

Reply to Reviewers

Manuscript ID WES-2026-116

Title: Effects of atmospheric thermal stratification on wake aerodynamics
of a regenerative wind farm unit

General overview

We sincerely thank the two reviewers for dedicating their time and expertise to reviewing our work. We are very pleased that both reviewers expressed a positive overall assessment of the manuscript and acknowledged the value of our work. Below, we provide point-by-point responses to all comments and suggestions, together with detailed descriptions of the corresponding revisions made to the manuscript. We believe that these revisions have adequately addressed the reviewers' concerns and suggestions, while also improving the clarity of the manuscript and strengthening several aspects of the analysis.

Reply to comments from Reviewer #1

Comment #1&2:

- 1. Introduction: MRSL appears to be a specific design within the broader family of RGWFs, which can employ different flow mechanisms to enhance wake recovery. This distinction should be made clearer throughout the manuscript.*
- 2. Introduction: Beyond the use of lifting devices, the multi-rotor configuration itself is a non-conventional design choice. Please briefly explain in the introduction why this design is preferred over a conventional wind farm layout;*

Reply:

We thank the reviewer for suggesting that these points be further clarified from a reader's perspective. In response, we have added an additional paragraph at the end of Introduction, as follows: "Finally, it is worth noting that the MRSL is not the only possible realization of the RGWF concept. At its core, RGWF aims to enhance the transport of higher-momentum flow from above the wind farm toward the turbines

located at lower altitudes. In this sense, the flow above a wind farm can be regarded as an energy reservoir available for vertical entrainment, and RGWF seeks to exploit this reservoir more effectively than conventional wind farms. Accordingly, any design capable of inducing large-scale flow structures that enhance such vertical transport may be regarded as part of the broader RGWF family. The MRSL represents one particularly practical realization of this concept, as the large wings used to generate streamwise vortices can be naturally integrated into the supporting structures of a multi-rotor system. Nevertheless, other implementations are also possible. For example, large-scale wing structures could be installed between conventional three-bladed horizontal-axis wind turbines in an existing wind farm, an approach investigated by Li et al. (2026b).. Such an implementation, however, would require additional supporting and foundation structures, potentially increasing its structural complexity and associated costs compared with the current integrated MRSL design.”

Comment #3:

Methodology: Neglecting Coriolis effects is a relevant simplification, particularly for the stratified flow case. Do the authors expect this to affect their findings? Please add a brief discussion of this point to the manuscript.

Reply:

We thank the reviewer for raising the important question of the possible influence of Coriolis effects on the wake aerodynamics of the investigated RGWF unit. We agree that this is a relevant and interesting aspect from the perspective of wind-farm operation. However, based on the present simulations and our current knowledge, it is difficult to provide a definitive assessment of the role of Coriolis effects.

We expect that Coriolis-induced effects, particularly the associated vertical wind veer, would not eliminate the beneficial influence of the lifting devices, since the accelerated wake recovery observed in the present study is primarily driven by strong advective transport induced by the generated vortical motions. This expectation is also partly supported by the observation that vertical velocity shear has only a limited influence on the streamwise swirling motions generated by the lifting devices (i.e., concept of RGWF works under both CBL and SBL). Nevertheless, the interaction between these

engineered flow structures and Coriolis-induced veer may quantitatively modify the wake development. A dedicated set of simulations including Coriolis forcing would therefore be required to assess these effects rigorously and is left for future research.

In response to this comment, we have slightly revised the final paragraph of the concluding section to explicitly identify the inclusion of Coriolis effects as an important direction for future research. The most significant one reads as “However, substantial research is still required before RGWF can become commercially viable, especially since the current work employs significant simplifications, such as omitting Coriolis effects.”, in which the part mentioning Coriolis effects are newly added text.

Reply to comments from Reviewer #2

Request #1:

Looking at Fig. 6, especially for the stable case, there appears to be a significant negative deficit, i.e., an acceleration of the flow, which reaches the lower part of the "rotor" starting at 6D in the DW case. This is quite interesting because it would imply a hidden benefit for downstream devices with down washing. However, when I looked at Fig. 15, somehow this advantage is not there or is washed out with the variable ξ . I think that the reason might be the limits of the y-integration in Eq. 12. Extending the calculation to 5D laterally is excessive because the available power that truly matters is just that going through the rotor. The reasoning that "wind direction changes continuously in a wind farm" is not really applicable in this case because the wind direction did not change at all in these simulations. Plus, again, even if the wind direction changes, the MRS� would always face the wind, thus only the lateral extent of $\pm 0.5D$ matters. I kindly request that you re-evaluate Eq. 12 and Fig. 15 using a more realistic range of $\pm 0.5D$ for the the y-integration. I suspect that the DW case will appear more appealing this way. This modification will affect Table 2 also.

