Authors response on the review comments on

Mitigation of offshore wind farm cluster wake effects by low-specific-rating, low-induction turbines

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Dear reviewers,

We would like to thank you for your valuable comments, which helped improving the quality of our manuscript. We have carefully considered all your comments and either incorporated them into the manuscript, where applicable, or provided our reasoning for retaining the original wording below. Your comments are shown in black, our responses to them in blue and direct quotes from the manuscript are marked in *green*.

<u>Comments of reviewer #1:</u>

<u>Minor comments</u>

1. Section "2.4 Data post-processing and applied metrics": the exclusion of the sector 180 deg < ϕ < 270 deg should be better clarified, as the reader could benefit from a simple explanation, in addition to the referenced work of Van Wijk (1990). Moreover, would it be possible to have an indication of the probability of wind coming from that sector? This piece of information is important to understand to what extent the employed data are representative of the real field conditions.

   We choose south-westerly wind directions, i.e. only including situations with wind directions between 180° and 270°. This is the main wind direction for the North Sea, with roughly 40% of all situations showing that wind direction. Regarding the depiction of the probability of the wind direction lying within the chosen range, we added a wind rose as a Figure within Section 2.

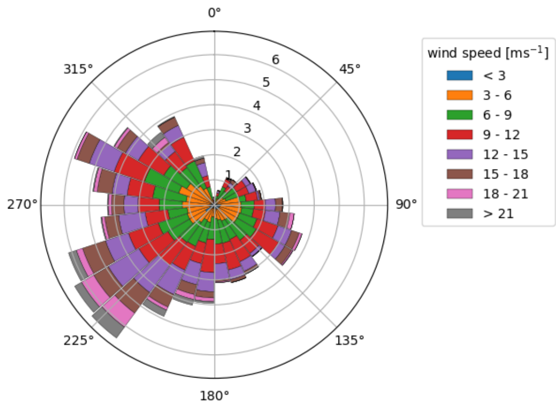

Figure 1: Wind direction and speed distributions, averaged across multiple positions in the German EEZ.

2. Section 2.1: typically, such tools may be strongly impacted by the grid resolution and by the number of refinement levels. Did the authors perform a sensitivity and convergence analysis of the simulations?

   Since the 3:1 ratio from parent to child is a well-established practice in the mesoscale modelling community, we did not perform a sensitivity analysis for the grid resolution and refinement levels. Further, while previous studies (e.g. Ma et al., 2022; Sengers et al., 2026, Tebboune et al., 2026) showed that the power production from simulations decreased with increasing resolution, Ma et al. (2022) found that this effect is mainly present when the wind direction is aligned with the turbine layout. In cases where the wind direction is not aligned with the turbine layout – which is often the case in these real-world simulations - the Fitch wind farm parametrization (WFP) has proven to be quite accurate. Also, Ma et al. (2022) showed that the bias of power production is not significantly reduced when increasing the resolution from 2km to 1km.

   Additionally, as we use the same layout for all scenarios with the same installed capacity, i.e. the turbines are placed at the exact same location the turbine density per cell does not change at all between the runs and the background wind field is also very similar between the scenarios.

3. Lines 186-188: The sentence expresses a correct idea, but as currently written is unclear: CP and CT functions do not exhibit purely cubic and quadratic behavior, hence a decrease in a has a larger impact on CP than CT only close to a = 0.33. In contrast, around a = 0, the two functions show the same trend. Please, clarify.

Yes, that is true. We were referring to the operating region close to the optimum axial induction factor of a=0.33. In this region towards lower *a* this behaviour is quite evident, hence we have rephrased the sentence as follows:

"From these equations it can be seen that close to the optimum axial induction factor of a = 0.33, the thrust coefficient scales quadratically with the induction factor, while the power coefficient scales with the induction factor cubed. This indicates that a decrease in a from that optimum point towards lower axial induction factors has a larger impact on the thrust of a wind turbine than on the power production."

