Review comments

June 29, 2026

1 Review 1

In response to the first round of reviews, the authors decided to break their article into two parts, which I agree with. I am a bit unclear on what the plan for publication is though—will these be separate WES papers with separate DOIs? The current format (two articles back to back) is a bit unclear.

In writing this review, I opted to review only Part II, as that is the article that is within my area of expertise. I am making no comment on Part I, and will admit to have only glanced over it and not read it carefully. I did, however, read the response to my first review and feel that the authors have suitably addressed my comments (including materials added to Part I).

I believe Part II works well now as a standalone study comparing various engineering wake models and wake model setups (varying vs constant TI, homogeneous vs heterogeneous inflows) to WRF. I appreciate the authors efforts in response to my previous comment to highlight that WRF itself is not necessarily the "truth". However, there are a few points that need to be clarified in the Part II article to ensure that it can be read without relying on Part I.

We would like to thank the reviewer for the suggestions made, which significantly improved the manuscript. All reviewer comments will be addressed, responses to the reviewers' comments are provided in bold, and changes made to the manuscript are highlighted in *blue bold italics*.

Major Comments:

- Most importantly, I missed the description of the concept of an "envelope" for the engineering wake models. I searched both in Part I and Part II for how the envelope is defined and evaluated, but I did not see this. This seems to be some sort of uncertainty evaluation. Without a description of what the authors mean by the envelope and how it is evaluated, it is difficult to interpret many of the figures in the article. I believe the first mention of the "envelope" is currently in line 288 of Part II ("WRF power estimates fall within the envelope of the engineering wake models..."), but this is simply a reference to a concept as though it has already been introduced. Please add a detailed description of the uncertainty envelope and how it is computed.

  We thank the reviewer for pointing this out. We have added the following paragraph.
  To facilitate comparison between WRF and the engineering wake models, envelope ranges are shown throughout this study. In each case, the solid line represents the mean estimate of the engineering wake models and/or model configurations considered in the analysis, while the envelope is defined by the corresponding minimum and maximum estimates. The envelope therefore represents the spread associated with these models and configurations. For figures showing differences relative to WRF, the differences are first computed for each engineering wake model or model configuration individually relative to WRF, after which the mean and envelope are determined from these differences.

- My second major comment is on the distinction between internal and external wakes in WRF/ engineering model comparisons. The authors call out in Section 2.3 (Lines 221–228) that "internal wakes" in WRF include the effects of external (non PE) wind farms. Then, throughout the article, internal wake losses from WRF are compared to those from engineering models, and that WRF predicts larger internal wake losses than engineering models (e.g. Section 3.3.1, lines 339–343). This is one of the major takeaways of the results. However, this seems a pretty flawed comparison as, by the authors own acknowledgement, we are comparing two unlike quantities ("internal wakes" means something different in the WRF case as in the engineering models case; and since "internal wakes" include some presence of external wakes in the WRF case, we might expect losses to be higher in the WRF case). I don't know exactly how this should be resolved, but I think more needs to be done to try to quantify how much the external farms add to the evaluation of "internal wakes" in WRF so that readers can understand whether the differences between WRF and engineering models could simply be due to differences in how the losses are defined.

We thank the reviewer for this important observation. We agree that the definition of internal wake losses is not strictly identical between the WRF simulations and the engineering wake models. To assess whether this difference could explain the larger internal wake losses predicted by WRF, we performed an additional sensitivity analysis in which all North Sea wind farms represented in the WRF simulations were also included in FLORIS. The analysis indicates that the contribution of the omitted surrounding wind farms is limited and cannot explain the differences observed between WRF and the engineering wake models. To make this assessment available to the reader, we have rephrased Section 2.3, and included the full sensitivity analysis in Appendix A.

- **Appendix A added**

  To assess whether the different treatment of surrounding wind farms in WRF and the engineering wake models affects the comparison of internal wake losses, an additional set of FLORIS simulations was performed in which all North Sea wind farms included in the WRF simulations were modeled. The results were compared against the reduced baseline configuration used throughout this paper, in which only the BE–NL and PE clusters are included. The reduced configuration contains 572 turbines, while the full North Sea configuration contains 1504 turbines.