Reply:

We thank the reviewer for raising this concern and for suggesting the additional analysis.

Upon revisiting the manuscript, we realized that our original explanation did not sufficiently clarify the rationale for selecting $-2.5D \leq y \leq 2.5D$, rather than $-0.5D \leq y \leq 0.5D$, as the lateral integration range. Our intention is to evaluate the aerodynamic influence of the MRSL in the context of wind farm deployment, where successive rows of MRSLs are not necessarily aligned with one another relative to the instantaneous inflow direction. Accordingly, we selected a lateral range corresponding to the lateral spacing adopted in the RGWF layouts investigated previously, namely $5D$. We have therefore rewritten the second paragraph of Section 6.6 to make this motivation clearer. For this reason, we retain $-2.5D \leq y \leq 2.5D$ as the principal integration range used in the manuscript.

The revised paragraph currently reads as “The selected lateral extent used to evaluate Ξ follows the RGWF layout investigated by Li et al. (2025d), in which a lateral spacing of $5D$ was adopted between adjacent turbine columns. Rather than restricting the analysis to the area projected by a single MRSL ($-0.5D \leq y \leq 0.5D$), a wider lateral extent corresponding to this spacing is considered to better capture the aerodynamic effects relevant to wind farm operation. As the wind direction varies, the apparent wind farm layout relative to the incoming flow changes accordingly (Wu and Porte-Agel, 2015), such that downstream machines are not necessarily aligned with their upstream counterparts in the flow direction. Consequently, even wake regions substantially displaced from $y = 0.0D$ may still significantly affect downstream machines. Evaluating Ξ over a wider lateral range, such as one corresponding to the lateral spacing between adjacent turbine columns, may therefore provide a more representative assessment of the aerodynamic influence of the wake in the context of wind farm operation than restricting the evaluation to $-0.5D \leq y \leq 0.5D$. Nevertheless, results obtained using the narrower range of $-0.5D \leq y \leq 0.5D$ are provided in Appendix F for completeness. Finally, although a lateral spacing of $5D$ is somewhat smaller than that commonly employed in present-day wind farms (Bosch et al., 2019), the accelerated wake recovery enabled by MRSLs may permit denser turbine spacing to become economically favorable.”.

Nevertheless, we fully agree that evaluating the available power over $-0.5D \leq y \leq 0.5D$ is also physically meaningful, since this range corresponds directly to the lateral extent of a single MRSL, acting as a characteristic scale. In response to the reviewer’s suggestion, we have therefore repeated the analysis presented in Section 6.6 using this narrower integration range. Following the structure of Eq. (12), we define the corresponding quantity as

$$\Xi_{\pm 0.5D}(x) \equiv \int_{z_b}^{z_t} \int_{-0.5D}^{0.5D} 0.5 \rho [\overline{u(x, y, z)}]^3 dy dz$$

and the resulting values are shown below in Fig. S1, a revised version of Fig. 15.

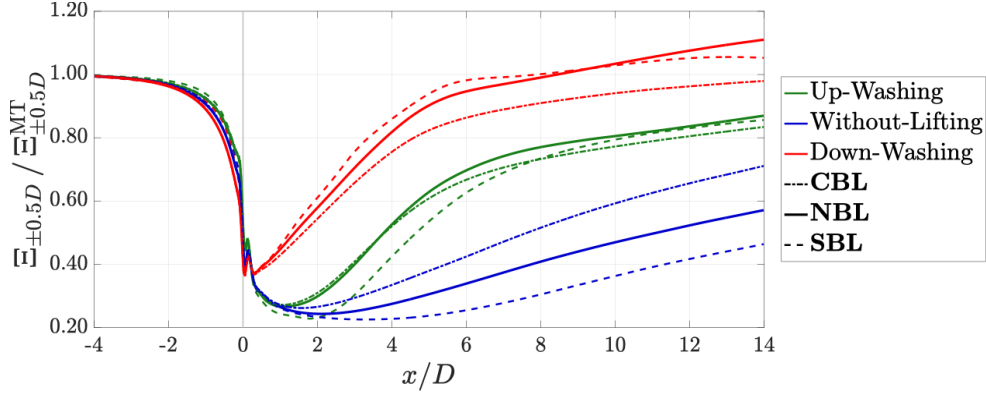


Fig. S1: Same as Fig. 15 but plotted with $\Xi_{\pm 0.5D}(x)$. That is, confining the lateral extent from $-2.5D \leq y \leq 2.5D$ to $-0.5D \leq y \leq 0.5D$. This figure is now included in the manuscript as Fig. F1.