4. Line 249-250: "we observe that in south-westerly direction and further away from the German coast higher capacity densities are planned compared to the clusters at the north-easterly boundaries of the EEZ". It is not clear if this observation is taken from Vollmer and Dörenkämper (2024) or if it results from an optimization performed in the present work.

   This observation indeed is based on the area development plan for the German Maritime and Hydrography Agency (BSH) and is not a result of either an optimization within this study nor by Vollmer and Dörenkämper (2024). The corresponding sentence has been rephrased to:

   "[...] we observe that in south-westerly direction and further away from the German coast higher capacity densities are currently planned by the German Maritime and Hydrography Agency (BSH) compared to the clusters at the north-easterly boundaries of the EEZ."

5. Line 285: the repetition of veq can be avoided to render the sentence smoother.

   The sentence has been rephrased to

"Subsequently, we normalise the acquired v_eq with the the reference simulations GB_ref following"

   To avoid the double usage of veq in such short succession.

6. Fig 5: is there a reason for the increase in the REWS between IEA and HL cases observed in the inter-farm regions (those colored in light red)? This could indicate that the reference turbines generate stronger wake deficit but that their wakes recover faster.

Yes indeed, lower wake deficit, but hence also higher power production/energy extraction by downstream turbines lead to stronger wake effects downstream of the wind farm clusters. Following Paulsen et al. (2024), the strength and distance required for the wake recovery are also different between the concepts.

7. Tab. 4: excellent table summarizing the main results. The fact that the reference upscaled turbine type (GB-IEA-D) is associated with a slightly lower CF than the HL one is the most important outcome of this analysis and should already be discussed at this point (without waiting for the discussion in section 4).

   To keep consistency within our manuscript we would like to keep the results section to be a presentation of our results, while the interpretation and discussion of the results are done in the discussion section of our manuscript. However, we added the following sentence in this section of our results to provide greater emphasis on the comparison between the upscaled IEA turbine and the HL concept.

   "Hence, we observe that despite both turbines having the same rotor dimensions in GB-IEA-D and GB-HL the wind farm efficiency is still increased from 47.3% to 49.3% purely due to the improved thrust characteristics and higher power production at low wind speeds and just below rated wind speeds for the HL-turbines."

8. Line 384 and Fig. 8: is there a reason for the results obtained in the cluster N12 and N19? It seems that the improvement due to HL concept is more significant for those two farms of the cluster.

   As mentioned in L. 379, we assume the great benefit for the N-12 cluster to stem from the fact that the gross yield does not include any external or internal wake losses. Since the N-12 cluster is located in the centre of the German EEZ it is exposed to cluster wakes from all directions. These situations with low wind speeds are especially beneficial for the HL concept, which is also seen from the doldrum analysis (cf. Sec. 3.3). For the N-19 cluster only very rarely external cluster wake effects are observed. However, as the cluster is significantly larger than clusters N-4 and N-5 the inner farm wakes have a large impact on the average turbine efficiency. As these are also not covered in the gross yield – and are lower for the HL turbines (cf. Fig 5) the HL turbines provide greater benefits compared to the gross yield and the two smaller clusters here as well.

9. Section 3.3: can the obtained results be simply explained by the fact that the HL turbines generate weaker wakes? If so, what additional insights can the authors derive from the farm-cluster analysis compared to single-farm simulations?

   During doldrum events most HL turbines operate in the low wind mode, which actually leads to stronger wake effects compared to situations with higher wind speeds (cf. Section 3.1). The higher power production of the HL turbines compared to the reference design is based on the increased rotor diameter as well as improved control design during low wind speeds. In single farm/cluster simulations (cf. Paulsen et al. 2024) similar results are observed, as the increased power production is especially evident at low wind speeds below 6.8m/s.

10. Table 6: Why do Authors choose to express the differences between CF values in percentage terms? It seems that they computed the percentage of a percentage. Please, consider expressing the differences in percentage points. For example, the difference between GB IEA and GB-NL-IEA is 41.1-40.3=0.8 percentage points.