  The power loss in the BE–NL cluster attributed to the additional surrounding wind farms is defined as

$$\Delta P_{\text{red}} = \frac{P_{\text{red}} - P_{\text{NS}}}{P_{\text{red}}} \times 100\,\%, \tag{1}$$

  where P_{red} ***is the BE–NL cluster power obtained with the reduced configuration and*** P_{NS} ***is the BE–NL cluster power obtained when all North Sea wind farms are included. Positive values of*** ΔP_{red} ***indicate that the omitted surrounding wind farms introduce additional wake losses not captured by the reduced configuration.***

  Figure 1 shows ΔP_{red} ***as a function of wind direction for an inflow wind speed of*** $8\,\mathrm{m\,s^{-1}}$***, chosen as a worst-case scenario to maximize wake impacts. Only the homogeneous FLORIS configuration with fixed turbulence intensity is considered. As expected, the impact of the additional wind farms is negligible for wind directions between approximately*** 0° ***and*** 230°***, for which no major wind farms are located upstream of the BE–NL cluster. For westerly to north-westerly directions (***$\sim 240^\circ$–350°***), corresponding to inflow from UK wind farm clusters,*** ΔP_{red} ***reaches up to*** $1.85\,\%$ ***for TurbOPark (***$A = 0.04$***) and*** $0.93\,\%$ ***for TurbOPark (***$A = 0.06$***), while remaining below*** $0.17\,\%$ ***for the Gauss-BPA and Jensen models. Since these directions are not dominant in the southern North Sea wind climate, the annual-average contribution is expected to be substantially smaller.***

These results indicate that the omission of surrounding North Sea wind farms in the reduced engineering-model configuration introduces only a limited bias in the estimated wake losses of the BE–NL cluster. Consequently, the differences between WRF and the engineering wake models reported in this paper cannot be explained solely by the different treatment of surrounding wind farms, and the comparison of internal wake losses remains meaningful despite the slightly different definitions.

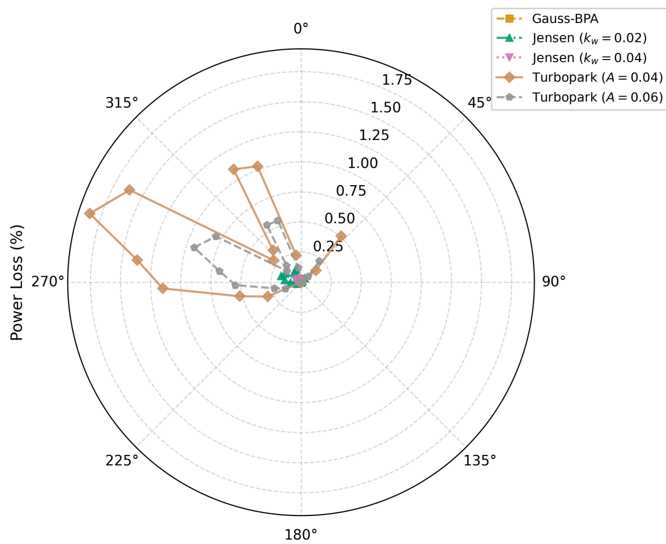

Figure 1: Additional external power loss ΔP_{red} in the BE–NL cluster resulting from the inclusion of all surrounding North Sea wind farms in FLORIS, shown as a function of wind direction at $8\,\mathrm{m\,s^{-1}}$ for five engineering wake models under homogeneous inflow with fixed TI. The Cumulative Curl model is omitted due to excessive computational cost on the full-domain configuration.

- **Rephrased Section 2.3**
  Note that the definition of internal wake energy losses is not strictly identical between the WRF simulations (Part I) and the engineering wake models (Part II). WRF-derived internal wake losses may contain a small contribution from neighbouring existing wind farms, whereas the engineering wake models only account for wake effects generated within the BE–NL cluster. Additional sensitivity analyses indicate that this contribution is minor and does not affect the conclusions of the model comparison (Appendix A).

- Third, I think a little more needs to be done to allow Part II to stand alone as a separate article from Part I. There are a couple of places that I noted where the user would have to have read Part I to understand the results. These could be fixed by adding a brief description of some terms in Part II to aid readers that are most interested in the engineering model/WRF comparison, but do not intend to read Part I. Most notably, Section 3.3.4 should explain the stability classifications used (introduced in Section 2.4 of Part I) in brief.
  We thank the reviewer for this suggestion. We agree that Part II should be understandable as a standalone manuscript. A brief description of the atmospheric stability classification (Section 2.4 of Part I) has been added to the Methods section. In addition, the description of the WRF simulations has been expanded with a concise summary of the model setup, while referring the reader to Part I for the complete details.

Minor Comment:

- The second sentence of the abstract (lines 3–4) seems to be incomplete, or I did not understand it as written. Perhaps this needs to be broken into two sentences at the first comma?
  Rephrased.
  Wind energy is regarded as an important component for global decarbonization strategies, and the rapid expansion of offshore wind farms has led to increasingly large and closely spaced wind farm clusters. As a result, assessing wake impacts between neighbouring wind farms has become increasingly important. Multiple numerical modeling approaches are available for such assessments and differ in their physical assumptions, representations of atmospheric processes, and computational cost. Numerical weather prediction models and fast-running engineering ...