As anticipated by the reviewer, when the lateral extent is restricted to $-0.5D \leq y \leq 0.5D$, the DW configuration becomes the most favorable of the three configurations. This result is consistent with the locally accelerated flow observed in Fig. 6, particularly under the neutral and the stable conditions. However, we note that part of this apparent advantage arises because the DW configuration redistributes the low-momentum wake laterally away from the regions close to $y = 0.0D$. While this is beneficial for a downstream MRSL located directly behind the upstream unit, the laterally displaced low-momentum region may still affect other downstream devices in a wind farm configuration, particularly when successive rows are laterally offset relative to the inflow direction.

For this reason, we consider the wider integration range to be more representative of the overall aerodynamic influence of an MRSL in the wind-farm context considered in this study, whereas the results of $\Xi_{\pm 0.5D}$ provide a complementary, device-centered perspective. To keep the discussion in the manuscript focused, we have therefore retained the wider-range analysis as the main metric. Nevertheless, for completeness, we have added the analysis based on $\Xi_{\pm 0.5D}$ to Appendix F, including the corresponding results and discussion presented in this response.

Request #2:

Similarly, I suspect that the benefits of the UW case might be over-estimated by considering such a high vertical extent in the integrals in Eqs. 9: why go as high as $3D$? For the practical purposes of generating power, again, only the vertical extent of the rotor matters. Who cares if there is a high wind speed deficit above the farm? (I mean for power generation only purposes; obviously it matters for boundary layer alterations). I would prefer to see results in Fig. 7 that are limited to $1D$ in the vertical (thus integrate from 0 to $1D$ in Eqs. 9 instead of $0-3D$).

Reply:

We thank the reviewer for raising this point and for giving us the opportunity to clarify the purpose of the integration range adopted in Eq. (9).

We would like to clarify that the quantity defined in Eq. (9) is not intended to quantify the power directly available to a potential downstream rotor. Rather, it is introduced to determine the wake center position of a standalone MRSL based on the spatial distribution of the velocity deficit. For this purpose, the integration domain should be sufficiently large to encompass the entire wake, particularly because the lifting devices can substantially displace the wake in the vertical direction. As shown in Figs. 4 to 6, the wake, especially for the UW configuration, can extend well above $z = 1.0D$. Restricting the integration to $z_b \leq z \leq z_t$, namely $0.1D \leq z \leq 1.1D$, would therefore truncate part of the wake and could bias the calculated wake-center position. The selected range, including an upper bound of $z = 3.0D$, was chosen to ensure that the relevant wake region is adequately captured. We have therefore retained the original integration range in Eq. (9) and we hope that these clarifications better explain the rationale for the vertical integration range adopted.

We also agree with the reviewer that, if the objective were specifically to evaluate the power available to a downstream rotor, the flow within the rotor-relevant vertical extent would be of primary interest. However, the velocity field above the nominal rotor region is also relevant to the broader RGWF concept, particularly when multiple rows of MRSLs are deployed. The key idea of RGWF concept is to promote the transport of higher-momentum flow from above the wind farm toward the turbines situated in the

lower altitudes, thereby enhancing energy replenishment within the farm (see Fig. 16 and the corresponding discussion). Therefore, if the flow above the RGWF is substantially depleted by the wakes of upstream devices, the regenerative capability of the farm may be weakened, since the flow entrained downward would contain less kinetic energy available for extraction by downstream devices. Put simply, the flow above a wind farm can be regarded as an energy reservoir for vertical entrainment, and the RGWF is designed to exploit this reservoir more effectively than a conventional wind farm. Thus, if the reservoir is depleted, the concept of RGWF is not likely to work.

Comment #1:

Why are the three cases starting at 0.3 in Fig. 7 (middle)?

Reply:

We thank the reviewer for carefully examining our results. There are two main reasons why $|y|^{WC}/D$ starts at approximately $0.3D$ for all twelve cases.

