wes-2025-63: Reductions in wind farm main bearing rating lives resulting from wake impingement

Response to Reviewer 1

We thank the reviewer for their comments, which we feel have helped improved the quality and clarity of this manuscript. Reviewer comments are listed below, followed by our responses in blue.

1. It seems there is a conflict between line 10 and line 19. Is there something missing in your calculation that is not consistent with the literature (Hart et al., 2023; EPRI, 2024) or just simplification in the calculation of the life? Please elaborate on how to correct the sentence in line 10 to resolve this conflict.

To clarify, line 10 concerns bearing rating life (the life derived at the design stage based on simulated loading and ISO bearing life equations) while line 19 concerns the observed field life (calculated from failure data on operational turbine fleets). The gap between rating life (calculated) and field (observed) is the focus of much ongoing research, with the current paper seeking to understand if some of that gap may be the results on simulation and model based life estimation lacking wake effects. When revising the manuscript we will consider if this distinction can be more clearly outlined to the reader.

2. Line 53 defines rating life as the life that 90 % of the bearing population is expected to attain or exceed. It is not a completely correct definition, and it seems the authors mean basic rating life, L10 (ISO 281), by this definition. Keep in mind that with a different a1, life modification factor for reliability, instead of value 1, different reliability and life will be achieved (Table 12 from ISO 281 standard).

This sentence was constructed this way to try and help ensure the concept is understandable to a wide audience, without additional baggage. This is why we wrote that “rating life is generally the life that 90% of the bearing population is expected to attain or exceed”. We of course agree that the modified rating life can extend this other levels of reliability, but this is not done for the main bearing (as far as we are aware). The inclusion of the word “generally” was inserted to indicate some level of simplification (while also avoiding a full unpacking of the ideas), but we will revise this part of the manuscript to try and improve clarity.

3. In formula 1, the basic dynamic load rating is defined as CD. Because the formula is intended to be for a radial roller bearing (using 10/3 for p value in L10 formula), it is recommended to stick to the ISO symbols and use Cr instead, which is the basic dynamic radial load rating. I'm not sure if the notation CD is common in the industry. It is the same with the dynamic equivalent radial load, Peq.

We adopted the notation used here in an earlier paper (https://doi.org/10.1002/we.2883), based on some of the literature and theory unpacked there. Since the current work is a very direct follow-on from that paper, we feel it is best to maintain consistent notation between these two papers.

4. In equation 3 the life is defined in the form of different proportions of time spent. Although this definition is not wrong and is used in some references, the L10 is originally defined per revolution instead of time spent. Even when you want to sum the different operating conditions, the summation should be done on different numbers of revolutions instead of the time spent. In addition, it is not clear how the lives in revolutions unit changed to years units in the results.

Thank you for raising this point. You are indeed correct that we neglect to mention that L10 is first calculated in revs, and then changed to time via a conversion that includes turbine rotational speed, while all these details appear in the earlier paper cited at this point in the manuscript (https://doi.org/10.1002/we.2883), we agree that more details on this in the current manuscript would also be beneficial. Concerning the "summation" across different operating conditions, we disagree with your assertion that this should necessarily be done in units of revolutions. One may combine across different operational conditions using any units (time or revs), so long as this is done correctly. Given the turbine operates at different rotational speeds, and that the full life of the turbine is not simulated directly (we simulate across expected conditions and then extrapolate to the full life), we argue that obtaining a resultant bearing life is more straightforward if one first converts to units of time. This happens by 1) calculating L10 in revs for set conditions 2) converting to L10 in years using a conversion factor that includes rotational speed 3) combining across different conditions by weighting according to the proportion of time spent in each condition. Note that this conversion naturally accounts for varying rotational speeds, removing the need for that to be accounted for later on.

5. In lines 73 to 78, the paper clarified why ISO 281 rating life is used. Strictly speaking, the paper used basic rating life because ISO 281 also proposes another, more advanced rating life named modified rating life, Lnm.

Fair point, we'll clarify here that we're using the ISO 281 basic rating life.

6. Line 140 presented the Weibull distribution as a standard model. Although it is true, it is important to say that considering the shape parameter of 2 leads to the Rayleigh distribution, which is a special state of the Weibull distribution, and it is presented in the IEC 61400-1 as well.

While this is true, we don't feel it's particularly important to point this out in the manuscript.

7. In the wind turbine simulation section, it is mentioned that the DTU 10 MW is considered; However, DTU 10 MW is a well-known reference wind turbine, it would be better to give some general information about its specification in this section, such as rotor diameter.

Agreed, we will add some relevant information about the rotor diameter and rated wind speed etc, as well as a diagram of the power and thrust curves for the DTU turbine.

8. In Line 181, the axial dimension of the middle of the shaft is presented from the hub. The value is 3.7 m, and if the length between the center of the bearing and to center of the shaft is deducted, the remaining length is 2.7 m (between the center of the front bearing and the center of the hub). According to DTU 10 MW specifications, the hub diameter is 5.6 m, which leads to 2.8 m in radius. Even with a main shaft-hub connection diameter of 3 meters, the length between the center of the hub and the shaft-hub connection would be 2.36 m, and there is only 0.34 m for the distance between the center of the front bearing and the shaft-hub connection. This value is so unrealistic.