- "Part I of the paper" and similar phrases are used a few times. Again, I'm not sure if the intention is two publish two separate articles (this would be my preference). In this case, I think the wording should be something like "Part I of the study", along with a citation—I at first was confused about whether the second part (Part II) itself has multiple parts. This would likely be fixed if/when the articles are split.
  We thank the reviewer for this comment. We agree that references such as "Part I of the paper" may be ambiguous when the manuscripts are read independently. As these studies are intended to be published as two separate papers, we will consult the editor regarding the preferred terminology and revise the wording consistently throughout both manuscripts.

- It may be worth mentioning that recalibrating the wake model parameters may help in reducing the spatiotemporally average power (Section 3.1), but that there would likely still be substantial differences when comparing time-step to time-step (Section 3.2). At least, that is what I have experienced when working with engineering wake models in comparison to farm operational data. I certainly can respect the authors' response to my comment on this; perhaps a similar statement to their response could be added to the article.
  We thank the reviewer for this suggestion. We agree that improved agreement in spatiotemporally averaged wake losses does not necessarily imply improved agreement at individual timesteps. A statement has been added at the transition between Sections 3.1 and 3.2.
  While calibration of engineering wake model parameters could potentially further improve agreement with WRF in terms of the spatiotemporally averaged metrics presented above, such calibration would not necessarily improve agreement at individual timesteps. The time-dependent behavior of the different modeling approaches is therefore investigated next.

- Line 363 claims "negative values can only occur in wake model setups that employ heterogeneous inflow", whereas Table 3 rows 1 and 4 contains negative values in both homogeneous and heterogeneous inflows. Can the authors clarify on this?
  We thank the reviewer for pointing this out. We agree that our original statement was not supported by the results, as slightly negative external wake energy losses also occur for some homogeneous inflow configurations. We have therefore revised the discussion to remove the attribution to a specific inflow setup. Instead, we now note that these slightly negative values occur only for engineering wake models predicting very weak external wake effects and that their origin requires further investigation. The paragraph has been rephrased accordingly:
  The slightly negative external wake energy losses obtained for Jensen with $k_w = 0.04$ and Gauss-BPA should not be interpreted as physically meaningful negative wake losses. These values occur only for engineering wake models predicting very weak external wake effects. Further investigation is required to better understand the origin of these slightly negative values.

- Figure 4 and others makes direct comparisons between engineering wake models and WRF (e.g. calculates a difference). Is the mean value for the engineering models used for these? How is the

"envelope" accounted for here?
Figure 4 itself does not show an engineering wake model envelope but presents the results for each engineering wake model individually together with the corresponding difference relative to WRF. The description of the envelope has nevertheless been expanded in the manuscript to clarify that, see main comment 1.

- Line 413 refers to Section 3.3.4, which is the current section. Is this meant to refer to Section 3.3.3 (or perhaps an earlier section)?
We thank the reviewer for noticing this error. The reference should point to the previous section and has been corrected accordingly.

- I do not understand the statement made on lines 464–465 "This may indicate that the large scale cluster partially affects how these transient events unfold across the domain". I don't see any particular evidence for this statement. As I see it, WRF can model transient atmospheric events, whereas the engineering models cannot; but that these transient events are partially a result of the clusters themselves is not at all clear to me. Can the authors refine this to explain their statement better?
We have tried to rephrased this more clearly.
In addition, the inflow velocity field used to drive TurbOPark (i.e. the no-farm WRF velocity field) differs substantially from the velocity field simulated by WRF when the wind farm is included, particularly during the transient event (Fig. 8, (c,d) and Fig. 9, (b)). For the steady case, the flow far from the wind farm remains broadly similar between FLORIS and WRF, indicating that the farm primarily affects the flow through its wake while having a limited impact on the surrounding large-scale flow field. In contrast, during the unsteady case, significant differences are observed even far from the farm. This suggests that the wind-farm cluster may actively modify the local atmospheric flow during transient conditions, for example through farm-induced blockage effects or changes in boundary-layer mixing. As a result, the no-farm WRF field used to drive FLORIS may no longer represent the actual inflow conditions experienced by the farm. A quantitative attribution of these mechanisms would require a dedicated comparison between no-farm and with-farm WRF simulations during transient periods, which is beyond the scope of the present study.

- I really appreciate the analysis around lines 475 explaining how often transient events might occur! That is very helpful.
We thank the reviewer for this positive comment and are pleased that this analysis was found to be helpful.

- Line 484 typo: "the presented in this work"
Rephrased.
"....the current work provides a framework to evaluate the spread in predicted wake effects at both the farm and farm–farm scale for both modeling approaches."