    Indeed, that is true. However, as all three considered performance parameters, i.e. AEP, CF and FLH are directly proportional to each other, we have chosen to express the difference between the two scenarios (GB-IEA vs GB-NL-IEA and GB-HL vs. BG-HL-NL) in percentage terms. This fact is now also stated in the last sentence of the table caption. We adjusted the caption to clarify as follows.

    "Characteristic performance indicators for the offshore wind farms of IEA and HL-clusters with and without Dutch wind farms taken into account. The relative difference is identical for AEP, CF and FLH and is hence represented as one single percentage parameter."

11. Line 467-469: this sentence explains the higher winds outside the farms observed in fig. 5. Could it be more appropriate to introduce this concept when commenting on Fig. 5? Please, consider this possibility.

    Exactly, here we interpret our findings introduced in Section 3. We have considered your comment, however, since the interpretation of the findings also builds on our findings from the power production of the turbines presented in

Section 3.2, we would like to stick to the description of the results in this Section of the paper.

Comments from Reviewer #2

Major comments:

1. It is reasonable to look at AEP as a first key metric for success. Nevertheless, if feasibility of the hybrid lambda rotor were to be established, then it seems to this reviewer that metrics covering the economic viability could become decisive. Some of the benefits of the novel concept may be lost due to changes in cut-in and cut-out speeds or higher installation and maintenance costs. It would be good to discuss this in the conclusions.

   For sure the economic viability of the HL concept is an important aspect in the future development and acceptance of low-specific-rating, low-induction concepts. A previous publication, introducing the concept of the HL concept showed decreases in both the levelized cost of energy (LCOE) as well as cost of valued energy (CVOE), i.e. taking into account the market value of electricity during the time of production, compared to the classical IEA 15MW design (Ribnitzky et al., 2024). This aspect is also discussed in the manuscript (cf. Section 4, L. 535ff). Further, Ribnitzky et al. (2024) also show that the revenue of the HL concept is higher than even for the upscaled version of the IEA 15MW turbine, with greatest benefits in cluster-wake-affected regions (cf. Sec. 1, L. 95ff).

2. The study is motivated by an improved grid integration potential. Why, in this context, full load hours (or capacity factor) matter is not clear to this reviewer and may need to be better motivated or put into context. On the other hand, the ability to help with demand matching, e.g. during doldrums, is of relevance. So is a possibly lower AEP loss due to cluster wakes. An assessment of the grid integration potential, ideally with a suitable metric, would be great to see in the conclusions.

   True, the possibly improved grid stability is one of the motivations behind the introduction of the Hybrid-lambda concept. And for the grid integration of individual turbines or small wind farms criteria for evaluating the certainly exist (e.g. grid codes). However, the scope of this study lies on the large-scale expansion of wind farms, using the German Bight as an example and hence, the focus was set to be more on the development of cluster wakes, wind farm efficiency and temporal characteristics of the power production. We aimed at providing a first outlook on the topic of grid integration potential by showing the increased performance during doldrum events, as well as the more evenly distributed power production across the year. To assess grid integration in this

large-scale context, various assumptions regarding the energy system and - where applicable - the electricity market are necessary, as well as considerations of other power plants and storage facilities.
This specific aspect of the HL turbine, however, is something we have in mind for future work and would from our point of view be out of the scope of the current study

3. The larger and even more slender rotor of the hybrid-lambda concept invites for challenges regarding installation and maintenance but also on validity of design tools and operability of the novel rotor concept with respect to physical phenomena related to aeroelasticity, erosion, dynamic stall, high Reynolds number or possibly even transonic flow effects. It may be appropriate to point out these risks in the manuscript, preferably together.

