation made in this response.

Q3. Further, there are several points where more details might help to better understand the work:

Q3.1. Section 3.1: You pointed out that the most important variable of the ambient condition is the wind direction. However, in Figure 4 you compare the wind speed from the lidar to the ones estimated by WTG 24 and 25.

A3.1. The reviewer is very correct in his/her observation and we have adjusted the manuscript accordingly. Namely, we have included a figure comparing the wind direction estimate from the turbines with that from the lidar system. We have also introduced a more elaborate discussion on the accuracy and validity of these estimates, and how this information is used for the field campaign.

Q3.2. Further, Section 3.1 is relatively short. It would be interesting to know (if this information can be shared):

Q.3.2.1. how and on which signals wind speed, wind direction and TI are estimated.

A.3.2.1. The estimates are derived by averaging the estimated quantities for WTG 24 and WTG 25, as reported in Section 3.1. Unfortunately, the authors cannot share the functioning of these wind turbine estimators for confidentiality reasons. Furthermore, a remark is added to Section 3.1 explaining how the wind direction estimates from the wind turbines were monitored and corrected by comparing at what wind direction the largest power dips occur at downstream turbines.

Q.3.2.2. Further, it is not clear in Figure 4 if datapoints are 1 min or 10 min averages.

A.3.2.2. The reviewer raises an excellent concern. The datapoints from WTG 26 are 1-minute averages, while the datapoints from the lidar system are 10-minute averages. The authors agree that this is not clear to the readers. Moreover, this also explains the notable spread in the plot. We have included a comment in Figure 4 in the manuscript.

Q.3.2.3. The lidar position could be included in Figure 3. Was it installed outside of the induction zone (based in standards more than 2.5 D) and was the data set filtered (e.g. sectors with wakes excluded)?

A3.2.3. We appreciate the reviewer's comment and agree with him/her that more information about the lidar system in the field campaign is valuable. Therefore, the lidar system's position in included in Figure 1. This figure shows that the lidar system lies at a distance of about 2.5-3D in front of WTG 26, and therefore lies outside of the induction zone as suggested by the reviewer. Additionally, with the additional plot, it becomes clear that no special filtering has been applied to remove sectors with wakes (e.g., there are several measurements near a wind direction of 90°). We have added a remark in the caption of Figure 4.

Q4. Section 3.2: More details about the optimization would be helpful: you mentioned that the yaw setpoints have been optimized in steps of 1 m/s, but then they are fixed between 5 and 11 m/s. Are the values based on an average? And maybe you could also use TI=13.5% since in the experiment the lower bound is 12%.

A4. We appreciate the reviewer's comment and agree that the current manuscript may cause confusion in how we ended up with the final lookup table. To clarify, optimal yaw angles were calculated for each wind speed, wind direction and turbulence intensity. Afterwards, these yaw angles were indeed averaged in the range of 5-11 m/s and smoothed. The final angles were verified by simulating them in FLORIS and reanalyzing the predicted power gains, which did not lead to noticeable losses compared to the initial angles. The authors have added clarifications in Section 3.2 to address this. Finally, the authors decided to proceed with to show the yaw angles and estimated power gains for the lower TI value in the main body of the manuscript to provide some theoretical estimated upper bound of the potential of the wake steering experiment.

Q5. Gaussian smoothing kernel: It definitely serves its purpose (reduces sensitivity) and looks fine in general. But at the "most important point", in a full wake situation (e.g. at 225 deg, WTG 26 in wake of WTG E5) in produces a setpoint of zero degree. Some comments of this drawback would be helpful, e.g. wouldn't a hysteresis or similar be more helpful?

A5. The reviewer makes an excellent suggestion. Indeed, full wake overlap between WTG E5 and WTG 10 (we assume this is what we reviewer implied) occurs at a wind direction of 225 degrees. When sweeping over this turbine from a wind direction below 225 degrees to a wind direction above 225 degrees, the optimal yaw angle has a discontinuous jump near 225 degrees. At that point, it becomes more valuable to steer the wake to the opposite side of the wind turbine and therefore the optimal yaw angle for WTG E5 goes from a large positive number to a large negative number. This would cause large wear on the yaw actuators and therefore we smoothed the angles as described in the manuscript. Indeed, this effectively leads to a near-zero yaw setpoint at 225 degrees. As the reviewer rightfully points out, hysteresis would be a much better solution to this. However, the current framework provided by the turbine manufacturer did not allow for such an implementation. We have elaborated on this in Section 3 and additionally included it as a recommendation for future experiments.

Q6. FarmFlow comparison: Results would be interesting, e.g. add line averaged over all wind speeds to Figure 6?

A6. We appreciate the reviewer's comment and have included the predicted average power gain from FarmFlow in Figures 6, A1 and A2.

Q7. Implementation: Here, more details than the last sentence in Section 3.2 would be helpful, e.g.

Q7.1. You describe, how the demanded yaw setpoint is derived from the estimated wind speed and wind direction via interpolation in a look-up-table. But it is not clear, if the estimated TI is used and if so, how? Sorry, if I missed it.

A7.1. We appreciate the reviewer's comment and agree that this may have been unclear in the manuscript. Actually, we interpolate the yaw angles over wind direction, wind speed and turbulence intensity. We have added a clarification in Section 3.

Q7.2. Why the controller is toggled every 35 min?

A7.2. We appreciate the reviewer's comment and understand that this is not clear to the reader. Actually, this number is chosen such that toggling is not equal every day, thereby reducing dependency on diurnal variations in the atmosphere. Additionally, a lower toggling time would lead to less usable data due to postprocessing, and a higher toggling time would reduce number of measurements obtained under comparable atmospheric conditions. The authors have added clarifications to the manuscript in Section 3.

Q7.3. How is the demanded yaw setpoint added to the turbine? As a real setpoint or by having an offset to the measurement signal?

A7.3. The yaw setpoint was assigned by adding an offset to the wind vane measurement, thereby "tricking" the turbine into yawing to a certain position.

Q7.4. How is the signal filtered?

A7.4. We assume this question relates to the estimated atmospheric quantities, being the wind direction, wind speed and turbulence intensity. Filtering and bias correction is part of the internal estimation algorithm of the wind turbines, and this information is not shared by the manufacturer. Additionally, averaging of the quantities between WTG 24 and WTG 25 provides some filtering.

Q7.5. If toggled off, is the turbine yawing instantaneously back or some time due to filtering?

A7.5. The turbine may take some time to yaw to their assigned setpoint due to the functioning of the yaw controller of the turbine. This is why, in postprocessing, data within 5 minutes after a toggle change was discarded. We have added a clarification in Section 4 on data processing.

Q7.6. How is the decision based on WTG 24 and 25 transferred to WTG E5 and 26?

A7.6. The reviewer clearly has eye for detail and the authors have indeed not explained this sufficiently in the manuscript. Actually, the estimated wind direction, wind speed and turbulence intensity of WTG 24 and WTG 25 are used to generate one mean ambient inflow wind direction, wind speed and turbulence intensity in front of WTG 26. These estimated quantities are used for interpolation to obtain setpoints for WTG E5 and 26. Note that the wind direction at WTG 26 is assumed to be equal to the wind direction of turbine E5. A part of the introduction of Section 3 has been rewritten for improved clarity.

Q7.7. Why there was a curtailment?

A7.7. Unfortunately this was without our knowledge and outside of our control. In an ideal situation, this curtailment would not have happened during our experiments.

Q8. Section 5:

Q8.1. Since you have been using the averaged estimates of WTG 24 and 25, wouldn't it be more consistent to use this average also for the postprocessing?

A8.1. The reviewer is exactly right and this is actually what the authors have done. We have added a clarifying statement to the first paragraph of Section 5.

Q8.2. And the yaw angle setpoints are shown. Wouldn't be the yaw misalignment be more interesting, since usually wind turbines don't follow the setpoint instantaneous? Maybe it could help to understand the effect between 295-320 deg.

A8.2. We completely agree with the reviewer that it would be more insightful to look at the achieved yaw angles rather than only the yaw angle setpoints. However, unfortunately, accurate yaw sensors for WTG 26 and E5 were only available during the first two months of the campaign. If we would produce a figure showing the estimated wind direction and nacelle yaw with the narrow bands on wind speed and turbulence intensity (following the regular postprocessing procedure as described in the manuscript), any similarity in the measured and predicted yaw curve is lost. Moreover, no useful plots can be made with the regular turbine wind vanes of WTG 26 and E5.
Using more data and different postprocessing may provide a curve that better resembles the assigned yaw curve, yet adding this to the manuscript would require an additional explanation of how the data is postprocessed, how that is different from the other data in the plot, and why. Furthermore, the bins would be based on different (less) data which further confuses the reader. To prevent further confusion in the manuscript, the authors decide not to include the additional lines in Figures 8 and 9.

Q8.3. Figure 9: why is the baseline from Floris not 1.3 as stated in the text for unwaked conditions, e.g. 200-240 deg?

A8.3. We appreciate the reviewer's excellent eye for detail. Actually, the baseline value for FLORIS in Figure 9 should be 1.2, after revising this simulation set-up in FLORIS. The authors initially believed it to be 1.3 because that was the highest value in the plot at a wind direction of approximately 310 degrees. However, at a wind direction of 310 degrees, the wake of WTG 24 starts impacting the power production of WTG 25. Thus, effectively the power production of WTG 25 is less. Since the power signal of WTG E5 is normalized to WTG 25, this wrongly raised the idea that the power production of WTG E5 was higher at this wind direction. We have corrected this in the manuscript and added a comment explaining the apparent increase in power production in Figure 9 at a 310 degrees.

Q8.4. Figure 11: How does the Floris prediction here corresponds to the ones in Figure 6, A1, A2? If there has been a scheduling on TI, one would expect an average. However, close to 310 deg there is a prediction of losses, not present in Figure 6, A1, A2

A8.4. The reviewer makes a rightful observation in that there are very slight losses predicted even by FLORIS at high wind directions. To clarify, the FLORIS predictions have been obtained by simulating the prescribed yaw setpoints and ambient conditions for each measurement in each bin, and then post-processing the outcomes in the same manner as with the measurement data. This process has also helped in finding errors in the postprocessing code. Notice that the predicted gains in Figure 11 share much similarity with the predicted gains in Figure A2. The loss at 310 degrees is likely to be explained with Figure 7. Figure 7 shows that there are very few datapoints in the bins above 300 degrees. Even though data entries are balanced within each bin to minimize dependencies on the wind speed and turbulence intensity, it may still happen that notable differences in the turbulence intensity or wind speed occur with sparsely populated bins. A narrower wind speed and turbulence intensity range may have been beneficial here, though it would probably lead to insufficient data to draw any conclusions. A discussion has been added to Section 4, which also answers Specific Remark 11 of Reviewer 1.