First, $|y|^{WC}/D$ does not start from zero because Eq. (9) is formulated using the absolute value of the lateral coordinate, $|y|$. Therefore, $|y|^{WC}/D$ represents the deficit-weighted mean absolute lateral distance from the centerline, rather than the signed lateral position of the wake center. Consequently, even for a laterally symmetric wake, $|y|^{WC}/D$ remains non-zero. If $|y|$ in Eq. (9) is instead replaced by the signed coordinate y , i.e., by defining

$$y^{WC} \equiv \frac{\int_{0.0D}^{3.0D} \int_{-2.5D}^{2.5D} y \bar{u}_{\text{Deficit}} dy dz}{\int_{0.0D}^{3.0D} \int_{-2.5D}^{2.5D} \bar{u}_{\text{Deficit}} dy dz},$$

the resulting signed wake-center position remains close to zero for all cases because of the lateral symmetry of the MRSL and its wake. This behavior can be directly observed in the middle panel of Fig. S2.

Second, the fact that $|y|^{WC}$ starts at a similar value of approximately $0.3D$ for all three configurations reflects the relatively similar lateral distributions of the velocity deficit in the near-wake region. This similarity can be seen directly in Fig. S3. As the wakes develop further downstream, the different vortical motions induced by the lifting-device configurations progressively modify the lateral deficit distributions, leading to the divergence among the twelve curves shown in Fig. 7.

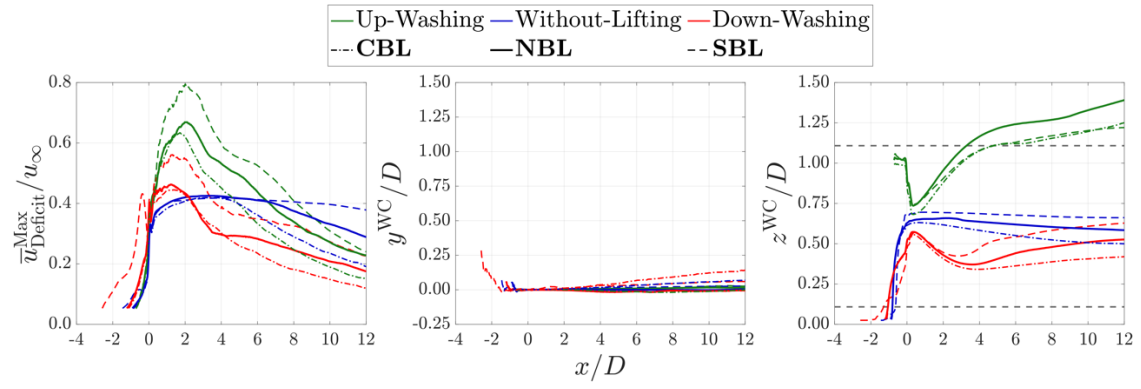


Fig. S2: Same as Fig. 7 but replaces $|y|^{\text{WC}}$ with y^{WC} and broadens the range for x , making it starting from $x/D = -4.0$.