True, these aspects have not been discussed thoroughly within our manuscript and also were only partially in the scope during the development of the concept. Regarding the transonic flow effects and leading edge erosion, the risks are similar to the IEA 15MW reference turbine, as the maximum blade tip speed of the HL concept is limited to $95 ms^{-1}$ – the same as the IEA 15MW concept. During the initial development of the turbine concept, the blade torsion has also been neglected due to the complexity of the task for such a large blade. Aeroelastic stability has only been tested for specific design load cases (Ribnitzky et al., 2024).
While for now, the concept is mostly designed based on aerodynamic considerations there is ongoing work on the HL-concept within the collaborative research centre (CRC) 1463 offshore megastructures which aims at tackling further topics, including aeroelastic considerations and improved control concepts.
We have added the aspects to the discussion part of the paper.

"However, it is important to note, that the HL concept is not yet a fully developed turbine design and further research is ongoing to assess the feasibility of the concept. Especially considerations with respect to the torsional blade deflection and aeroelastic stability of the turbine during a variety of operating conditions, as well as the long-term fatigue loads and the implementation of advanced control concepts have been out of the scope of the initial design phase, but are addressed in the current work within the CRC1463 Offshore Megastructures."

Minor comments:

- Page 2, line 37: Note that also the demand is usually intermittent! Maybe rephrase as the current sentence may be misunderstood as if intermittent renewable sources by themselves are a problem rather than a demand and supply mismatch.

  We rephrased the sentence in our introduction as follows:

  "Further, substantial penetration of intermittent energy supply which is not necessarily meeting the fluctuating demand in the electricity grid, such as wind power, generates an increased demand for the provision of ancillary services (i.e. Frequency Containment Reserve, Automatic Frequency Restoration Reserve and Minute Reserve)."

- Page 2, line 52, unclear sentence: Are the wake losses reduced by 18% or the energy production? How does this value relate to the 30% stated in the sentence before?

  In the cited study, the authors compare the gross yield, i.e. the theoretical annual energy production (AEP) of the installed capacity, with the AEP when considering wakes. If the planned capacity expansion is planned on a national level, as is the case right now, then the difference between AEP with and without wakes considered lies at 30%. If the installed capacities are distributed more evenly across different countries' exclusive economic zones (EEZ), these losses can by reduced down to a total loss of 18% in AEP. The formulation used in the manuscript was hence also mixed up and the corresponding sentences have been rephrased to:

  "Fliegner et al. (2025) analysed one proposal of mitigating cluster wakes, by distributing the installed turbines in the North Sea more equally across national borders. Assessing the turbulent kinetic energy budget in the lower atmosphere, they show that by adhering to national borders and current policies, wake induced losses of up to 30% in the combined AEP of all wind farm clusters are expected. Positioning the wind turbines more balanced across the Dutch, German and Danish EEZ instead, only shows wake induced losses of 18% in the AEP. While the very simplified modelling approach applied by Fliegner et al. (2025) only a assumes homogeneous distribution of wind farms across large boxes, their insights show promise for cross-border collaboration especially between the Netherlands, Germany and Denmark."

- Page 4, line 117: Introduce the acronym WFP at first use.

  The acronym has now been introduced at first use.

- Page 7, line 176: Isn't it "Collaborative Research Centre"?

  Yes, that is correct and has been changed in the revised manuscript.

- Page 8, line 224: by the IEA … (missing article)

  The missing article has been inserted.

- Page 9, figure 2: Maybe add inserts for the power and thrust curves to better discern deviations or plot a difference between concepts. The figure is described in the text but not self-contained as information is missing. For example, please add the specific ratings.

  Additionally to the thrust and power curves, we have now added separate lines denoting the difference between the different concepts. Additionally, we have added the specific rating of the respective concepts to the legend. The revised figure is depicted below.