Q9. Conclusions: It is not clear, why the “transition regions” lead to poor performance. Are those not only part of the postprocessing? Floris should optimize the yaw angles without this concept.

A9. The appreciate the reviewer’s comment. Actually, the transition regions are not only for postprocessing. Namely, if all turbines were included in the yaw optimization, then turbines (especially E5) would attempt to steer their wake in between downstream turbines. This is difficult and would lead to smaller yaw misalignment angles and smaller power gains than when following the approach used currently in the manuscript. This was previously addressed in Section 2.2. Consequently, since turbine scheduling was included in the yaw optimization, there are sudden transition points at which different turbines become the turbines of interest. This may cause strong gradients in the optimal yaw angle and thereby, after smoothing, are more sensitive to power losses. For clarification, a remark has been added to Section 3 stating that the optimization was done using the wind-direction-scheduled layout.

Specific remarks

SR1. l25f: Measurement uncertainties should be also present in wind tunnel experiments. Do you mean that the wind turbines are not measuring the wind direction by themselves? Would be good to specify.

A1. We agree with the reviewer and we have made modifications to the manuscript accordingly.

SR2. l87, Figure 2: Predominant wind directions seem to be west and south-east (and not south-west)

A2. We agree with the reviewer and we have made modifications to the manuscript accordingly.

SR3. l165, Figure 6: γ has not been introduced. Maybe use yaw setpoint instead?

A3. We thank the reviewer for his eye for detail and have explained the symbol in the text.

SR4. l171: Maybe add 285+295 (WTG 31 in wake of WTG E5) to the list.

A4. We agree with the reviewer and we have made modifications to the manuscript accordingly.

SR5. Figures 8-11: you mentioned that the wind direction of interest are 200 to 320 deg. However, only 200 to 310 deg are shown.

A5. The reviewer is correct. Unfortunately, very few measurements are available at high wind directions. Additionally, there is no yaw misalignment at the wind direction range of 310-320 degrees. Therefore, we decided not to show these values in the final results. We have added a remark to Section 4 noting this.

SR6. l256: It might be better to write "for the three-turbine-interaction", since the third turbine changes.

A6. We appreciate the reviewer's remark and have made modifications to the manuscript accordingly.

SR7. l286. plural "s" missing for "these turbines".

A7. We thank the reviewer and have made modifications to the manuscript accordingly.

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Field experiment for open-loop yaw-based wake steering at a commercial onshore wind farm in Italy

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Abstract. The concept of wake steering in wind farms for power maximization has gained significant popularity over the last decade. Recent field trials described in the literature demonstrate the real potential of wake steering on commercial wind farms, but also show that wake steering does not yet consistently lead to an increase in energy production for all inflow conditions. Moreover, a recent survey among experts shows that validation of the concept remains the largest barrier for adoption currently. In response, this article presents the results of a field experiment investigating wake steering in three-turbine arrays at an onshore wind farm in Italy. This experiment was performed as part of the European CL-Windcon project. While important, this experiment excludes an analysis of the structural loads and focuses solely on the effects of wake steering on power production. The measurements show increases in power production of up to 35% for two-turbine interactions and up to 16% for ~~three-turbine interactions~~three-turbine-interactions. However, losses in power production are seen for various regions of wind directions too. In addition to the gains achieved through wake steering at downstream turbines, more interesting to note is that a significant share in gains are from the upstream turbines, showing an increased power production of the yawed turbine itself compared to baseline operation for some wind directions. Furthermore, the surrogate model, while capturing the general trends of wake interaction, lacks the details necessary to accurately represent the measurements. This article supports the notion that further research is necessary, notably on the topics of wind farm modeling and experiment design, before wake steering will lead to consistent energy gains in commercial wind farms.

1 Introduction

Over the last years, the concept of wake steering in wind farms has gained significant popularity in the literature (Boersma et al., 2017; Kheirabadi and Nagamune, 2019). Fundamentally, wake steering leverages the principle that intentional yaw misalignment of a wind turbine displaces its downstream wake. Thus, by choosing the right yaw misalignment, the wake formed by an upstream turbine can be directed away from a downstream turbine at the cost of a small reduction in its own power production and a change in mechanical loads on the turbine structure. Consequently, this concept enables a net increase in the power production of downstream turbines and, at large, wind farms. In high-fidelity simulations, wake steering strategies are shown to increase the wind-farm-wide power production by 15% for wake-loss-heavy situations (e.g., Gebraad et al., 2016). Moreover, wind tunnel experiments indicate increases in the wind farm's power production of up to $4 - 12\%$ for two-turbine arrays (Adaramola and Krogstad, 2011; Schottler et al., 2016; Bartl et al., 2018), up to $15 - 33\%$ for three-turbine arrays (Campagnolo et al., 2016a, b; Park et al., 2016), and up to 17% for a five-turbine array (Bastankhah and Fernando, 2019). However, these experiments neglect realistic wind variability and measurement uncertainty; often, the wind direction is known a priori and fed directly to the controller. A field experiment of wake steering in a scaled wind farm by Wagenaar et al. (2012) is inconclusive compared to baseline operation. In response, there has been a surge in the interest towards the development of reliable wake steering solutions that address issues of wind variability and measurement uncertainty (e.g., Rott et al., 2018; Simley et al., 2019; Kanev, 2020; Doekemeijer et al., 2020). Additionally, interest towards the effect of yaw misalignment on the turbine structural loads is rising, with publications showing both reductions and increases in structural loads, depending on the turbine component, misalignment angle and wind profile (e.g., Kragh and Hansen, 2014; Damiani et al., 2018; Ennis et al., 2018). The scope of this article is limited to the effects of wake steering on power production.

A small number of articles focus on the validation of wake steering for power maximization at full-scale turbines and commercial wind farms. Fleming et al. (2017a) instrumented a GE 1.5MW turbine with a lidar and operated the turbine at various yaw misalignments to study the wake deflection downstream. Then, Fleming et al. (2017b) demonstrated wake steering at an offshore commercial wind farm with relatively large turbine spacing of 7 to 14 times the rotor diameter (7–14D). These field trials involved yawing an upstream wind turbine and investigating the change in power production at the downstream turbine. When looking at two turbine pairs spaced $7D$ and $8D$ apart respectively, a gain was seen in the power production of the second turbine for most wind directions, at the cost of a much smaller loss on the upstream machine. This led to an increase in the combined power production of up to 10% for various wind directions. No significant improvements were seen for third turbine pair spaced at $14D$. However, the uncertainty bounds remain fairly large and the results also suggest that the net energy yield reduces due to wake steering for a smaller number of cases. Thereafter, Fleming et al. (2019, 2020) evaluated wake steering at a closely spaced (3–5D) onshore wind farm surrounded by complex terrain, again considering two-turbine interactions. Measurements show that the net energy yield can increase by up to 7% and reduce by up to the same amount for the $3D$-spaced turbine pair, depending on the wind direction. Similarly, the change in the net energy yield for the $5D$-spaced turbine pair is between $+3\%$ and -2.5%. It must be noted that the situations that lead to an increase in power production outnumber those that show a decrease in power production. Furthermore, Howland et al. (2019) assessed the concept of wake steering on an onshore 6-turbine wind farm with $3.5D$ turbine spacing. While significant gains in power production of up to 47% for low wind speeds and up to 13% for higher wind speeds are reported for particular situations, the authors also state that the net energy gain of the wind farm over annual operation is negligible compared to baseline operation.

~~Considering the~~ The current literature on wake-steering field experiments ~~, it is apparent~~ suggests that wake steering has real potential to increase the net energy production in wind farms, yet does not consistently lead to an increase in power production for all inflow conditions. Moreover, only Howland et al. (2019) address multiple-turbine interaction, rather than the two-turbine interactions addressed in Fleming et al. (2017b, 2019, 2020). Clearly, additional research and validation is necessary for the industry-wide adoption of wake steering control algorithms for commercial wind farms. This is in agreement with a recent survey among experts in academia and industry working on wind farm control (van Wingerden et al., 2020), which shows that the lack of validation is currently the primary barrier preventing implementation of wind farm control.

In this regard, this article presents the results of a field campaign for wake steering at an onshore wind farm with complex terrain in Italy, as part of the European CL-Windcon project (European Commission, 2020). The goal of this experiment is to assess the potential of the current wake steering strategies for such complicated, commercial wind farms. The contributions of this work are:

- As one of the few in the literature, demonstrating the potential of a state-of-the-art wind farm control algorithm for wake steering at an commercial onshore wind farm with complex terrain.
- Investigating wake interactions in non-aligned (i.e., not in a straight line) three-turbine arrays, in which yaw misalignments are applied to the first two turbines. The yaw misalignments are computed offline, based on the optimization of a simplified mathematical model of the wind farm. Wake steering for non-aligned turbine arrays has not been treated in the existing field experiments.
- The assigned yaw misalignment covers both negative and positive angles, depending on the wind direction. In the existing literature, turbines were only misaligned in one direction.
- Addressing multiple turbine types. Namely, the second turbine, WTG E5, has a different hub height and rotor diameter than the other turbines. This has not yet been assessed in the existing field experiments.

The article is structured as follows. Section 2 outlines the wind farm and the experiment. Section 3 shows the turbine control setpoints, calculated using state-of-the-art wind farm control solutions. Section 4 describes the data post-processing. Section 5 presents the results of the field experiment. Finally, the article is concluded in Section 6.

2 Methodology

This section outlines the details of the experiment. In Section 2.1, the wind farm layout, terrain, and turbine properties are depicted. Then, Section 2.2 addresses the wake steering experiment itself and discusses several challenges faced compared to previous field tests. Finally, Section 2.3 describes what data is collected during the experiment.