Reviewer 2

June 29, 2026

The study aims to support understanding the validity and variability of industrial wake model output for wind farm planning and power generation estimations running the models for a whole year (selected to be most representative). It consists of two parts, part one which presents the generation of WRF simulations later used as references, and part two applying different industrial models. In both parts it is tried to best separate internal and external wake losses, as well as investigating deviations and their causes, e.g. stability, homogeneity, temporal evolution. Please have in mind that some of my comments might not be valid as answers can be found within the text - in such cases please consider stating things more clearly to increase accessibility for the readers. The study is generally well written, but nevertheless needs some work to be optimally supporting the community with the findings. Colours need to be adjusted for accessibility. E.g. I strongly suggest that all co-authors proofread the next revision to ensure the referees do not have to deal with spelling or phrase doublings. At some point I struggled with understanding whether the active or passive form of writing has been chosen, or if it differs from chapter to chapter.

We would like to thank the reviewer for the suggestions made, which significantly improved the manuscript. All reviewer comments will be addressed in the appropriate manuscript (Part I or Part II). Responses to the reviewers' comments are provided in bold, and changes made to the manuscript are highlighted in *blue bold italics*.

General/Throughout:

- Choose colors accessible for many more people (including their limited printers)
  We thank the reviewer for this suggestion. Colour accessibility has been considered throughout the revised manuscript. Where highlighted by the reviewer, figures have been modified to improve accessibility by adopting more distinguishable colours and symbols, while maintaining consistency across the manuscript.

- Subfigure identifier better outside the figure upper left
  We thank the reviewer for this suggestion. The subfigure identifiers have been moved outside the figures to the upper-left corner throughout Part I & II.

- Unit notation in brackets or standard parentheses (SI)?
  We thank the reviewer for this comment. Unit notation has been made consistent throughout the manuscript. Units in figures and tables are now consistently reported in square brackets, whereas units in the running text follow standard SI notation.

- Region II uppercase/lowercase?
  We have revised the manuscript to use the notation "Region II" consistently throughout the paper.

- no WF and other identifiers for the simulations italic without space for better readability?
  We changed these expression to italic font, *no WF*, *with PE* and *without PE*.

- Correct spelling/case for e.g. TurbOPark and other models? Check throughout!
  We thank the reviewer for pointing this out. The spelling and capitalization of all model names have been checked and made consistent throughout the manuscript.

- Passive/active speech? Switches a lot - consider to be consistent.
  We thank the reviewer for this comment. The manuscript was reviewed for consistency in writing style and minor revisions were made where appropriate to improve consistency between active and passive voice.

- Br. or Am. spelling?
  Thank you for noticing this inconsistency. We have revised the manuscript to ensure consistent use of American English spelling throughout.

- where possible in the figures, use identical limits
  Thank you for pointing this out, where possible this has been adjusted.

Part I:

- **Abstract:**
  - I miss a phrase about present coupling or non-coupling with the sea surface (SWAN/WAM/..) - at least a hint why it is omitted if so.
    In the present study, we use the atmospheric WRF model in a stand-alone configuration and do not include explicit coupling with wave models such as SWAN or WAM. Since the focus of this work is on the annual variability of wind-farm wake interactions under varying atmospheric conditions, air–sea wave coupling is considered outside the scope of the current analysis. Nevertheless, waves may influence offshore wake development and could be investigated in future work using a coupled modeling framework.

    Added Lines
    The simulations were performed using the atmospheric WRF model in a stand-alone configuration without explicit coupling to an ocean or wave model (e.g. ROMS, SWAN or WAM).
    Added Lines
    Future studies could also investigate the influence of explicit atmosphere–wave coupling on offshore wake development and farm–farm interactions.
  - Region II is mentioned: throughout the paper "Region II" uppercase/lowercase?
    We have revised the manuscript to use the notation "Region II" consistently throughout the paper.
  - Line 18: external wake (energy?) losses - with or without "energy"?
    Modified to wake energy losses.

- **Introduction and ff:**
  - Line 25: consider replacing "clean energy" with "renewable energy production" or a similar term to potentially avoid discussions about circular economy (resin/fiber recycling)
    Modified to renewable energy production.
  - L80: 1990-2020: Are there projections about future "common" wind climate - e.g. for 2030 or 2050?
    While future climate projections for offshore wind conditions are available, the objective of the present study is to quantify representative present-day wake interactions for the planned Princess Elisabeth cluster. Therefore, we selected a representative year based on the 1990–2020 climatology to analyse typical wake effects under present-day atmospheric conditions. Investigating how climate change may alter future wake interactions towards 2030 or 2050 would indeed be an interesting topic for future work.

    Added Lines
    The present study thus focuses on representative present-day atmospheric conditions and potential changes in offshore wind climate under future climate scenarios are outside the scope of this work.

