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Enhancing Wind Farm Efficiency Through Active Control of the Atmospheric Boundary Layer's Vertical Entrainment of Momentum

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Abstract.
In contemporary wind farm design, the primary focus has traditionally been on reducing wake interference to optimize energy capture from horizontal wind flows. However, with the scaling up of wind farms, their interaction with the Atmospheric Boundary Layer (ABL) evolves, making vertical entrainment the main mechanism for the exchange of momentum and energy. This study introduces a methodical approach to augment the efficiency of large-scale offshore wind farms by actively controlling this vertical entrainment of momentum within the ABL. The strategy involves the precise engineering of advection fluxes to alter wind flow dynamics, utilizing turbines as effective vortex generators, toward a process of "regenerative wind farming." This setup aims to create a vorticity and vertical flux system akin to those observed in highly unstable ABLs. Expanding upon previous studies that focused on single Vertical Axis Wind Turbines (VAWTs), our research explores the implementation of multi-rotor systems equipped with lift-generating wings. These systems are designed to exert forces perpendicular to the prevailing wind direction, thus creating trailing vortices and directing the flow orthogonally for improved vertical advection. This research is part of a comprehensive investigative framework that combines experiments and multifidelity simulations. The current study extends those findings to wind farm simulations, aiming to assess the impact of ABL control on a full wind farm scale. The first part of the work validates an established analytical wind farm performance model against real wind farm data for thirty-one wind farms in the North Sea and Baltic Sea. The results confirm the predicted trend of decreased performance with increased wind farm size and density. The model is used to calculate the performance of a wind farm for varying regimes of vertical entrainment due to the creation of large-scale circulatory systems. The results are compared against 3D vortex simulations of the full wind farm in "regenerative wind farming" mode. Our results demonstrate a notable improvement in wind speeds at the turbine hub height and the potential to double the feasible density of wind farms without compromising efficiency compared to traditional setups. These findings suggest a promising pathway towards a more sustainable and profitable future in wind energy, achieved through the strategic manipulation of ABL momentum, regenerating the energy in the wind farm.

Keywords: Regenerative wind farming, vertical entrainment of momentum, infinite wind farm, wind farm efficiency, Atmospheric Boundary Layer control

1. Introduction

The increasing scale and density of vast offshore wind farms pose novel challenges in atmospheric interactions. Widn farms effectively approach "infinite wind farms," where their scale significantly surpasses typical Atmospheric Boundary Layer (ABL) scales. In such scenarios, the previously dominant undisturbed horizontal flow becomes secondary, and the interaction with the ABL shifts, making vertical entrainment the primary mechanism for momentum and energy exchange.

This has profound implications. The increased roughness due to turbine trhust results in lower wind speeds and wind farm efficiency, with potential decreases to below 50%. These effects have been demonstrated by [Calaf et al., 2010], [Dupont et al., 2018], [Frandsen, 2007], [Meyers and Meneveau, 2012], [Sørensen and Larsen, 2021], [Sørensen et al., 2021] and [Pryor et al., 2021], challenging the reliability, economic feasibility, and environmental sustainability of wind energy. With our current Horizontal Axis Wind Turbine technology, vertical entrainment relies predominantly on turbulent mixing. Consequently, techniques like wind farm layout optimization and wake control diminish in effectiveness within the heart of expansive "infinite wind farm" regions. Therefore, understanding and controlling the dynamics of vertical entrainment is imperative for ensuring the sustainable future of wind energy.

In response to these challenges and aiming towards vertical entrainment, we aim to actively engineer advection fluxes to manipulate the wind flow, driving wake-filled air upwards while simultaneously channeling high-momentum wind downwards. Our goal is to leverage turbines not merely as energy extractors but as vortex generators impacting airflow at the ABL scale, an approach we named "regenerative wind farming". This approach implies rethinking how wind turbines are envisioned and utilized. Our ambition is to design turbines that not only oppose the wind (drag force) to generate power but also create lift. Lift forces, perpendicular to the wind, would cause vertical deflection of airflows, thereby fostering our envisioned system of vertical advection. Conventional Horizontal Axis Wind Turbines (HAWTs) function primarily as actuator discs, opposing the wind direction to extract power. Their ability to exert forces in other directions is limited, achievable only when deliberately tilted or yawed. Previous research with Vertical Axis Wind Turbines (VAWTs) demonstrated that is possible to generate lift forces perpendicular to the oncoming wind. Such configurations allow for more controlled and effective vertical advection, channeling wakes and high-momentum flows in desired directions, as evidenced by experimental and CFD simulations [Huang, 2023].