2.1 The wind farm

The wake-steering field campaign has been executed on a subset of turbines in a commercial, onshore wind farm near Sedini on the island of Sardinia, Italy. The field experiment is part of the European CL-Windcon project. The wind farm, owned and operated by ENEL Green Power (EGP), is typically operated for commercial purposes, not for testing. ~~EGP is a global~~

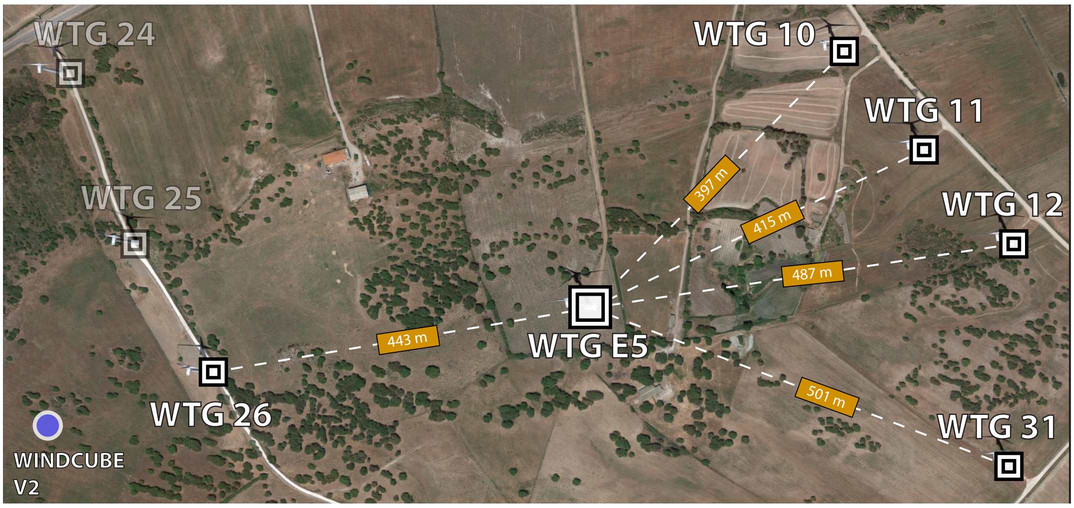

Figure 1. Positions of the wind turbines used in the wake steering campaign. Turbines WTG 26 and E5 are operated at a yaw misalignment to steer the wakes away from downstream turbines WTG E5, 10, 11, 12, and 31. WTG 25 is used for normalization. WTG E5 is a GE 1.5sle turbine, and all others are GE 1.5s turbines. A WindCube V2 lidar system is used to characterize the inflow in front of WTG 26 for a short period of the field campaign. Imagery ©2020 Google, Imagery ©2020 CNES / Airbus, Maxar Technologies, Map data ©2020.

Table 1. General properties of the GE 1.5s and GE 1.5sle wind turbines

Variable	GE 1.5s	GE 1.5sle
Rated power (MW)	1.5	1.5
Cut-in wind speed (m/s)	4.0	3.5
Rated wind speed (m/s)	13.0	12.0
Rotor diameter (m)	70.5	77.0
Hub height (m)	65	80

~~leader in the green energy sector with a managed capacity of around 46 GW across a generation mix that includes wind, solar, geothermal and hydropower, and is at the forefront of integrating innovative technologies into renewable power plants.~~ The wind farm contains a total of 43 GE wind turbines, of which 36 turbines are of the type GE 1.5s, and 7 turbines of the type GE 1.5sle. Properties of the two turbine types found in this farm are listed in Table 1. The relevant subset of the wind farm layout is shown in Figure 1. In the wake steering campaign, WTG E5 is of the type GE 1.5sle, and all other turbines are of the type GE 1.5s.

The Sedini wind farm is located in a relatively flat area with an average elevation of 360 m to 400 m above sea level, surrounded by hills of $400-450$ m above sea level. The site vegetation consists of scrub and clear areas. The predominant wind directions are from the west and ~~south-west~~south-east. The mean wind speed is $4-6$ m/s, depending on the season. The site has a median ambient turbulence intensity of $15-25\%$ with a mean shear exponent of 0.05 to 0.25 for day and night,

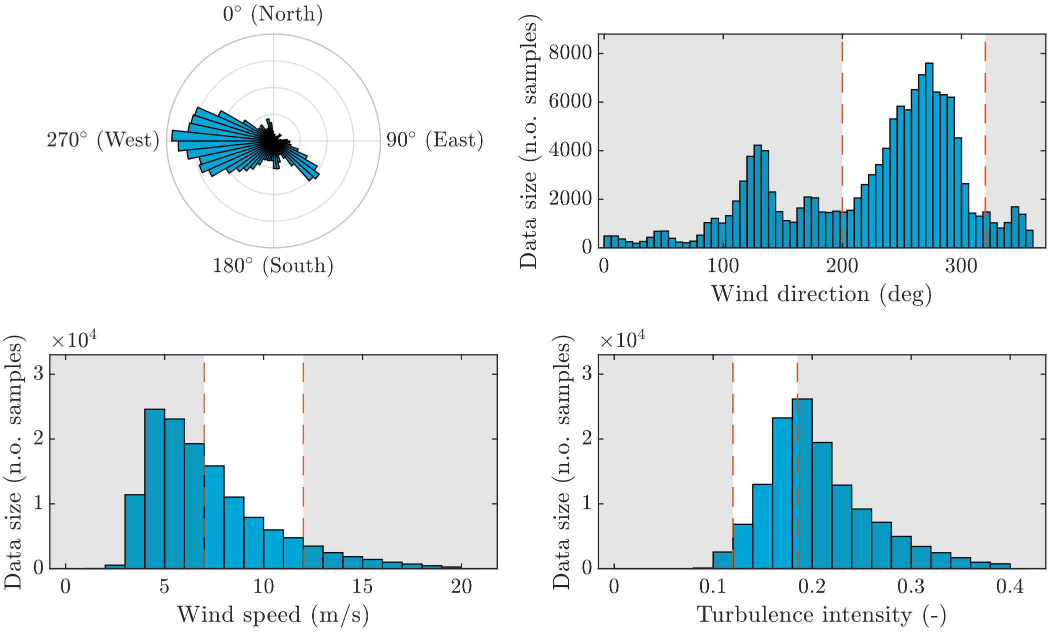

Figure 2. All measured data from 19 August 2019 until 3 February 2020, binned by wind direction, wind speed, and turbulence intensity. Wind comes predominantly from the west, which is within the scope of the wake steering experiment. Furthermore, wind speeds are relatively low and turbulence intensities are high. The gray area covers data that is discarded in analysis of the wake steering experiments.

respectively (Kern et al., 2017). Figure 2 shows the estimated wind direction, wind speed, and turbulence intensity of the data collected by the upstream turbines.

2.2 Experiment design

For the wake steering experiments, eight turbines are used: WTG 10, 11, 12, 24, 25, 26, 31, and E5, as shown in Figure 1. The situations of interest are when WTG 26 sheds a wake on WTG E5 and one or both turbines shed wakes on turbines WTG 10, 11 or 12. Additionally, for north-west wind directions, the situation where turbine WTG E5 sheds a wake on WTG 31 is of interest. For all situations, WTG 25 is used as a reference turbine, and WTG 24 and WTG 25 are used to estimate the inflow ambient conditions for WTG 26 and WTG E5. While this layout lends itself well to wake steering, this field campaign faces several challenges, namely:

- Part of the experiment is in late summer, with higher turbulence levels and lower wind speeds compared to winter. Moreover, onshore wind farms typically experience a higher turbulence intensity than offshore farms. Higher turbulence levels generally yield lower benefits for yaw-based wake steering (Appendix A).
- There are variations in the terrain, turbine hub heights, and turbine rotor diameters throughout the wind farm. Specifically, hilly terrain is likely to contribute to variations in the ambient wind speed and wind direction between different upstream

Table 2. Wind turbines of interest, scheduled according to the wind direction. To maximize the benefits of wake steering, only three turbines are considered at a time, depending on the ambient wind direction.

Wind direction	Turbines of interest
$< 235°$	WTG 26, WTG E5, and WTG 10
$235°$ – $253°$	WTG 26, WTG E5, and WTG 11
$253°$ – $276°$	WTG 26, WTG E5, and WTG 12
$\geq 276°$	WTG 26, WTG E5, and WTG 31

wind turbines. However, almost all surrogate models in the literature assume a uniform (homogeneous) ambient inflow, where each upstream turbine experiences the same wind speed, wind direction and turbulence intensity (Boersma et al., 2017). Variations in the ambient wind direction have a large influence on wakes, and thereby on the wake steering campaign. Additionally, as can be seen in Figure 1, various types of vegetation are present on the ground. The surface roughness varies with the type of vegetation, which in turn impacts the level of turbulence and thereby wake recovery. Due to its high level of complexity, surrogate models address these effects to a very limited degree and lack validation with higher-fidelity and experimental data. The surrogate model used in this work will be discussed in Section 3.2.

- The downstream turbines are closely spaced, implying that gains due to wake steering are hardly noticable when considering the complete downstream array. For example, if the wake of WTG E5 is redirected away from WTG 10, then the combined net gain of WTG 26, E5, 10, 11, 12 and 31 would be relatively small. In addition, wake steering should be very precise, as the wake must be redirected in between WTG 10, 11, 12, and 31 to lead to a net energy increase. For example, if the wake is deflected away from WTG 11, it may be moved on top of WTG 10 or 12, thereby effectively leading to zero net gain.
- The ambient conditions are to be estimated using existing turbine sensors, rather than external measurement equipment such as a lidar system. This is likely to be less accurate but more realistic for the future commercialization of wake steering.

These challenges, in addition to common challenges such as irregular turbine behavior and measurement uncertainty, have led to the decision to consider only one of the downstream turbines (WTGs 10, 11, 12, 31) at a time, scheduled according to the ambient wind direction, as listed in Table 2. Thus, the remaining downstream turbines are ignored in the analysis. This means that the wake can be steered away from the considered turbines and onto the ignored turbines. This is exemplified in Figure 3, depicting what wake interactions are considered per wind direction.