– L111: Does the selection of 2016 rely only on wind? What about stability, wave climate, water temperature etc? Some reasoning about how representative 2016 really is (respecting relevant parameters used in the study) in terms of the conducted analysis would be helpful.
The representative-year selection was based on the long-term distributions of wind speed and wind direction. Other parameters, such as atmospheric stability, wave climate, and sea surface temperature, may also influence offshore wake development, but were not explicitly considered in the representative-year selection and could be included in future work.

Added Lines
(Part I) Other parameters, such as atmospheric stability and wave conditions, were not explicitly considered and could be included in future work.

– L123: introduce "recovery rate"
We have clarified this in the manuscript.

Added Lines
representing the percentage of available measurements relative to the total expected measurements during 2016.

– T1: the table would benefit from some formatting
Table has been reformatted.

– T3: Introduce abbreviations (VU/NN/VS) here?
We thank the reviewer for this suggestion. The abbreviations VS, S, NN, U, and VU have now been introduced in Table 3 (Part I).

– Around Eq 1-6, add AEP and AEP changes / loss to be able to follow the text.
We are sorry but this comment is not clear to us.

– The expressions "with PE", "without PE" and "no WF" are hard to catch within the fluid text if not enclosed by using e.g. italic font or other marks.
We changed these expression to italic font.

– L204: spelling
Corrected energly to energy.

– L228: Phrase a bit unclear
Rephrased
This is especially visible at the location of WH, whereas the location in SL is less affected by wakes, as indicated by the smaller differences between the no WF, without PE, and with PE simulations. This is because SL is generally located upstream of the wind farms for the prevailing southwesterly wind direction in this region of the North Sea (Ivanova et al., 2023).

– L230: why mentioning "relatively small"? Is there a reference value?
Removed relatively small.

– L242: downwind? what do you mean here?
Clarified
"...which is located downwind of the BE-NL wind farm cluster during the prevailing wind direction..."

– T4/T5: I struggle with wind direction comparisons, as the direction is not well defined in low wind conditions - so errors/differences are better presented in north-vector and east-vector differences (with speed and direction deviation to be calculated easily). Here, the used values such as R2/RMSE in Part II could help understanding the effects /comparison much better and potentially build some trust.
We thank the reviewer for this suggestion. We agree that a vector-based analysis could provide additional insight into wind direction errors. However, the purpose of this section is primarily to demonstrate that the simulated background meteorological conditions are sufficiently realistic for the wake analysis, rather than to investigate the origin of model biases in detail. We therefore consider such an analysis beyond the scope of the present study. In addition,

wind direction becomes less relevant under very low wind speed conditions, since wind turbines are typically not operating and wake effects are negligible. Consequently, larger errors in wind direction under these conditions are not expected to affect the wake analysis. We note, however, that the wind direction biases are comparable to those reported in previous WRF validation studies (e.g. Rosencrans et al., 2024).

- T5: the wind speed bias looks quite systematic. is this a boundary layer effect to be looked at more deeply in your model setup/comparison?
  We thank the reviewer for this comment. The purpose of this section is to assess whether the simulated background wind field is sufficiently realistic for the wake analysis, rather than to investigate the origin of model biases. The magnitude and vertical variation of the wind speed bias are comparable to those reported in previous offshore WRF validation studies discussed in the manuscript.As mentioned in the manuscript, the simulations were performed using a standard WRF configuration, without case-specific tuning or optimization.

- L272: "does not include zero" is ok to understand after reading the whole paper, but consider to clarify this here.
  Rephrased.
  While the 95% confidence interval of the simulated AEP difference excludes zero, indicating a statistically significant difference, ...

- 276: phrase?
  Rephrased
  The observed long-distance impacts underscore the importance of accounting for AEP losses in both existing and planned wind farms during future siting decisions and yield assessments. This applies not only to nearby wind farms, but also to more distant farms. This consideration becomes increasingly important as the density of offshore wind farms is projected to increase in the coming years (Borgers et al., 2024).

- F3: are you consistent with the definition of deviation/losses/differences? Actual-reference = difference?
  We thank the reviewer for this comment. We reviewed the terminology throughout the manuscript to improve consistency. The term "deviation" has been removed to avoid ambiguity. Wake energy losses are explicitly defined in the Methods section and sign conventions are clarified in the relevant text and figure captions.

- 288: "not proportional" - consider omitting "strictly"
  Removed strictly

- T6: Sort table? Add direction from/to PE?
  The table has been sorted and the bearing direction from PE has been added, we also added a small reference to this new bearing direction.
  Table 6 shows that distance alone does not explain the magnitude of the AEP impact, highlighting the importance of the relative location of the wind farm with respect to the prevailing southwesterly winds.

- 301: Phrase sounds strange, interpunctuation?
  Rephrased
  WRF simulations of planned wind farm deployments along the East Coast of the United States also predict internal wake losses of a similar magnitude, despite differences in wind farm configuration (Rosencrans et al., 2024; Rybchuk et al., 2022).