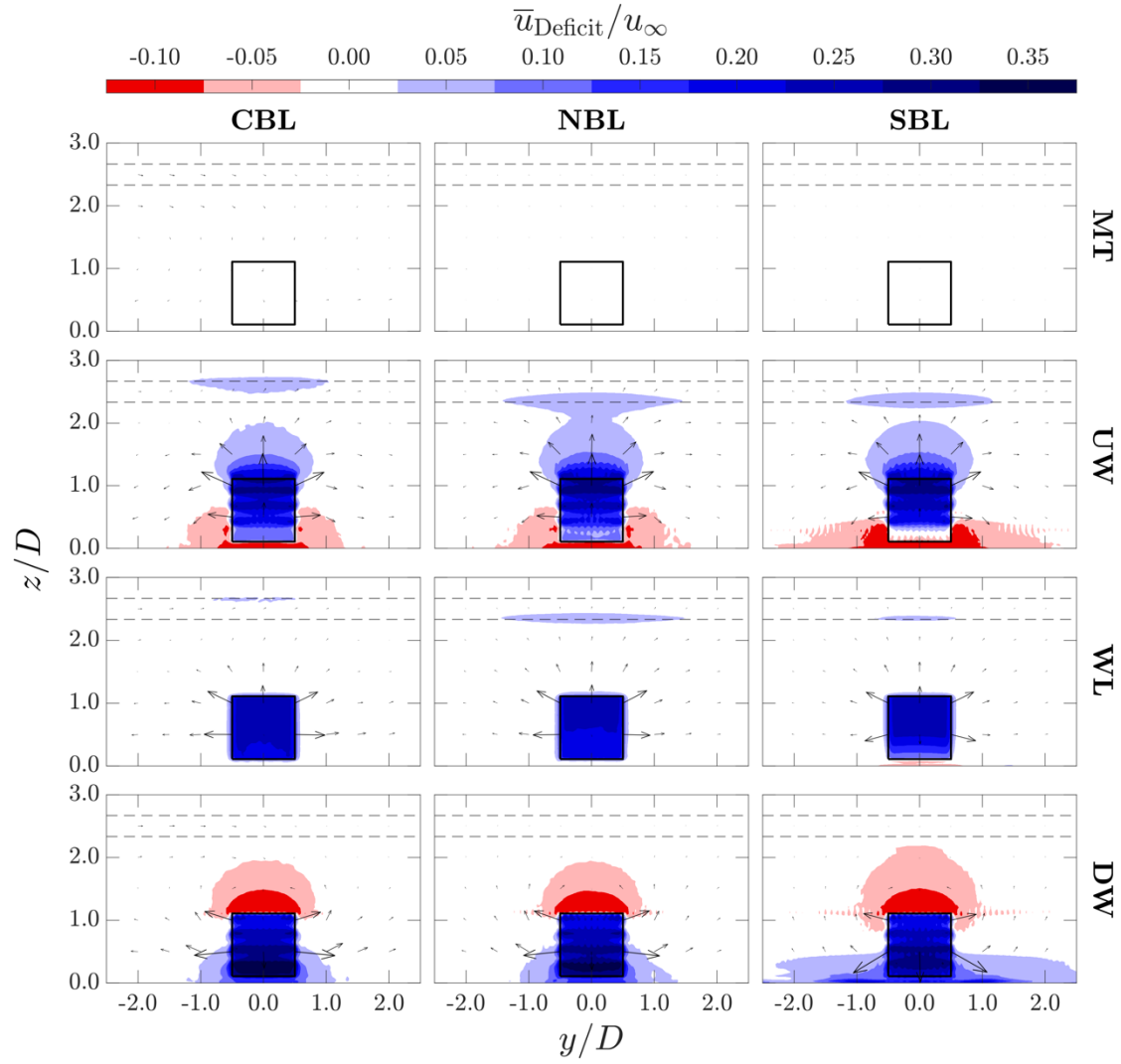


Fig. S3: Contours of the time averaged velocity deficits at $x/D = 0.0$ for the 12 cases.

Comment #2:

Why does the wake center first rise and then drop in the DW case, and vice versa in the UW case, in Fig. 7 (right)?

Reply:

We thank the reviewer for carefully examining our results and for raising this interesting question. We had also noticed this behavior during our analysis, but decided not to discuss it in detail in the previous version of manuscript because its physical interpretation is not yet sufficiently clear and such a discussion could distract from the main focus of the present work.

To provide a more complete picture, we have extended the wake-center results further upstream, as shown in the right panel of Fig. S2. It can be seen that the vertical wake-center positions already differ considerably among the configurations. However, these values should be interpreted with caution. As shown in the left panel of Fig. S2, the velocity deficit is still relatively small in this region. Consequently, the deficit-weighted wake-center position becomes sensitive to relatively small variations in the velocity field, and its physical interpretation is therefore less robust.

For this reason, we consider the wake-center position to be more physically meaningful after the pressure-recovery process has largely ceased, which approximately corresponds to the streamwise location where the maximum velocity deficit reaches its peak. Beyond this region, the velocity deficit is sufficiently developed for the wake-center metric to provide a more representative indication of the overall wake displacement. This downstream region is also of greater practical relevance when considering interactions with subsequent MRSLs in a wind-farm configuration. We have added this clarification to the second paragraph of Section 6.2, reads as following: “Here, it should be noted that interpretations based on the wake-center positions are most meaningful after the pressure recovery process has ceased, which is typically identified as the streamwise location where $\bar{u}_{\text{Deficit}}^{\text{Max}}$ reaches its peak according to the classical actuator-disk theory (Manwell et al., 2010). Prior to this location, $\bar{u}_{\text{Deficit}}$ remains relatively small as the wake continues to decelerate, making the deficit-weighted wake-center positions less representative of the developed wake.”

Regarding the specific reason why the wake center initially rises and then drops for the DW configuration, while exhibiting the opposite tendency for the UW configuration, we cannot provide a definitive explanation based on the present analysis. We suspect that this behavior may be related to the resulting induced velocity field due to the bound circulation system of the lifting devices. However, further dedicated analysis would be required to confirm this interpretation, and we therefore prefer not to draw a firm conclusion at this stage.

Other remarks:

We have made couple of typos when it comes to the conversion between the turbulent kinetic energy (TKE) and the turbulent intensity (TI), which have now been corrected (see Eqs. (1), (7), and (11)). Note that these mistakes are merely typographical errors, they had been correctly handled numerical wise.