2.3 Data acquisition

The benefit of wake steering strongly depends on the ambient conditions. Therefore, it is important to accurately characterize these inflow conditions. In this field campaign, data is acquired from a number of sources. A met mast with a height of 63.5 m

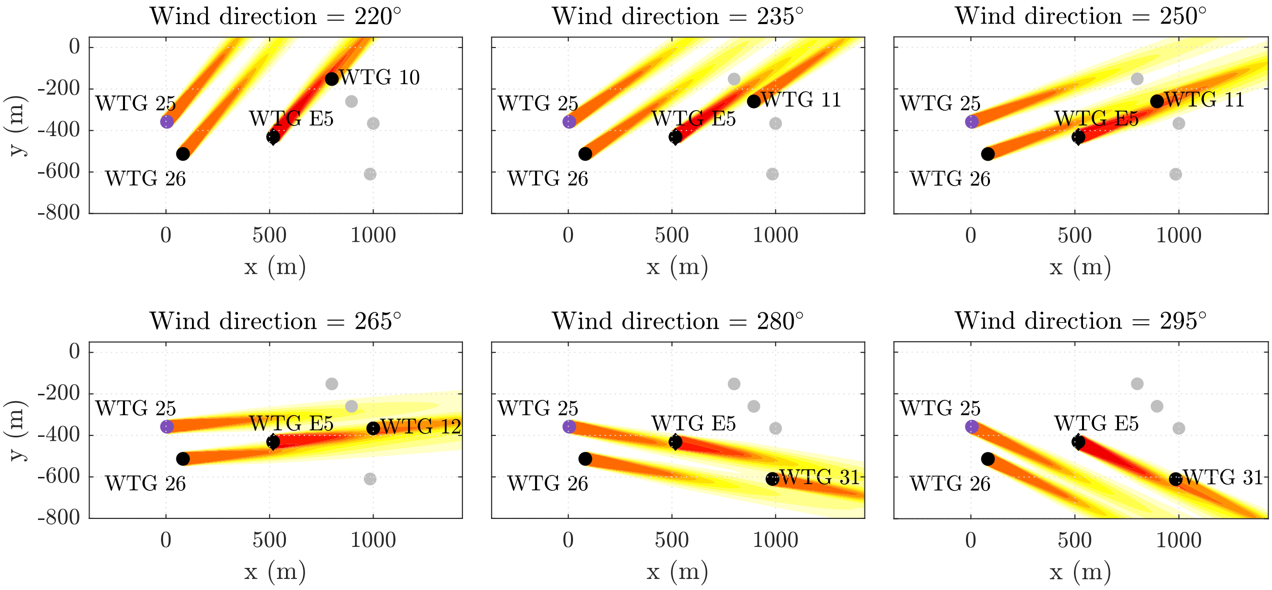

Figure 3. Predicted flow fields for various wind directions in baseline operation. To maximize the benefits of wake steering, only three turbines are considered at a time, depending on the ambient wind direction. The considered turbines are WTG 26, WTG E5, and one of the downstream turbines (operated without yaw misalignment). The schedule of which turbines are considered is listed in Table 2. Note that this figure is shown for explanatory purposes and therefore the simulation setup is not described in detail.

is installed 0.5 km north of WTG 25. The met mast provides information about the wind speed, wind direction, vertical shear, temperature, and humidity in the wind farm. However, ambient conditions vary significantly throughout the farm, not in the least due to this being an onshore wind farm. For this reason, a mobile, ground-based vertical lidar system of the type Leosphere WindCube ~~v2~~ V2 is installed to measure the inflow at WTG 26 for the first several months of the wake steering field campaign~~.~~ , as shown in Figure 1. The WindCube is installed at an estimated distance of 3 D in front of WTG 26, thereby lying outside of the turbine's induction zone. This lidar system measures the wind speed at a 0.1 m/s accuracy and the wind direction with a 2° accuracy at 12 programmable heights up to 200 m, with a sampling rate of 1 Hz. This lidar system cannot communicate with the control algorithm in real time and thus was only used in postprocessing to validate the ambient wind ~~speed~~ conditions estimated in front of WTG 26 using WTG 24 and WTG 25. The validation is shown in Figure 4, displaying a good fit ~~.~~ for the wind speed. Note that a bias is seen in the wind direction estimates.

In addition to the lidar system, WTG 26 and WTG E5 are instrumented with an additional, accurate nacelle anemometer. Also, WTG 12, 26, and E5 are each instrumented with an additional, accurate nacelle position sensor. Note that these sensors were only available during the first months of the field experiment, used for calibration and monitoring. The GE wind turbines provide standardized SCADA data such as the generator power, the wind speed measured by the anemometer, the wind direction measured by the wind vane, and the yaw orientation measured with the yaw sensor. An algorithm internal to the GE

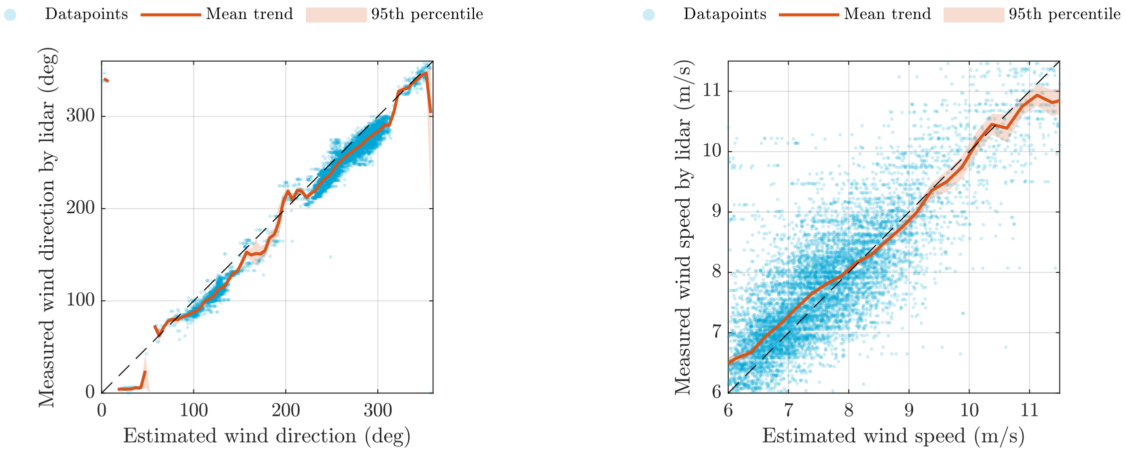

Figure 4. Comparison of wind direction and wind speed estimates from the lidar (10-minute averages) and from the turbine anemometers (1-minute averages). For the field campaign, the freestream wind direction, wind speed and turbulence intensity at WTG 26 ~~is~~ are estimated using upstream turbines WTG 25 and WTG 24. This approach is validated by comparing the estimates to measurements of the Leosphere WindCube v2 lidar, installed in front of WTG 26 throughout the first several months of the field campaign. The figure shows that the estimates largely match the measurements and the 95% uncertainty bounds, denoted by the shaded region, are narrow. Note that waked sectors (e.g., zone at $80-90°$) are not removed in these plots.

turbine provides estimates of the 1-minute-averaged wind speed, 1-minute-averaged wind direction, and 10-minute-averaged turbulence intensity.

3 Controller synthesis

As the research field in wind farm control is quickly evolving, an increasing amount of focus is put on closed-loop wind farm control solutions (Doekemeijer et al., 2019). However, implementing and testing such a closed-loop wind farm control algorithm is not feasible for the designated field campaign and instead an open-loop solution is opted for. Closed-loop solutions require additional communication infrastructure compared to open-loop solutions. Also, the actual turbine behavior becomes less predictable as the complexity of the controller increases significantly.

The controller consists of two components. Firstly, the ambient conditions ~~are estimated, as the optimal turbine yaw setpoints vary with the inflow conditions, of which the wind directionis the most important variable. How the ambient conditions~~ (being the wind direction, wind speed, turbulence intensity) are estimated. How these variables are estimated is described in Section 3.1. Secondly, the optimal turbine yaw setpoints for WTG 26 and WTG E5 are ~~assigned to the turbines from a~~ interpolated from a three-dimensional look-up table using the estimated atmospheric conditions. The synthesis of this three-dimensional look-up table is outlined in Section 3.2.

3.1 Estimation of the ambient conditions

As outlined in Section 2.3, the ground-based lidar cannot be used in real-time for the wind farm control solution. Moreover, the met mast is located too far away to give a reliable estimate of the ambient conditions. Therefore, turbine SCADA data is used to derive an averaged freestream wind speed, wind direction, and turbulence intensity for the inflow of WTG 26. This estimated wind direction is also assumed to be the wind direction at WTG ~~26 and WTG~~ E5. ~~For this purpose~~To obtain the ambient wind condition estimate in front of WTG 26, the individual estimates from turbines WTG 24 and WTG 25 are averaged, which operate in freestream flow for the wind direction range considered for the wake steering experiments. Note that a bias in the wind direction estimate was previously seen in Figure 4. Rather than using the lidar which is likely prone to bias and uncertainty, this is corrected for by comparing the estimated position (wind direction) of the largest power deficits at downstream turbines from FLORIS to the SCADA measurements.

3.2 Optimization of the turbine control setpoints

The turbine yaw angles are optimized using the FLOw Redirection and Induction in Steady-state (FLORIS) surrogate model, developed by CU Boulder, NREL and the Delft University of Technology (Gebraad et al., 2016; Doekemeijer and Storm, 2019). FLORIS is a surrogate wind farm model that combines several submodels from the literature, such as the single-wake model from Bastankhah and Porté-Agel (2016), the turbine-induced turbulence model by Crespo and Hernández (1996), and the wake superposition model by Katic et al. (1987). The surrogate model predicts the steady three-dimensional flow field and turbines' operating conditions of a wind farm under a predefined inflow at a low computational cost in the order of 10 ms to 1 s. Note that FLORIS has been fit to high-fidelity simulation data previously (Doekemeijer et al., 2019), and therefore inherently includes the time-averaged effects of dynamic flow behavior such as wake meandering. Figure 5 shows a flowchart of the inputs and outputs of FLORIS.

The yaw angles of WTG 26 and E5 were optimized in FLORIS for a range of wind directions (200° to 320° in steps of 2°), wind speeds (3 m/s to 13 m/s in steps of 1 m/s), and turbulence intensities (7.5%, 13.5%, and 18.0%). ~~This~~ Note that the optimization was done using the wind-direction-scheduled layout as described in Section 2.2. The optimization took approximately 10^2 CPU hours. The yaw angles are were then averaged and fixed between wind speeds of 5 m/s and 11 m/s in postprocessing to reduce yaw actuation at a negligible loss in the expected gains~~(Kanev, 2020). From wind speeds~~, verified by simulations in FLORIS and supported by findings from the literature (Kanev, 2020). Below wind speeds of 5 m/s and above 11 m/s, the angles are interpolated linearly to a yaw angle of $\gamma = 0^\circ$ at 3 m/s and 13 m/s, respectively. This is to avoid undesirable behavior near cut-in and rated operation.