- 309: ".. overlap zero loss"? One could reconsider the naming of the cases (no WF, with PE, ..) and "external" and "internal" losses. Also recap "internal" and "external" losses around here?
  As suggested, to improve clarity, we added a brief reminder of the definitions of internal and external wake energy losses. We also revised the wording regarding

confidence intervals to explicitly state that, for several distant wind farms, the estimated external wake losses are not statistically distinguishable from zero.
Rephrased
As shown in Table 7, the internal wake energy losses (i.e. wake losses experienced by the existing wind farms in the absence of the PE wind farm cluster) are larger than the external wake energy losses (i.e. the additional wake losses induced by the PE wind farm cluster).
Rephrased
For several distant wind farms, such as Scroby Sands, East Anglia ONE, Kentish Flats, Egmond aan Zee, Gunfleet Sands, and Prinses Amalia, the 95% confidence intervals of the external wake losses include zero. This suggests that the estimated external wake losses for these distant farms are not statistically distinguishable from zero and may reflect numerical variability or random fluctuations rather than a true physical wake effect.

– Fig4: Is it worth mentioning or thinking about inversion presence and height?
We thank the reviewer for this suggestion. We agree that inversion height may provide additional insight into the observed wake losses, as inversions can influence turbulent mixing and wake recovery. A brief discussion has been added to the manuscript, while a detailed analysis of inversion characteristics is considered beyond the scope of the present study.
Temperature inversion height may also contribute to the observed stability dependence of wake losses and could be investigated in future work.

– L347: decreasing? better generally decreasing (as it is not really consistent)?
Added generally

– L350: Phrase beginning here (including ref to Rosencrans 2024) seems very artificial and unnecessary here.
Removed sentence

– L353: SST/Air Temperature: Also in spring?
Modified to
"....particularly during spring and summer.."

– L359: Consider weakening the statement to ".. , potentially leading to longer .."
Added potentially

– L361: "generating significant thrust" - reconsider wording?
Changed to
"...while still generating high trust"

– L367: Here you mention "global blockage" - better give a definition / reference
Added reference (Porté-Agel et al., 2020)

– L371: is "recently" correct here (references from 2015)?
Modified
"....received comparatively limited attention in the literature"

– L385: spelling
Modified knwon to known.

– Around L385: Phrase doubling (likely from the writing process)
Modified the second sentence
"...associated with wind directions for which many turbines are aligned in the flow direction."

– F11: right ticks
Modified.

– L409: is there a clear research question why you seek to understand this? What is the expectation?
We agree that the research question was not clearly articulated. We have revised the introduction of this section to clarify it.
To better understand the interaction between external and internal wake effects,

we investigate how the presence of wakes from the upstream PE wind farm cluster modifies the development of internal wakes within the downstream BE–NL wind farm cluster. To this end, we analyze five successive turbine-containing grid cells for two representative wind directions, one for which the BE–NL cluster is not affected by PE wakes and one for which it is.

- F12: these figures are rather complex. some more guiding in the caption might help. Are the results significant? Error Bar?
  Reworded caption
  (a,f) Wind turbine locations considered for two representative wind directions (black arrows): (a) 105°, corresponding to a case where the BE–NL wind farm cluster is not influenced by wakes from the PE wind farm cluster, and (f) 234°, corresponding to a case where the BE–NL cluster is waked by the PE wind farm cluster. The red dots indicate the turbine used for the analysis. Panels (b–e) and (g–j) show turbine quantities as a function of turbine row number, illustrating how wake interactions evolve through the wind farm under unwaked and waked conditions (blue and orange, respectively). Specifically, (b,g) show turbine power normalized by the no WF front-row turbine power, (c,h) show turbine power normalized by the front-row turbine power, (d,i) show wind speed deficits relative to the no WF simulation and normalized by the front row, and (e,j) show added TKE relative to the no WF simulation and normalized by the front row.

- F13: UTC/Local Time? Consider averaging for every hour and every month (additional bars between 2d-field and axes), identifier hardly visible
  We thank the reviewer for this suggestion. Additional hourly and monthly averages could provide a useful summary of the patterns shown in Fig. 13. However, the purpose of the figure is to illustrate the temporal evolution and co-variability of wake losses and atmospheric conditions throughout the year. We therefore retained the current presentation to avoid overloading the figure. The panel identifiers have been repositioned to improve readability.
  Added to caption.
  Hourly variations are given in UTC.

- L443: "representative year" - still not completely convinced.
  This has been addressed earlier.

- L448: Sentence "The internal.." not clear
  Rephrased
  The largest internal wake energy losses occur for wind directions for which many turbines within the wind farm are aligned with the incoming flow.