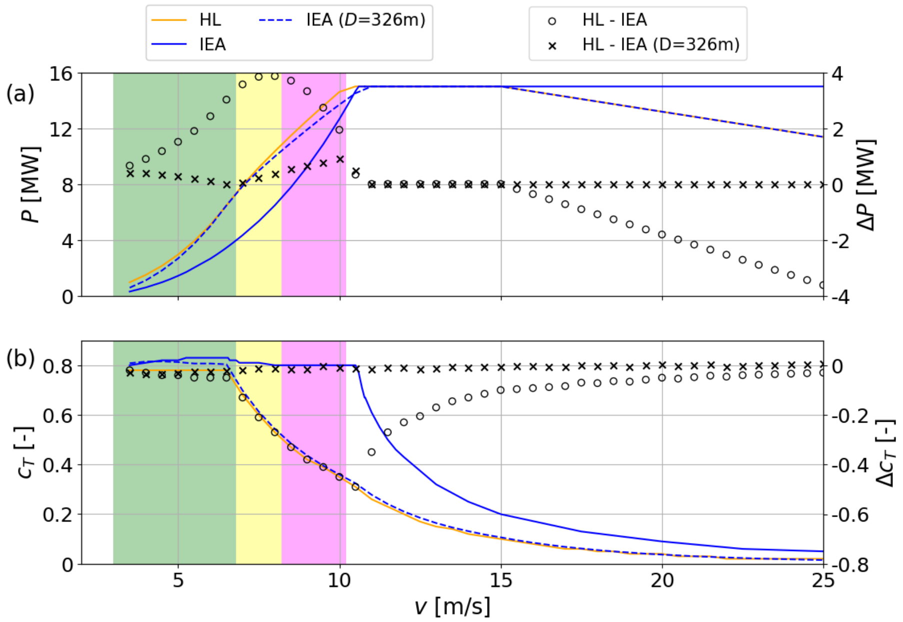

Figure 2: Power (a) and thrust coefficient (b) curves of the different design concepts used in the simulations, respectively. The HL (orange) and standard IEA (blue) turbine designs are marked by solid lines, while the upscaled IEA-15\,MW turbine is depicted as a dashed blue line. Further, the difference in power and thrust coefficient between the concepts is depicted on the secondary axis using markers. The light-wind mode is shaded in green, the transition region in yellow and the strong wind mode in magenta for the HL turbine. Subfigure (c) compares the dimensions of the HL turbine (orange swept area) with the IEA turbine (blue swept area).

- Page 9, line 242: brackets misplaced in citation.

  The citation has been corrected.

- Page 10, figure 3, maybe switch plots for better orientation (Netherland on the left).

The figures have been changed for improved orientation.

- Page 10, first paragraph: Why was the option for layout optimization chosen?

We chose a geometric layout optimization, as optimising the layout for each wind farm cluster based on the main wind direction and speeds would have been quite the demanding task, as here each of the neighbouring clusters would have to be considered for optimization.
Further, the grid resolution in WRF is too coarse to reflect actual layout effects of the clusters. Hence we used the computationally cheaper and easier to comprehend path for layout optimisation. The corresponding information has been added to the manuscript:

"The layout optimization carried out is thus purely geometrical and not based on the main wind direction or potential wakes induced by nearby wind turbines or wind farms, as the layout optimization on the scale of the entire German EEZ would be quite a complex task and WRF is - due to the grid resolution chosen in this study - not able to resolve the exact effects of the layout."

- Page 10, last paragraph: Maybe also look at AEP gain per wind bin?

Considering different wind speed bins for the generation of new layouts and running an entire year of simulations to match the AEP would have been computationally too expensive and not feasible to implement for this study. Hence, we chose to do the AEP matching across all different wind conditions.

- Page 13, line 300: introduce t_tot as hours in a year.

t_tot has now been introduced after the equation.

- Page 13, line 320, unclear sentence: "causing the integration of wind speeds at higher altitudes"

The sentence has been adjusted to better phrase what we meant, i.e. that for the rotor equivalent wind speed in the GB-HL case, wind speeds at higher altitudes are considered, due to the fact that the upper blade tip reaches higher into the atmosphere. The revised manuscript now reads

"One driver for the increased REWS in the GB-HL case is the increased hub height and rotor diameter of the HL turbines, as this leads to wind speeds at higher altitudes being included in the computation."