Furthermore, to reduce sensitivity of the optimized yaw setpoints to the wind direction, a Gaussian smoothing kernel was applied to the table of optimized setpoints with a standard deviation of 1.5°. ~~The resulting~~ This is necessary because, when sweeping over the wind direction, there are situations in which it would be better to displace a wake to the other side of a downstream turbine. This results in a discontinuous change in the yaw misalignment (Rott et al., 2018). A better solution would be hysteresis (e.g., Kanev, 2020), but this is not possible in the current framework of the turbine manufacturer. The

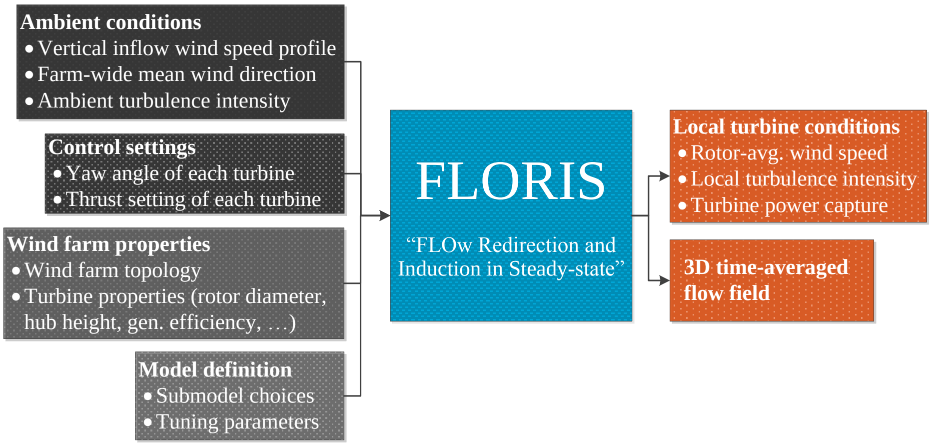

Figure 5. Flowchart of the FLORIS model. This model has four classes of inputs: the ambient conditions, a set of model parameters, the turbine control settings, and the wind farm properties (e.g., layout). FLORIS maps these inputs in a static fashion to a set of turbine outputs being the power capture and the three-dimensional flow field.

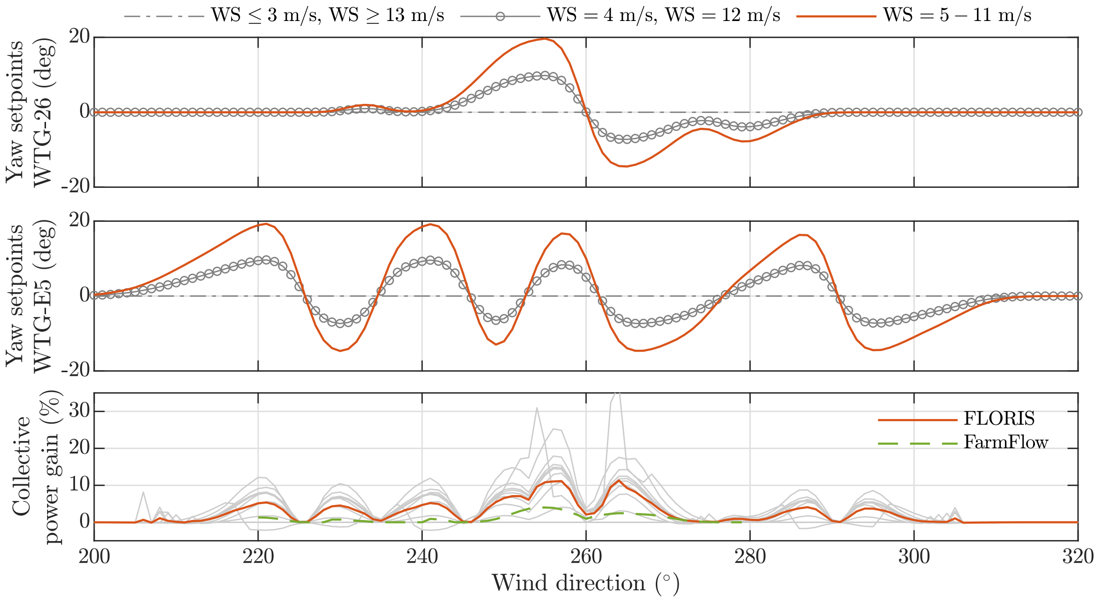

Figure 6. The turbine yaw setpoints for WTG 26 and WTG E5 for a freestream turbulence intensity of 7.5%. The yaw angles hold constant values for wind speeds of 5 m/s to 11 m/s. At lower respectively higher wind speeds, the setpoints are interpolated to a yaw angle of $\gamma = 0^\circ$ at 3 m/s and 13 m/s. The collective power gain of WTG 26, WTG E5, and the downstream turbine (WTG 10, 11, 12, or 31) averaged over all wind speeds is shown as the solid orange line (FLORIS) and the green dashed line (FarmFlow) in the bottom plot. The gray lines therein represent the predicted gains for one wind speed by FLORIS.

smoothed look-up table for a turbulence intensity of 7.5% is shown in Figure 6. This figure also shows the predicted gains in power capture for the specified subset of turbines according to FLORIS in idealized conditions. It is seen that gains of 5% to 15% are expected near the wind directions 255° and 265° at a turbulence intensity of 7.5%. Furthermore, smaller gains in the order of 5% can be expected for wind directions 220°, 230°, ~~and~~ 240°, 285° and 295° at a turbulence intensity of 7.5%. The look-up tables for higher turbulence intensities are included in Appendix A and indicate a strong decrease in expected gains for higher turbulence intensities.

FLORIS makes compromising assumptions about the wind farm terrain and wake behavior. Thus, these predictions hold a high uncertainty. As a first step to check its robustness, the optimized yaw angles from FLORIS are simulated in FarmFlow, the in-house wind farm model of TNO (Kanev et al., 2018). FarmFlow is of the same fidelity of FLORIS, but has a different set of underlying equations and therefore provides different predictions. While FarmFlow predicts lower gains, which empirically is a common trend for FarmFlow compared to FLORIS, it also predicts little to no losses compared to baseline operation for most table entries, thereby solidifying confidence in the synthesized table of setpoints. Furthermore, after implementation in the real wind farm, the presented control module is toggled on/off every 35 minutes~~to allow a comparison of wake steering with baseline operation~~. This number is chosen such that toggling is not equal every day, thereby reducing dependency on diurnal variations in the atmosphere. Additionally, a lower toggling time would lead to less usable data due to postprocessing (step 5 of Section 4), and a higher toggling time would reduce number of measurements obtained under comparable atmospheric conditions. The optimal toggling time for such experiments remains uncertain in the literature.

4 Data processing

Sections 2 and 3 outlined the steps taken prior to the experiment. This section now addresses how the data is processed after the experiment. One-minute-averages of SCADA data are collected from August 19th, 2019 onward. Analysis was performed on data up until February 3rd, 2020. The data is postprocessed to eliminate any faulty or irrelevant entries as follows:

1. All data with SCADA-based wind direction estimates outside of the region of interest (200° to 320°) is discarded. Note that the plots in Section 5 will instead be cut off at a wind direction of 310° due to lack of data and yaw activity for higher wind directions.
2. All data with SCADA-based ambient wind speed estimates lower than 7 m/s and higher than 12 m/s is discarded, because of high noise levels and/or the optimized yaw angle setpoints being very small in these regions (Figure 6).
3. All data with SCADA-based turbulence intensity estimates lower than 12% and higher than 18.0% are discarded. The upper bound is because a high turbulence intensity reduces wake effects and thereby the expected gains. Moreover, a narrow turbulence intensity range is desired with as many datapoints as possible for a fair and statistically sound analysis, explaining the lower bound. The turbulence intensity range is on the higher side due to the nature of the experiment. The specified bounds allow for a sufficient number of measurements such that a sound statistical analysis can be performed.
4. All data where the turbines of interest produce less than 200 kW of power are discarded, to reduce the relative variance in power and eliminate any situations in which turbines exhibit cut-in and cut-out behaviour.

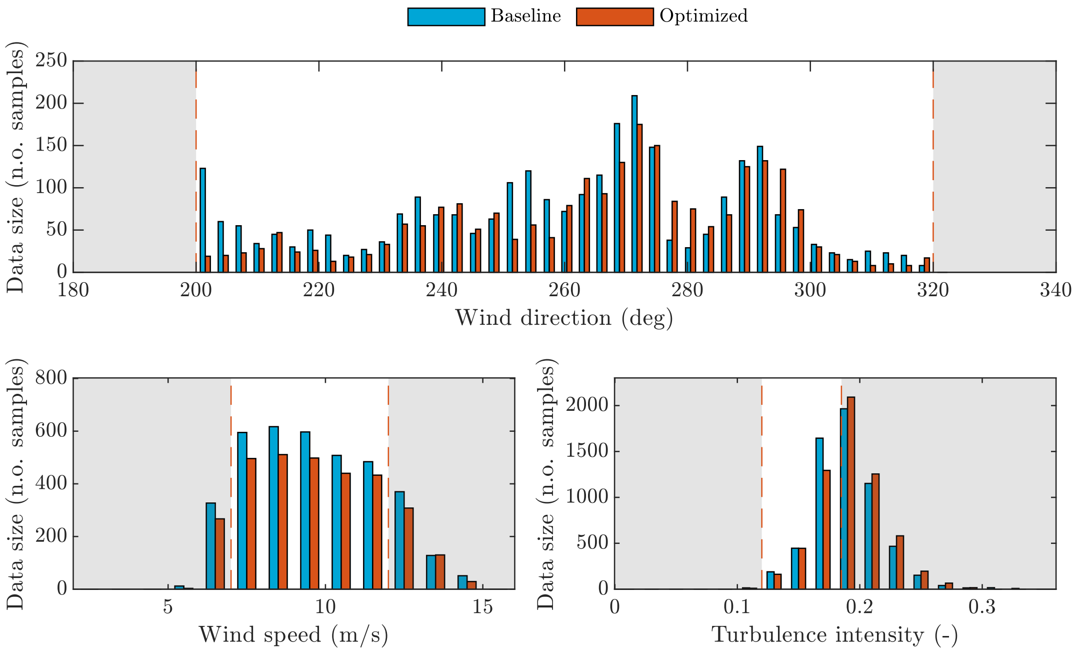

Figure 7. Filtered measurement data from 19 August 2019 until 3 February 2020, binned as a function of wind direction, wind speed, and turbulence intensity.

5. Data within 5 minutes after a toggle change (baseline vs. optimized operation) is discarded. Namely, due to the functioning of the turbine yaw controller, turbines do not instantly follow their yaw setpoint to limit usage of the yaw motor.
6. Power measurements are time filtered using a (non-causal) moving average with a centered time horizon of 5 minutes.
7. The datasets are separated according to their operational mode: baseline and optimized. The datasets are then balanced such that for each wind direction and wind speed (in steps of 1 m/s), the number of measurements for baseline operation and optimized operation are equal. This reduces bias in the analysis for unbalanced bins.

Note that a narrower wind speed and turbulence intensity range than used in this manuscript should, in theory, better quantify the change in power production due to wake steering. However, with the sparsity in the data set, further narrowing these ranges leads to a significant increase in statistical uncertainty. The current turbulence intensity and wind speed ranges are obtained through an iterative process in pursuit of narrow uncertainty bounds and clear trends. With the filtered data, the energy ratio method from Fleming et al. (2019) is then used to calculate the gains due to wake steering. Important to note is that WTG 10 and WTG 11 are curtailed to a maximum of 500 kW for long periods of time during the measurement campaign. To prevent the elimination of this dataset, a part of the analysis is performed using the freestream-equivalent wind speed estimates of the local wind turbine controllers, rather than the generated power signals. Note that the analysis for WTG 10 and WTG 11 is exclusively done with measurements during curtailed operation, while the analysis for the other turbines relies on measurements during normal operation – curtailed and non-curtailed measurements are not mixed within bins.