This appears to be a simple misunderstanding. The "hub diameter" for the turbine in question concerns the hub's radial size in the rotational plane (the plane through which the blades sweep). This dimension is therefore orthogonal to that of the drivetrain. As the hub is not a sphere, this same dimension cannot assume to provide any information concerning the plane in which the drivetrain sits. The drivetrain dimensions used here are in line with those of other turbines of a similar size in the literature (e.g. https://doi.org/10.1002/we.2476) and are both sensible and consistent with the turbine model being used.

9. In line 191, it is presented that the weighing is equal across all time steps. Does the turbine rotate at a constant speed? Otherwise, how can such an assumption be justified? If this is not the case, please clarify what the assumption means.

The benefit of working with basic L10 lives converted to units of time is that varying rotational speeds have already been accounted for, and it is simply the relative time spent under each condition that determines the resultant life ratings. In our prior paper on this topic (https://doi.org/10.1002/we.2883) we showed that resultant lives may be calculated in stages, rather than needing to combine across all cases and conditions in one go. At this stage of the paper we are therefore combing bearing lives associated with each time-step of a single simulation, into a single resultant bearing life for that simulation. In this instance, a bearing life associated with each time step in the simulation was calculated, and each of those persist for the same amount of time (one timestep). Hence, they all have equal weighting. Later in the analysis, these rating lives are further combined using Weibull distribution and wind rose weightings, so the equal-weighting comment only applies to this first step to go from lots of timesteps in a simulation to a single resultant bearing rating-life for that simulation. We will review out discussion of this in the manuscript when revising, to see if these points can be clarified.

10. The information about the bearings is limited to lines 186 to 193 and table 1. Please provide more details such as type of bearings, general dimensions, Value X and Y (dynamic radial and axial load factors), and manufacturer design code.

We will seek to provide further details of the bearings themselves in the revised manuscript. Note, off the shelf bearings are not generally suitable for application in such a large wind turbine, and technical specifications for more bespoke commercial offerings are not publically available. The bearings analysed in the current work were therefore shared by project partners in the Offshore Renewable Energy Catapult, who developed a drivetrain design as part of a benchmarking study for a commercial project. As the detailed design and study results from that commercial project are proprietary, some details may not be shareable. We will however include what we can. We would also point out that the current analysis is mostly concerned with the “relative” impacts of waking, which can be shown to remain the same even if the bearing dynamic rating changes. We will elaborate on that point too when revising the manuscript, as it helps demonstrate a broader generalisability for our results.

11. In line 194, 5D is considered for the downstream distance between turbines. Because this value will be fixed for the whole simulation in parametric analysis, it needs to be referenced and justified.

We determined that 5D was a fair representation of typical distances between turbines. In our analysis, we did include 3D and 4D spacing. However, we felt the trends revealed in the 5D analysis were representative. In other words, the presence/location of a partial wake is much more influential than its exact magnitude. We will add further discussion of this when revising the paper, and a reference to justify 5D as a reasonable nominal value.

12. In line 198, three different wind speeds are assumed. None of them are rated or cut-out wind speeds. It is not clear to readers how these wind speeds were chosen.

These wind speeds were chosen to represent different regions of the turbine’s power-curve. We will add this clarification into the revised manuscript.

13. In line 200, it is mentioned that the simulation was 2000 s and 1000 s is discarded. There are two notes in this item. First, what is the reason for doing a 2000-second

simulation? To my understanding standard proposes a 10-minute simulation. Second, 1000 s discarding means putting away half of the data. If one discards half of the data, do the turbulence intensity and the characteristics of the wind remain untouched? Please ensure wind field characteristics remain consistent post-discard.

We will add to the text to explain that the 1,000 second simulation times were done to edge on the side of more data, as opposed to the standard 600 seconds that is a standard amount. The burn-in perdiods were selected to ensure that the flow simulation had developed for several flow passthroughs before recording the relevant measurements. Discarding burn-in period data ensures the targeted wind field characteristics are representative, by removing earlier transients which would diverge from those which are being sought. As such, wind characteristics are preserved by this process.

14. In section 3.2, it is not clear what the wind characteristics are. Please include a table describing wind and site conditions.

Thank you for this suggestion. We will include these characteristics as a table, and provide some additional explanation.

15. In section 3.3, the questions about simulation time (comment 13) are valid. The questions are more significant for 6 and 8 m/s.

We will add text to explain that the simulation must be “spun-up” for enough time for the wake of the front turbine to propogate to the back turbine and that, for the 32 wind turbine case, the 2,000 seconds were necessary for this propogation to be achieved for the 6 and 8 m/s inflow cases.