- Page 14, figure 4: difficult to discern differences. Maybe also add a plot with the difference

That is a valid point, we have added the difference plot to the figures now as well. The updated figure is depicted below:

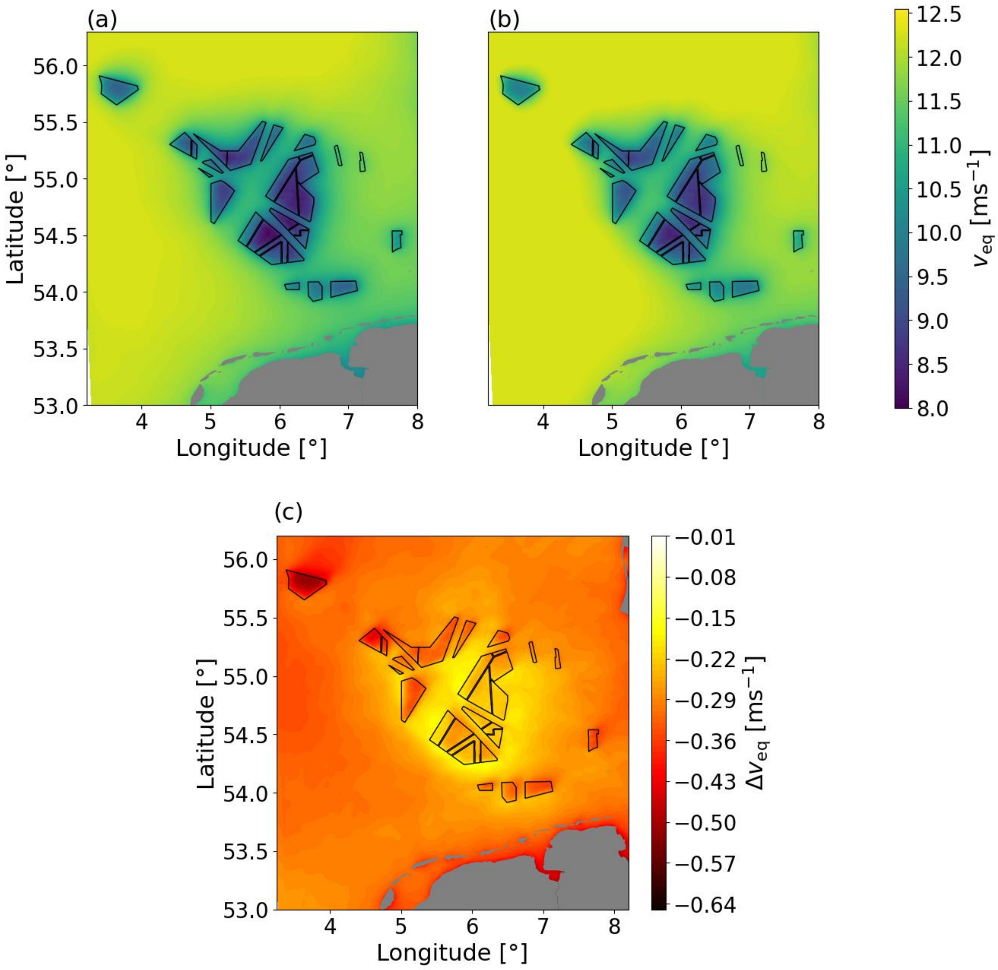

Figure 3: Average REWS across the entire year for GB-IEA (a) and GB-HL (b). Additionally, the difference between the average REWS is depicted (c).

- Page 17, table 4: How do these values compare to other studies, e.g. full load hours of an IEA-type wind farm at the same or a similar location?