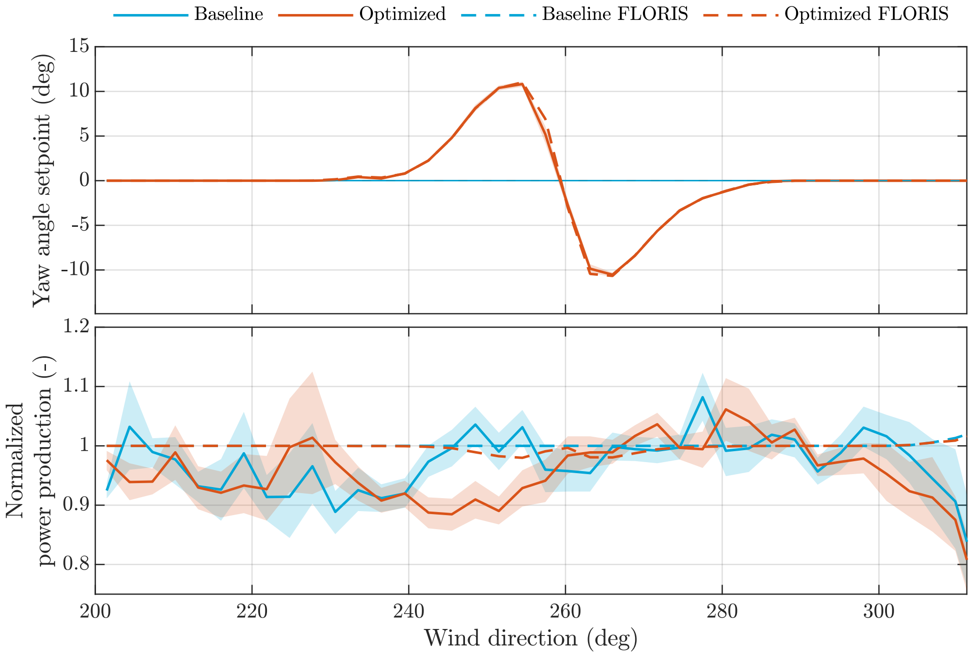

Figure 8. Yaw misalignments and corresponding power production for WTG 26, normalized with respect to WTG 25. The shaded areas show the 95% confidence bounds. The dashed lines represent the predictions for the measured inflow conditions by FLORIS. The number of samples in each bin is shown in Figure 7.

Figure 7 shows the histograms of the postprocessed dataset, divided into *baseline* and *optimized* data. The relatively high turbulence intensity shown in this figure corresponds to gains in power production in the order of 2% to 6% according to FLORIS.

5 Results & discussion

This section analyzes the measurement data and quantifies the change in performance due to wake steering compared to baseline operation. Note that all local wind speed estimates and power production signals are normalized with respect to the measurements from WTG 25, to reduce the sensitivity of variables to the estimated ambient wind speed. Furthermore, 95% confidence intervals are calculated through bootstrapping (Efron and Tibshirani, 1993) for the results presented in this section. Additionally, the results shown here are with respect to the estimated mean atmospheric conditions in front of WTG 26, derived from WTG 24 and WTG 25 as described in Section 3.

Figure 8 portrays the yaw misalignment setpoints and the power production of WTG 26. The dashed lines represent the predictions from FLORIS, and the solid lines represent the measurement. Since WTG 26 is not misaligned for wind directions lower than 230 degrees and higher than 290 degrees, the normalized power production should equal to 1.0, as reflected in the FLORIS predictions. Around wind directions of 255° and 265°, yaw misaligments are assigned to the turbine, expected to lead

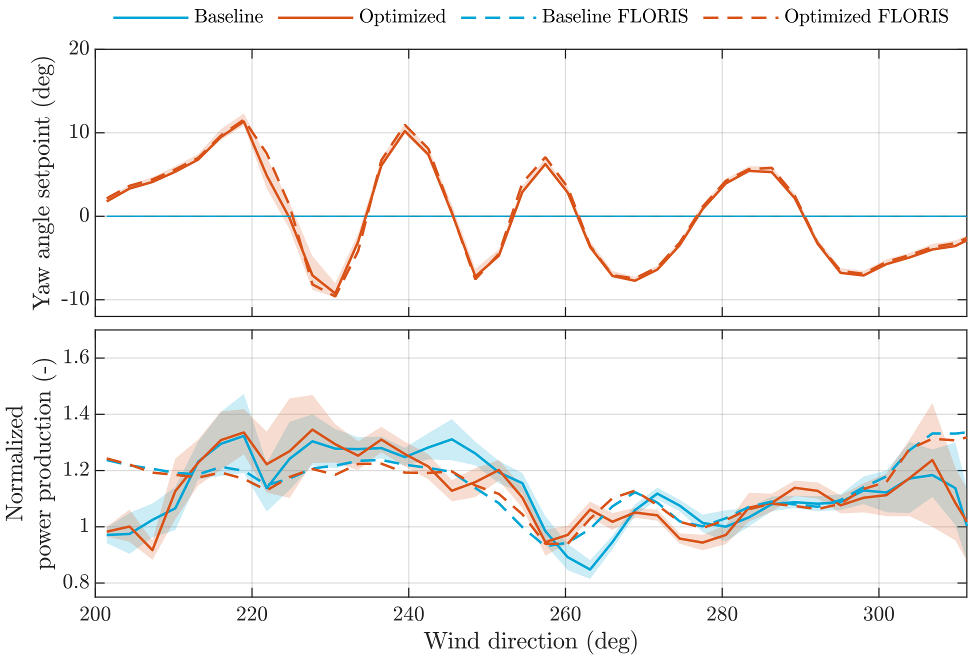

Figure 9. Yaw misalignments and power production for WTG E5, normalized with respect to WTG 25. The shaded areas show the 95% confidence bounds. The dashed lines represent the predictions for the measured inflow conditions by FLORIS. The number of samples in each bin is shown in Figure 7.

to a loss in its power production. Looking at the measurements, the yaw setpoints are successfully assigned for all wind directions. However, the predicted loss in power production due to yaw misalignment is not reflected in the measurements. Rather, it appears that positive yaw misalignment angles lead to a significant decrease of about 10% in the power production (wind directions of 240 − 250°), while negative yaw misalignment angles even lead to a slight increase in the power production compared to baseline operation (wind directions of 255 − 295°). This indicates asymmetry and a high sensitivity in the power curve for yaw misalignment, which are both not accounted for in FLORIS. These observations were confirmed with measurement data from a different GE 1.5s turbine, briefly addressed in Appendix B. ~~Moreover,~~ It may be that this asymmetry is partially due to bias in the wind vane sensor and consequently in the wind direction estimate. Literature suggests that a bias in these measurements is common in operational wind turbines (e.g., Fleming et al., 2014; Scholbrock et al., 2015; Kragh and Hansen, 2015), and the claim is further supported by the relatively large uncertainty seen in Figure 8. Furthermore, wind shear and veer are also known to skew the yaw-power curve (Howland et al., 2020), though both were quite benign in this experiment. More research is necessary to explain this yaw-power relationship for WTG 26. During the experiment, the wind direction bias was addressed by comparing what FLORIS predicts to be the wind direction where the largest wake losses are at downstream turbines to the actually measured power losses and wind directions. Though, it is not unreasonable to assume that this was insufficient. Moreover, Figure 8 shows that unknown factors lead to a systematically lower power production in the region 200 − 225°

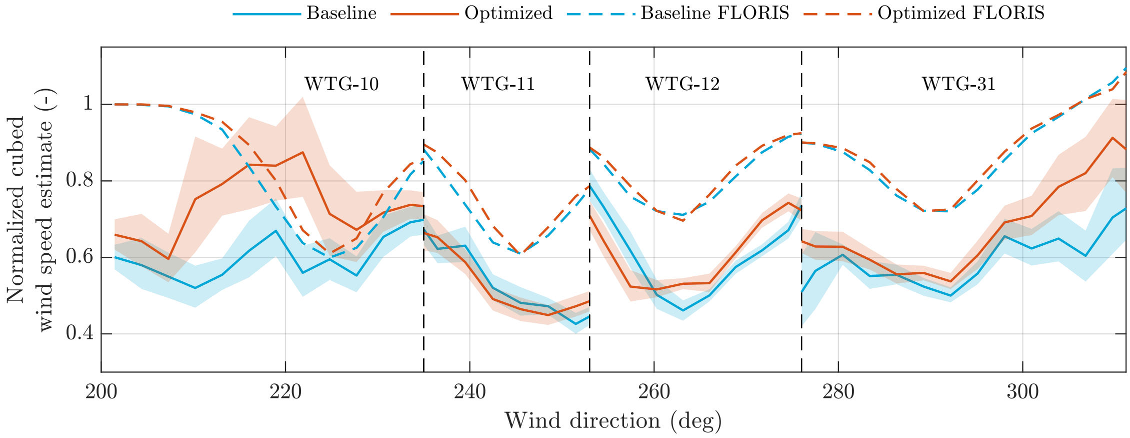

Figure 10. The cubed wind speed estimates of the downstream WTG of interest, serving as a surrogate for the power production under turbine derating. The results are normalized with respect to WTG 25. The shaded areas show the 95% confidence bounds. FLORIS ~~captures~~ underpredicts the ~~trends well, though~~ wake losses~~are underestimated~~. Moreover, the optimized dataset appears to outperform the baseline dataset, showing a benefit due to wake steering. The number of samples in each bin is shown in Figure 7.

compared to WTG 25. Also, even though both datasets operate at zero yaw misalignment in the region $295-320°$, the *optimized* dataset shows a consistent loss compared to *baseline* operation for unidentified reasons. Hypothesized reasons for these discrepancies include terrain effects and differences in inflow conditions and turbine behavior between WTG 26 and WTG 25 to which the signals are normalized.