16. In section 3.3, it is not clear what wind characteristics are besides an annual mean wind speed.

In the wind farm analysis the full wind rose is represented. There are therefore directional proportions, a Weibull distribution in each sector, and simulations performed across wind speed values from 4 to 24 m/s. A constant turbulence intensity of 5% and a power law shear coefficient of 0.2. We will consider whether any of the above information could be better highlighted in this section.

17. In Fig. 2b, a matrix of 32 turbines is considered in a symmetric pattern. Because of a symmetric pattern, even with consideration of different flow angles, it seems 16 turbines are enough. Please explain more about using 32 wind turbines and justify this assumption.

The TotalControl wind farm is a standard benchmark that we did not invent. While there are certainly symmetries present, which might allow for computational cost savings in some contexts, we do not see how one could obtain the same results as in our reported analysis using only 16 wind turbines – especially given that we simulate about the full wind rose. Outside of possible computational savings, we do not see further benefit from seeking to reduce the number of turbines simulated.

18. In Fig. 2b, there is no information about the arrangement and distances of the turbines. Also, out of curiosity, is there any reason to start turbine numbers from 0? It is suggested to add a table of turbine coordinates and naming conventions to make the layout traceable.

The utilised wind farm is a literature reference farm, the TotalControl standard wind farm, which has a standard definition (including arrangement, distances between all turbines etc) available via the reference provided in the text. We will check to ensure the standard nature of the utilised wind farm, and the link to its data and info, are prominent in the text of this section – along with key wind farm info such as turbine separation in x and y.

19. In line 215, equal weighing is used in rating life for turbulent wind model conditions. How do the authors justify such an assumption by considering variability in shaft speed due to the turbulence regime?

Combining across turbulent seeds is the second step in the process of combining rating lives. Step 1 was to turn each individual simulation into a single resultant rating life. It is in that step that rotational speed variations are accounted for, by converting each L10 life to units of time (accounting for rotational speed) and then combining. At the level of turbulent seeds, we are accounting for natural variability in the resultant rating life arising for any individual simulation at a given mean wind speed. It follows that we combine these resultant lives using equal weightings, since none occurs "more" than the others in this context.

20. According to Fig. 4, the life results for the bearings for both turbines are in a different order. How do the authors describe such a phenomenon? Is the assumption of the taking loads by the front bearing reasonable? It should be noted that the bearings have the same order of radial dynamic load rating, and when the life has a different order, it shows a different order of loads.

We assume you are referring to the relative difference in rating life between the two main bearings for the unwaked front turbine. This is driven by the fact that the rotor-side bearing reacts axial and radial loads, and the generator-side bearing only reacts radial loads. As a result the upwind bearing sees considerably higher loads, and also loading with differing qualitative characteristics due to the design of the turbine aerodynamic thrust curve (which peaks near where rated power is first reached). Yes, axial load reaction by the front bearing is one of the possible configurations which has been applied in practice. Note, due to effects related to thermal shaft expansion, only one of the main bearings may be axially supporting. Concerning your final point, yes we agree, and as above this stems from the rotor-side bearing seeing both axial and radial loads, with the former being significant.

21. Interestingly, the trend of the basic rating life of the bearing in the rotor and generator side regarding the wind speed in front turbine is different. The life of the rotor side at 7.5 m/s is higher than 11 m/s. On the other hand, on the generator side, the bearing life at 7.5 m/s is almost half of the other wind speeds. It would be valuable if the authors discussed more about this happening.

This effect you describe appears (unless we're looking at the wrong part of the plot) to only manifest for large value of Back Turbine Offset. In such cases there is little or no wake impacting the downstream turbine, and we can see that in those cases the results tend towards those seen for the front (unwaked) turbine. Hence it seems this is again an observation of your observation in point 20, above. We will consider if any of these effects would benefit from further discussion in the manuscript.

22. The results in Fig. 4 show the difference between the life of the bearings in front and back turbines. It would be useful to present the average power in the same figure, as maybe less power is one of the reasons behind the shorter life of the bearings.

We will consider whether power results here might provide valuable additional context to this figure. It might help highlight that there is a trade-off here between increased power capture under partial waking (relative to a full wake) and main bearing design lives. We don't quite follow your second point, and can't see why reduced power might lead to a shorter bearing life? Irrespective of this, we'll consider these points and seek to enhance the discussion of these results in the manuscript.

23. In line 257, the standard grid spacing claim needs a reference.

We'll add a source for this, thanks for point out that there currently isn't one.

24. Please add the illustration of the wind rose used in Fig. 5a. It can be added in Fig.3.

This is a great suggestion! We'll certainly do this.

25. In line 267, it is observed that the basic rating life always decreases in the bearing, while in a few specific conditions in the parametric study, the life increases. To have a fair claim, the condition of the turbine in spacing and wind conditions should be the same.

We feel this is a reasonable claim to make based on what we have shown in the paper, but perhaps we can improve on the wording a little… we'll revise this sentence to read: "Therefore, while it has been shown that some specific conditions can result in rating life increases (see Fig. 4), the more commonly observed life-reducing cases appear to dominate overall"

26. Typing error in line 37: Redundant Kenworthy et al.

Thanks, this has now been sorted.