  There have been several studies in the past analysing the potential capacity factor (CF) and/or full load hours (FLH) of wind farm clusters equipped with IEA 15MW turbines. However, the only study to the knowledge of the authors dealing with such a wind farm in the North Sea is Paulsen et al. (2024). Here, the authors observed for simulations only including the N4 cluster with an installed capacity of 1.23GW a CF of 53.22% across one year during the representative wind year 2006. In a different study, Martini et al. (2016) observed an average lifespan CF of 50.26% for a 500MW wind farm off the coast of Scotland, using 20 years of WRF simulated wind speeds, and analytical wake model and including losses due to shut down during extreme wave events. Further, Beiter et al. (2020) analysed the performance of a 1GW floating offshore wind farm at different offshore development areas off the coast of California and observed gross CF (i.e. excluding losses through wake effects) between 54.5% and 61.8%. Within our study we also computed the gross yield of an IEA 15MW wind farm at the location of the N-4 cluster, resulting in a CF of 59.56%, i.e. lying in a similar range compared to Martini et al. (2016)

However, due to the different locations and metrics applied, the inter-comparability between the studies is not given.

- Page 18, line 378-380: What is the role of the wake model?

  In the referred Section we compare the difference between the gross AEP, i.e. excluding wakes with the AEP obtained from our WRF simulation with active WFP. The role of the wake model here is a more accurate estimation of the wind farm efficiency by also modelling the intra- and inter-wind farm cluster wakes. This of course leads to a reduction in the AEP.

- Page 19, line 394: Why is the median of interest and not the mean?

  Here, we chose the median, as the distribution of the ratios is not symmetric around the mean of all ratios. Further, the mean in these cases might be influenced by outliers, due to some turbines at high wind speeds might be derated, while at low wind speeds, some turbines might be below cut-in wind speed. Hence, the median allows for a more robust interpretation of the ratios. We have added the information the manuscript:

  “In this comparison, we explicitly choose to compare the median increase in power production, as this metric is less sensitive to outliers, which are present when comparing the power production of the two concepts due to turbines reaching cut-out wind speeds and/or derating at high wind speeds, as well as turbines experiencing wind speeds below the cut-in wind speed and thus producing no power at all during low-wind speed situations.“

- Page 21, figure 10: Maybe add the unity line for reference?

  Yes the unity line has been added now for reference.

- Page 24, table 6: Can you say something about the order of uncertainties expected and consider the corresponding relevant digits? -2.13% vs -1.73% is only a 0.4 percentage point difference!

  We acknowledge that there are inherent variations in the model output present, due to the stochastic perturbations introduced in the radiation modelling. Previous studies mainly focused on variations between model runs with different runtime, parametrisations or initial conditions. Since our simulations all feature the same physics parametrization, initial conditions and start and end times, we expect the inter model variations in wind speed and hence power production to be quite small.

Since running an entire ensemble of WRF simulations with the same turbine setup as an addition this study is not feasible, we instead aimed at computing the inter model variations based on the simulations carried out already. We choose six locations within our model domain, which are located quite far away from all wind farm clusters such that they are mostly unaffected by the wind farm wakes (cf. Fig, 4).

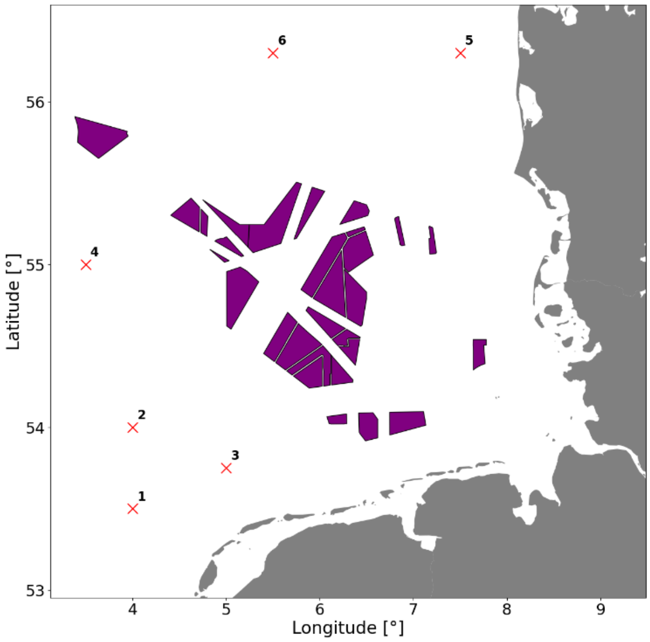

Figure 4: Locations for the analysis of inter-model variability marked (X).