Figure 9 depicts the yaw misalignment setpoints and the power production of WTG E5. This turbine contains considerably more yaw variation between wind directions due to the close spacing and the scheduling of the considered downstream turbine (Table 2 and Figure 6). This figure shows that the yaw setpoints are applied successfully with little error. Further, note that the normalized power production for unwaked conditions is about ~~1.3~~ 1.2 instead of 1.0 due to the larger rotor size and the higher tower of WTG E5. ~~Wakes of WTG~~ Note that the high relative power production at 310 degrees is due to WTG 25 operating in the wake of WTG 24 and thereby producing less power, to which the power production of WTG E5 is normalized to. Moreover, wakes of WTG 25 and WTG 26 cause losses in power production in both *baseline* and *optimized* operation for various wind directions in Figure 9. These effects are both reflected in the measurements and seen in the FLORIS predictions. Notably, clear dips in the power production for both *baseline* and *optimized* operation are seen at 260° and 278° caused by wake losses. FLORIS predicts these losses, but lacks the accuracy to represent the finer trends in the measurements. Moreover, changes in the power production due to a yaw misalignment on WTG E5 appear inconsistent (e.g., large loss at 245°, no losses for 210° to 240°) compared to what was seen for WTG 26. The authors speculate that this may be either due to WTG E5 being of a different turbine type than WTG 26, or due to different bias corrections in the wind vanes.

Figure 10 displays the cubed wind speed estimate of the downstream turbine of interest. The reason that this variable is displayed instead of the power production is due to the fact that WTG 10 and WTG 11 are curtailed for long periods of time,

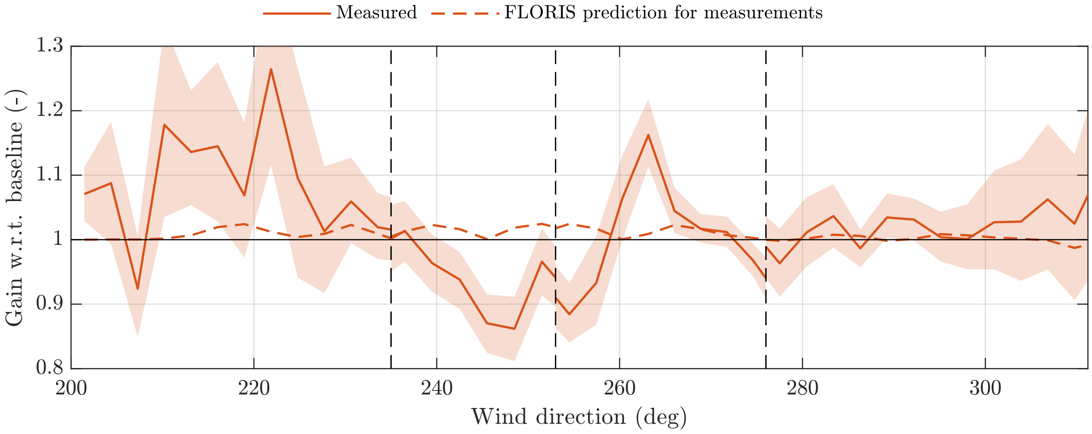

Figure 11. The estimated net gain of the three turbines for wake steering compared to baseline operation. The shaded area shows the 95% confidence bounds. The number of samples in each bin is shown in Figure 7.

rendering the power measurements unusable. FLORIS predictions show a clear trend in power production losses due to wake interactions of upstream turbines, notably at 225°, 245°, 265° and 290°. Since none of the downstream turbines are yawed, FLORIS predicts that optimized operation should never lead to any losses compared to baseline operation. When looking at the measurements, ~~these predictions are largely reflected~~this prediction is incorrect for WTG 11 and WTG 12. However, FLORIS is reasonably accurate in predicting at what wind directions the largest dips in power production occur for downwind turbines. However, FLORIS overestimates the wake recovery, and the power losses due to wake interactions are therefore larger than predicted. This ~~is~~ suggests that FLORIS predicts wake positions reasonably well, though lacks the accuracy to predict the subtle effects of a yaw misalignment. These model discrepancies are hypothesized to be not in the least due to the lack of an accurate terrain model. Because of the underestimated wake effects in FLORIS, wake steering ~~should~~ may have a higher potential than predicted, and the optimal yaw angles depicted in Section 3 may be underestimated. Moreover, the figure shows a very large increase in power production for the region $205-235°$ between optimized and baseline operation. This is due to WTG E5 steering away its wake from WTG 10. These two turbines are positioned closest together in the wind farm, and wake losses are therefore predicted to be the highest (Figure 1). Furthermore, gains in power production are seen in the region $260-320°$. This somewhat agrees with where FLORIS predicts gains to be. However, the measurements also show losses near 255°. This is possibly due to the strong gradients in the yaw misalignment setpoints and thereby the sensitivity to noisy inflow conditions. Also, FLORIS predicts zero wake losses for a wind direction of 200° for both the baseline and optimized dataset, yet the measurements show a much lower wind speed. This is hypothesized to be due to topology effects and turbine interaction that was underestimated or not accounted for in FLORIS. The measurement uncertainty bounds are often larger than the potential gains predicted by FLORIS, which is largely due to poor the modeling performance of FLORIS than it is due to a high measurement uncertainty.

Finally, the change in performance for the combined three turbines is displayed in Figure 11. FLORIS predicts a relatively small but consistent gain across different wind directions of about 3%. This is largely due to high turbulence levels and the underestimated wake losses in FLORIS (Figure 10). This in turn leads to the underestimation of the benefits of wake steering. When looking at the measurements, a very large gain of up to 26% is seen at 222°. Interesting to note is that this 26% gain is the situation where WTG E5 steers its wake away from WTG 10 (Figure 3), and WTG 26 has no influence on this interaction. If we only consider turbines WTG E5 and WTG 10, the combined gain in power production of turbines WTG E5 and WTG 10 is 35%. Though, it must be noted that the uncertainty bands are large for this bin. Generally, notable gains in power production are measured in the region $260-273°$ with a gain of 16% at 263°, concerned with ~~three-turbine interaction~~three-turbine-interaction. Interesting to note is that all three turbines experience an increase in power production for this wind direction, be it due to a yaw misalignment or due to a steered wake. Among these three turbines, the largest gain comes from WTG E5 with a 29% increase in power by itself. Furthermore, Figure 11 also shows notable losses, especially in the region near 250°, due to large losses at WTG 26 originating from yaw misalignment and no gains downstream. Losses are also seen near the transition regions (black dashed vertical lines), possibly due to strong gradients in the yaw angles at these wind directions.

In addition to the mismatch between FLORIS and the actual yaw-power curve of WTG 26 and WTG E5, the lack of terrain effects in FLORIS are expected to have a significant impact on the results. This may be one of the key reasons for the overestimation of wake recovery in the FLORIS model, which in turn leads to an underestimation of the benefits of wake steering. Moreover, unmodeled effects such as secondary steering (Martínez-Tossas et al., 2018) may be a source of error. These unmodeled effects can have a positive effect on the success of wake steering. This leads to an underestimation of the potential benefits of wake steering and consequently to suboptimal yaw misalignment setpoints. Historical operational data may also be used to reduce the model-plant mismatch (Schreiber et al., 2019).

6 Conclusions and recommendations

This article presented a field experiment for wake steering at a commercial onshore wind farm in Italy. ~~Three-turbine interaction~~ Three-turbine-interaction was considered, with the first two turbines operating under yaw misalignments to maximize the collective power production. The yaw setpoints were calculated according to an open-loop steady-state and model-based wind farm control solution. The field experiment shows significant gains, especially for two-turbine interaction, with an increase in combined power production of up to 35% for one particular two-turbine situation. Moreover, gains in power production for the three-turbine array up to 16% were measured for particular wind directions. However, the measurements also show notable losses for a region of wind directions, largely due to losses at the yaw-misaligned upstream turbines and due to insufficient or incorrect wake steering downstream.

Several important observations were made from the measurement data. Measurements shows that upstream turbines may benefit from nonzero yaw misalignment compared to the wind vane sensor, already leading to an effective increase in power production at these ~~turbine~~ turbines without considering the phenomenon of wake steering downstream. Such effects have a large influence on the results presented in this article and are likely due to poor calibration of the wind vane sensors, rather than a physical property of the turbine. Moreover, the potential of wake steering was confirmed for a large range of conditions. ~~These two factors effectively suggest that the power production in wind farms could be increased for “free”, thus allowing~~ The flatness of the turbine power curve effectively allows wake steering without losing ~~or even increasing the energy yield~~ much energy upstream. Also, while the surrogate model leveraged in this work is able to predict the dominant trends of wake interaction ~~,~~ (i.e., FLORIS accurately predicts at what wind directions the wake losses are highest), large discrepancies are seen between its predictions and the field measurements. Notably, FLORIS assumes a symmetrical yaw-power curve of WTG 26 and WTG E5, assuming peak power production at zero yaw misalignment. In addition, FLORIS lacks important terrain effects and appears to overestimate wake recovery. Consequently, FLORIS underestimates the benefits of wake steering and the assigned yaw angles in this experiment are suboptimal.

At large, ~~important lessons learned from this experiment are~~the following recommendations can be made for future wind farm validation trials:

- ~~An accurate characterization of the physical wind turbines in the surrogate model is essential.~~ This article demonstrated the ~~strong need for an accurate~~ asymmetry and flatness one may find in the yaw-power curve of ~~each turbine to maximize the benefits of wake steering~~ commercial wind turbines. This curve is particularly important to characterize accurately for wake steering. Therefore, future trials should perform experiments to allow such a characterization. At a higher level, this experiment showed the significant discrepancies between FLORIS and the measurements, especially at downstream turbines. One may want to perform simple and shorter wake steering tests to generate data for model tuning, such as keeping an upstream turbine and fixed yaw misalignment angles of $-20°$ to $+20°$ in steps of $5°$ for periods at a time under various wind shear and veer conditions (Howland et al., 2020). However, this may go at the cost of the plant's energy production and therefore also depends on the willingness of the wind farm operator. Doing such a model calibration may also indicate weaknesses in the model, such as the absence of ground effects, inaccuracies in the turbulence model, and variations in the surface level.

- A difficult trade-off must be made between the value of additional accurate measurements and the higher costs involved. Ideally, one would also measure the complete wake profiles downstream at a at least a 1 minute sampling rate, measure the fluid density and atmospheric temperature at various heights from the ground, and ~~operation under yaw misalignment .~~ identify the incoming turbulence levels. Furthermore, both for model tuning and the actual wake steering trials, an accurate characterization of the inflow conditions is essential, both in front of turbine WTG 26 but also in front of WTG E5. This could be achieved using lidar systems. Though, the authors cannot make a definitive conclusion on what equipment would provide most value and where it should be placed in a hypothetical future experiment. Rather, the scope of this article lies with the analysis of the experiment outcomes, rather than experiment design.

- ~~To clearly distinguish the benefits of wake steering from baseline operation, a reliable baseline controller must be established and implemented. This may require more accurate wind direction and yaw sensors that ensure that upstream turbines accurately track~~ Subsequently, an accurate baseline yaw controller that tracks the wind direction ~~and maximize their power production.~~ is necessary to present a reliable baseline case to which the wake steering controller can be compared. Measured gains from wake steering should originate from gains at downstream rather than upstream turbines.