- L458: Connect phrases?
  Rephrased and connected
  These temporal variations can largely be explained by differences in atmospheric stability and wind speed, with stable conditions and below-rated wind speeds resulting in higher wake energy losses.

- L465: spelling
  Corrected to and instead of en

- L456-end: consider streamlining the text / whole conclusion.
  We reviewed the conclusion and made minor edits to improve readability while retaining the main findings and outlook of the study.

- Table A1: consider adding WF density (What is a common measure? Summed- RotorArea/WF-area?)
  We thank the reviewer for this suggestion. While wind farm density is relevant for wake development, it is not a primary variable considered in this study. We therefore decided not to include an additional density metric in Table A1, as its definition would require additional assumptions regarding wind farm boundaries and layouts.

- B1: Mention the idea/parameters of Perkins Skill Score? Future Climate projections?
  A brief explanation of the Perkins Skill Score has been added to the appendix. Specifically, we now clarify that the Perkins Skill Score quantifies the similarity between the wind climate of an individual year and that of the 30-year reference period, with higher values indicating a more representative year.

Part II

- **Abstract:**
  - The strong statement in the beginning should be relativated as e.g. "Wind energy is regarded essential for ...". After the first phrase, there is a hard break into the next phrase incorporating models. This should be refined. Consider also to say something about external/internal wakes. Line 6, even NWPs can be based on different assumptions -please reconsider the phrases.
    Thank you for notifying. This has been rephrased.
    Wind energy is regarded as an important component for global decarbonization strategies, and the rapid expansion of offshore wind farms has led to increasingly large and closely spaced wind farm clusters. As a result, assessing wake impacts between neighbouring wind farms has become increasingly important. Multiple numerical modeling approaches are available for such assessments and differ in their physical assumptions, representations of atmospheric processes, and computational cost.

- **Introduction and ff:**
  - Same phrase in the beginning as in the abstract - please vary a bit (and preferably include "regarded")
    Rephrased.
    Driven by global decarbonization ambitions, wind energy capacity has expanded rapidly in recent years,...
  - L48: spelling
    See next comment.
  - L48: between 1 km and 3 km to improve reading?
    Rephrased.
    ...have horizontal spatial resolutions that are typically between 1 and 3 km..
  - L60ff: consider introducing model names here
    Included.
    Fast-running engineering models, such as Jensen, Gauss-BPA, TurbOPark, and cumulative curl models, have been widely used to estimate the yearly production and wake losses of wind farms,...
  - L65ff: is there a reason for the fast recovery?
    Added.
    This is partly because these wake models do not represent all the boundary-layer processes that control momentum replenishment and thus wake recovery in large wind farm clusters.
  - L69: it's Emeis - please also correct in the bibliography
    Modified.
  - L76-77: a reference to justify this statement?
    Same reference as previous sentence, thus rephrased.
    The same study showed...
  - L79: name the new developments
    Rephrased.
    Recently, new developments such as the TurbOPark wake model and the cumulative curl model have...

- L98: Part I without hyphen
  No hyphen present.
- L105: rather "adapted" than "extrapolated"?
  Modified to adapted.
- L112: consider naming the reason for this limitation
  Added the limitation.
  The implications of this simplification are discussed in Section 2.3 and further evaluated in Appendix A.
- L119: For readers not knowing FLORIS, better introduce it as a framework (?) for engineering wake modeling.
  Rephrased to framework.
- L154: Explain what you mean with "hyperparameter" here, or is it clear to the community?
  Changed to parameter.
- Page6 general: Maybe figures how the different models are built / "act" might help?
  We thank the reviewer for this suggestion. Illustrations of the considered engineering wake models are already available in several review papers (such as Porté-Agel et al., 2019). Since the focus of the present study is on the comparison between engineering wake models and mesoscale simulations rather than on the formulation of the individual engineering models, we have chosen not to include an additional overview figure.
- L175: spelling?
  Corrected.
- L205: consider to elaborate why you do not expect long range effects
  We are not clear to what this comment is referring to considering the text on line 205.
- L222: "In WRF, .." -¿ rather "we defined the internal wake in WRF simulations as.."?
  This sentence is not present anymore.
- L245-260: Hard to read and likely not necessary as such? Basically a table expressed in words.
  We understand that this paragraph may appear to describe the contents of Table 2 in words. However, we chose to retain it because Table 2 contains a substantial amount of information, and the accompanying text helps guide the reader to the main findings and quantitative trends without requiring them to interpret all individual values directly.
- T2: "each metric" -¿ Colour coding over all setups or granular? Colorbar is important to get color order!
  We thank the reviewer for this comment, it was indeed not clear enough, we have revised the caption of the table.
  R^2, RMSE [GW], and mean bias [GW] for the different engineering wake models (without PE) compared against WRF, shown for the four model setups: homogeneous fixed TI, homogeneous varying TI, heterogeneous fixed TI, and heterogeneous varying TI. Colour shading highlights relative performance ranking of the engineering wake models within each metric column (R^2, RMSE, and mean bias for a given inflow setup) ranging from dark red (worst), light red, orange, yellow, light green, to dark green (best). Typographic emphasis (best = bold, worst = italic & underlined) highlights the relative performance of the different inflow setups within a given engineering wake model.
- L288: Envelope? Do you mean Min/Max?
  We thank the reviewer for pointing this out. We have added the following paragraph.
  To facilitate comparison between WRF and the engineering wake models, envelope ranges are shown throughout this study. In each case, the envelope is defined by the minimum and maximum estimates obtained from the set of engineering wake models and/or model configurations considered in that particular