Next we computed the bias and RMSE of all the runs against the ensemble average and took the average across all chosen locations and calculated the model spread σ of the wind speed at 150m between the different runs (GB-HL, GB-IEA, GB-IEA-D and GB-IEA-HH and GB-ref) for the entire year of simulations.

We observe maximum bias of 0.004ms^{-1} and a maximum RMSE of 0.019ms^{-1}. Notably these maximum values also always occur between the reference simulations and ensemble average, indicating that there might be wind farm induced effects influencing the results after all. Comparing only simulations with active WFP, the differences between the different runs are becoming even smaller. Further, a maximum spread of 0.04ms^{-1} is observed at one location, while all other locations lie below 0.02ms^{-1}.
If we, additionally use the power curve of the HL-concept to transfer the wind speeds at the specified locations into power and compute the AEP at each location for each of the simulations, we a observe a maximum model spread of $\sigma=7.3\cdot10^{-7}$TWh (at position 5), which lies well below the difference of 0.4 percentage points stated in the manuscript.

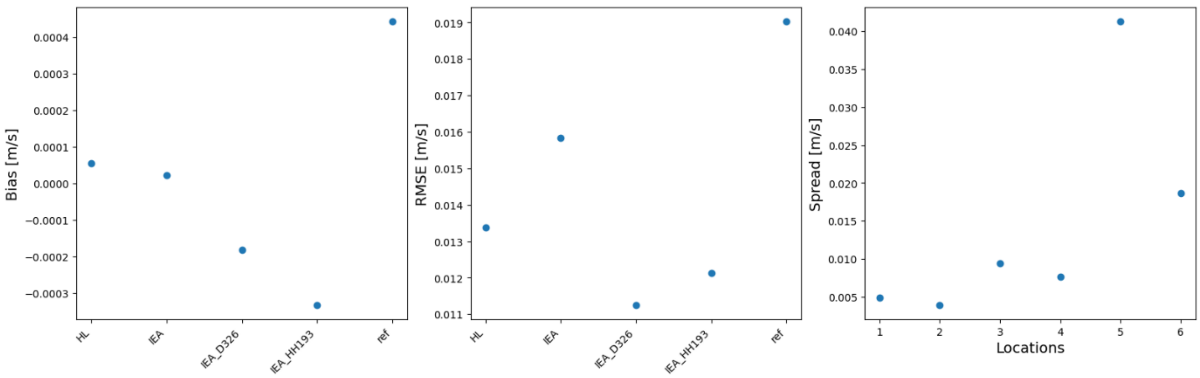

Figure 5: Average Bias (left), RMSE (centre) across all the different locations as well as the spread (right) between the different runs at each location.

- Page 28, line 573: Can you comment on the uncertainty of the wake modelling with respect to the expected benefit due to reduced wake losses?

  It is true, that mesoscale simulations are not able to resolve single turbine wakes. Hence, intra-farm wakes are subject to uncertainties, with Sanchez Gomez et al. (2024) showing an underestimation of internal wake effects when the wind is aligned with the turbine layout and an overestimation of wake effects when the wind direction is not aligned with the turbine layout. However, as Sanchez Gomez et al. (2024) show, the effects of cluster wakes modelled using the Fitch WFP on the first rows of downstream wind farm clusters are represented accurately. Further, we also use the same turbine spacing and WFP between GB-HL, GB-IEA, GB-IEA-HH and GB-IEA-D and since the inter model variability between the runs with active WFP is very small, we deem the differences between the different turbine concepts to provide meaningful results. Nevertheless, we have added the following information to the Discussion of the manuscript:

  "Moreover, Sanchez Gomez et al. (2024) also show, that the effect of cluster wakes on the first row of downstream wind farm clusters are depicted accurately, while intra-farm wakes are underestimated when the wind direction is aligned with the wind farm layout and underestimated when the wind direction is not aligned with the layout if the horizontal resolution is small enough to depict these differences."

References:

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