- Field campaigns should run for at least one year to minimize the impact of measurement uncertainty. Moreover, experiments ran throughout the year will provide a realistic idea of the efficacy of the tested concept and its impact on the annual energy production.
- In this experiment, which turbine was considered to be the “downstream turbine of interest” was decided according to the wind direction to maximize the potential benefits of wake steering. Unfortunately, this is expected to be the reason for poor performance near the transition regions. Such scheduling requires more research before implementation, and rather should be avoided whenever possible.
- ~~The surrogate model is hypothesized to lack, i.a ., essential temporal dynamics and complex terrain effects, leading to suboptimal yaw setpoints and controller performance. Moreover, the turbulence model in FLORIS should be improved and ideally calibrated to field data before usage.~~
- ~~Field campaigns should run for at least one year to minimize the impact of measurement uncertainty. Moreover, experiments ran throughout the year will provide a realistic idea of the efficacy of the tested concept and its impact on the annual energy production.~~ Additionally, rather than smoothing the yaw angles with a Gaussian kernel to reduce yaw travel, it is valuable to look into solutions such as hysteresis (e.g., Kanev, 2020).

Finally, loads are neglected in this work, but play a vital role in adoption of the concept~~(e.g., Damiani et al., 2018)~~. Otherwise noteworthy research topics to explore include dynamic models and the inclusion of heterogeneous inflow effects. In conclusion, this article supports the notion that further research is necessary, notably on the topic of wind farm modeling, before wake steering will lead to consistent energy gains in commercial wind farms.

Code availability. FLORIS is developed by the Delft University of Technology and the National Renewable Energy Laboratory. A research-oriented MATLAB implementation is developed by Delft University of Technology, available at its Github repository (Doekemeijer and Storm, 2019). Note that a numerically efficient Python implementation of FLORIS is developed by the National Renewable Energy Laboratory, available at its Github repository (NREL, 2019). The work presented in this article uses the MATLAB implementation.

Appendix A: Additional look-up table figures

The turbine yaw setpoints were optimized for a large range of inflow conditions as described in Section 3.2. Figure 6 previously showed the optimal yaw setpoints for a low turbulence intensity of 7.5%. This appendix shows the optimal yaw setpoints for turbulence intensities of 13.5% and 18.0%.

The optimal turbine yaw setpoints for a turbulence intensity of 13.5% are shown in Figure A1. Compared to the situation with a turbulence intensity of 7.5%, the forecasted performance gains notably reduce. A higher ambient turbulence leads to

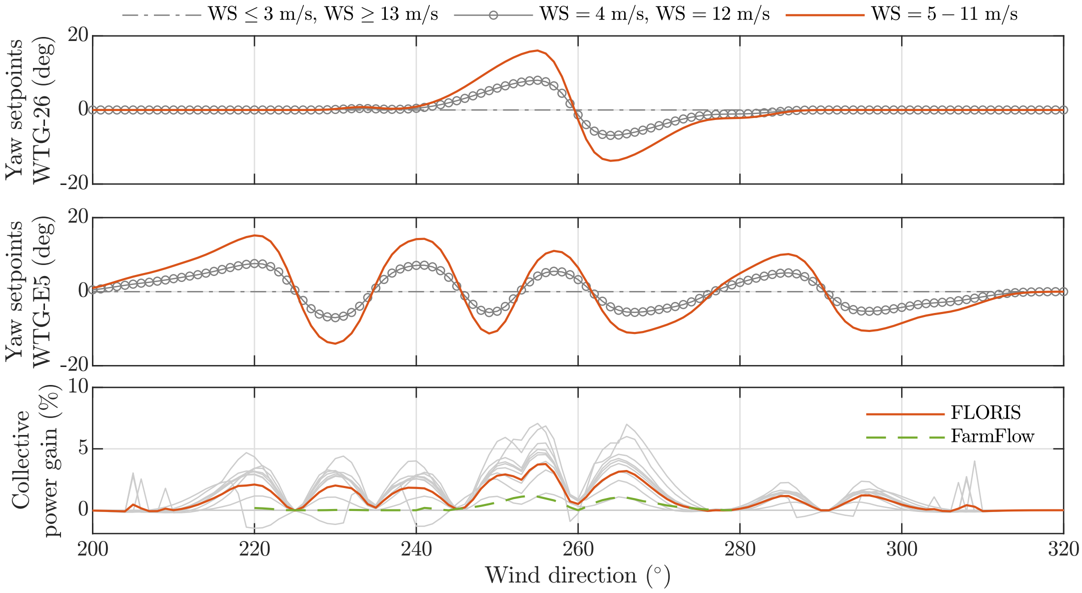

Figure A1. The optimal turbine yaw angle setpoints for WTG 26 and E5 for a freestream turbulence intensity of 13.5%. The averaged collective power gain of WTG 26, WTG E5 and the downstream machine (WTG 10, 11, 12, or 31) is shown as the solid orange line (FLORIS) and the green dashed line (FarmFlow) in the bottom plot. The gray lines therein represent the predicted gains for one wind speed by FLORIS.

more wake recovery, and thus the benefits of wake steering become less apparent. The optimal turbine yaw setpoints for a turbulence intensity of 18.0% are shown in Figure A2. Compared to the situations with turbulence intensities of 7.5% and 13.5%, the gains are very small. In practice, these gains are expected to drown in statistical uncertainty.

Appendix B: Yaw-power relationship for a GE 1.5s turbine

The experimental results from Section 5 indicate that negative yaw misalignment in WTG 26 leads to very small losses and sometimes even to a power gain compared to aligned operation. This behavior is verified by studying experimental data from a different GE 1.5s turbine inside the Sedini wind farm that is not included in the wake steering experiments: WTG 30. SCADA data of this turbine is used to plot the normalized power production of the turbine against its yaw misalignment angle, shown in Figure B1. This figure shows that there is practically no decrease in power production when misaligning the turbine in the negative direction by less than 10°. ~~This is in~~ It is likely that this asymmetry is partially due to bias on the wind direction measurement, which has been seen more often in operational wind turbines as reported in the literature (e.g., Fleming et al., 2014; Scholbrock et al., 2015; Kragh and Hansen, 2015). Furthermore, wind shear and veer are also known to skew the yaw-power curve Howland et al. (2020), though both were quite benign in this experiment. More research is necessary to explain this yaw-power relationship for WTG 26. During the experiment, the wind direction bias was

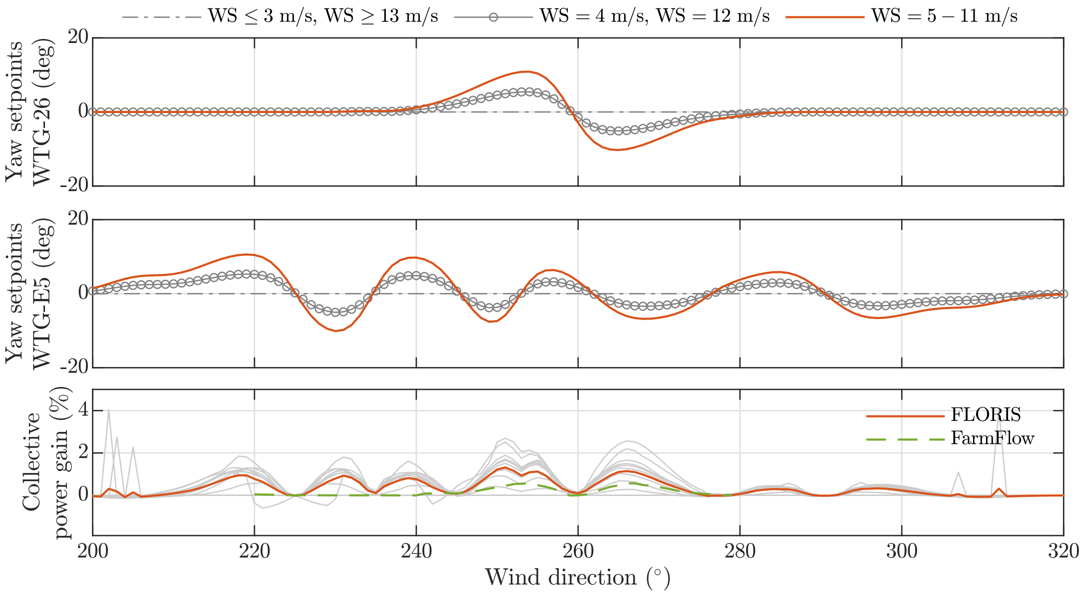

Figure A2. The optimal turbine yaw angle setpoints for WTG 26 and E5 for a freestream turbulence intensity of 18.0%. The averaged collective power gain of WTG 26, WTG E5 and the downstream machine (WTG 10, 11, 12, or 31) is shown as the solid orange line (FLORIS) and the green dashed line (FarmFlow) in the bottom plot. The gray lines therein represent the predicted gains for one wind speed by FLORIS.

addressed by comparing what FLORIS predicts to be the wind direction where the largest wake losses are at downstream turbines to the actually measured power losses and wind directions. Though, it is not unreasonable to assume that this was insufficient. The observations made for this wind turbine are in agreement with the behavior seen in WTG 26 and explains the large gains around the 260 – 280° region in the field experiments shown in Figure 11~~: wake steering effectively comes “for free” here~~.

Competing interests. The authors declare that they have had no competing interests in executing and publishing this work.

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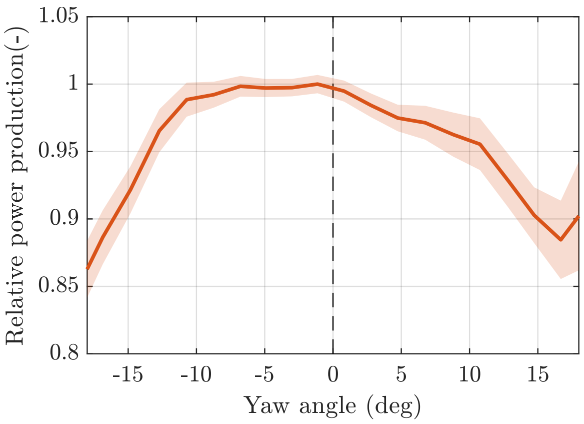

Figure B1. Relationship between the normalized power production and the yaw misalignment angle for an arbitrary GE 1.5s wind turbine in the Sedini wind farm. The data was collected for the range of 6 m/s to 12 m/s wind speeds. The asymmetry is clearly seen. Moreover, negative yaw misalignment shows a much smaller loss or even a very slight gain in power production compared to positive yaw misalignment.

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