analysis. The envelope therefore represents the spread associated with the engineering model and/or model configuration.

– L294: replace "calibrated" with "adjusted" or "tuned"?
Modified to tuned.

– F2: Mention date selection for further analyses?
Added to the caption of F2.
The zoom periods were selected to show periods with the largest differences between WRF and the engineering wake models.

– F3: Colours not friendly.
We thank the reviewer for this comment. The line colours are already distinguishable through the use of different line styles and therefore do not rely solely on colour. We interpreted the comment as referring to the location markers and boxes. To improve accessibility, we have modified the figure and the caption by introducing different marker symbols (circle, pentagon, and star) to distinguish the farm-centre, coastal, and open-sea locations, respectively, in addition to the existing colour coding.

– L377: Reflection to wind farm density?
We thank the reviewer for pointing this out. Added the following sentence.
This difference may partly be related to local wind farm density, as internal wake losses are largest in the densely packed interior of the wind farm.

– L378: between -¿ between which ones? Or do you mean something like "within"?
Thank you for pointing this out, rephrased.
For the external wake energy losses, the spatial agreement between WRF and the engineering wake models exhibits a larger spread than for the internal wake energy losses....

– F4: Here you begin to use "percentage points" - is there a reason for this?
We use percentage points [pp] for the difference plots because the wake energy losses themselves are expressed as percentages. The difference between two percentage values is therefore most appropriately expressed in percentage points rather than percent. We have clarified this in the figure caption.
The second (h-m) and fourth (u-z) rows show the corresponding differences in wake energy losses, expressed in percentage points, between each engineering wake model and the WRF simulation for internal and external wake losses, respectively.

– L393: Restructure phrase?
Phrase has been restructured.
For the external wake energy losses (Fig. 6 (c)), differences between modeling approaches range from 1 to 6 pp in winter and increase to 4–11 pp in summer. Although these absolute differences are smaller than those found for the internal wake energy losses (Fig. 5 (c)), the external wake energy losses predicted by WRF are also considerably smaller, resulting in larger relative differences between the modeling approaches for external wake energy losses.

– L395: "relatively larger"?
See previous comment.

– F5: consider similar scale as Fig4?
We thank the reviewer for this suggestion. Since Figure 4 shows annual averages and Figure 5 monthly values, the range of differences in wake energy losses is different between the figures. Using the same scale would reduce the readability of the monthly variability, and we therefore retained the original scaling.

– F7: I'd prefer to see identical scales for (a) & (b) as well as for (c) and (d). Colours not very reader-friendly.
The y-axis scales have been made identical for panels (a) and (b), and for panels (c) and (d), to facilitate direct comparison. In addition, the line styles

have been modified to provide a clearer distinction between the different model configurations.

- L466: do you mean "temporal evolution" or "wake dynamics"?
  Modified
  "...for the temporal evolution of wakes..."
- F8: Arrows are wind vectors? Length identically scaled?
  The arrows represent wind vectors and are identically scaled in all panels. This has been clarified in the figure caption.
  Arrows indicate wind vectors and are shown using the same scale in all panels.
- F9: Targeted period poorly visible
  This had been modified.
- L493 Phrase "In particular .." sounds strange to me.
  Changed to "Specifically"
- L509: "relatively larger"?
  Rephrased.
  Although external wake energy losses are smaller in absolute magnitude than internal wake energy losses, the relative deviations from WRF are larger, particularly during summer, because the external wake losses themselves are comparatively small.
- L518: spelling
  Corrected to "present".
- Table B1: color bar
  The color bar is explained in the caption of the figure.
- Appendix: Include/explain Appendices some more
  We are not entirely sure which appendix this comment refers to. Appendices A–C already include text, whereas Appendices D–F primarily present supplementary figures for completeness. These appendices are referenced in the main text wherever similarities or deviations from the primary results are discussed, and we believe this provides sufficient context for their interpretation.
- L577: check reference
  Corrected.