Building upon this, we delve into the design of Multi-Rotor Systems equipped with a series of wings (Figure 1), strategically placed to generate necessary lift forces, thereby driving the vertical deflection of wakes. Two works presented in this conference by [Broertjes et al., 2024] and [Martins et al., 2024]. The two studies explore the performance and near-wake dynamics of a VAWT-based Multi-Rotor System (MRS) in both its baseline configuration and with external lift-generating devices for wake control operations. The wake of a scaled VAWT-based MRS (Figure 2) was measured in a wind tunnel using Particle Tracking Velocimetry, with lift-generating devices, including a 3-element cascading wing on top and a single-element wing in the middle of the MRS, enhancing wake control and deflection as consequence of the trailing vortical system (see Figure 3). Measurements revealed notable differences in wake behavior between configurations with and without these devices. Without them, the wake remained concentrated in the actuator surface's projected downstream area with minimal crossflow diffusion. Conversely, the configuration with lift-generating devices exhibited significant wake deformation, including axial expansion and lateral contraction, promoting streamwise momentum recovery, resulting in a significant increase in available power downstream compared to the clean MRS. OpenFOAM Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations were conducted for both turbine setups (see Figure 4) and validated against the experimental data. These simulations facilitate an in-depth analysis of wake advection, power gains, and momentum interactions within the ABL.

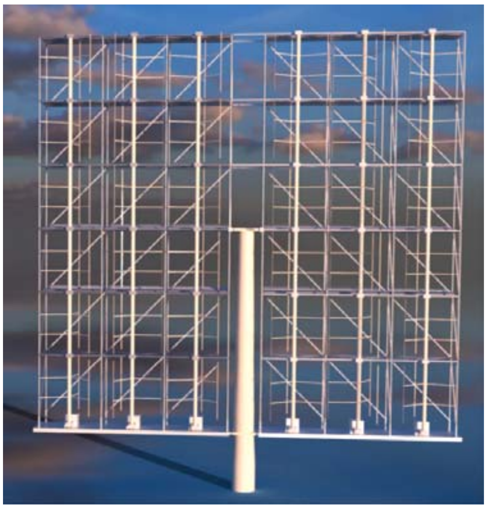

Figure 1. Concept of a Multi-Rotor System with Vertical Axis Wind Turbine Rotors and four wing systems for wake deflection and Atmospheric Boundary Layer control, from the work by [Distelbrink et al., 2023]

Figure 2. 3D Visualization of the Multi-Rotor System (MRS) with lift-generating wings. Full details in [Broertjes et al., 2024]

In this paper we extend the simulation work to full wind farm scale, first by a simplified 3D vortex model of the wind farm, capable of simulating the advection of the wind farm wake and ABL. Second, by using the extended infinite wind farm model by [Peña and Rathmann, 2014] to simulate the impact in an infinite wind farm, considering that the vortical structures and vertical flux of the controlled ABL are similar to those of a very unstable ABL. We further take this result to calculate the impact in wind farm efficiency as a function of wind farm density. The work of [Peña and Rathmann, 2014] is extended with the approach of [Sørensen and Larsen, 2021] to calculate the impact of capacity factor. The models used by [Sørensen and Larsen, 2021] and [Peña and Rathmann, 2014] are validated against real data of capacity factors of thirty-one wind farms in the North Sea and Baltic Sea. This result is also used to demonstrate the severity of challenge and the need for a disruptive technology.

2. Methodology

To analyze the advection of the wake and ABL influenced by vertical fluxes, we developed a simplified 3D model of a wind farm with multiple actuator surfaces. These represent the multi-rotor system with lift devices described previously. The lift system, oriented perpendicular to the wind, allows for multiple lift elements. The dynamics of trailing vortices, crucial to the overall wind flow within the farm, are comprehensively modeled. The simulation employs a simplified diffusion model, with a focus on advection processes as the dominant forces shaping ABL development. Our model was validated against higher-fidelity OpenFOAM simulations and wind tunnel experiments. The flow is advect in a lagrangian representation of the kinematics of particle tracers, representing the flow field and the trailing vortex systems. The momentum exchange at the actuators is represented by a change in the velocity field of a region of the flow containing the particle tracers that crossed the actuator. The code is implemented in OpenCL to run in graphical processing units. The primary aim of these simulations and validations was to analyze the velocity profile of the wind farm wake and

Figure 3. Render of the Multi-Rotor System (MRS) illustrating the wing configuration. This image also provides a visual representation of the trailing vortices generated by the wing tips, which will drive the vertical flux at both the wind farm scale and within the Atmospheric Boundary Layer. Further details are available in [Broertjes et al., 2024].

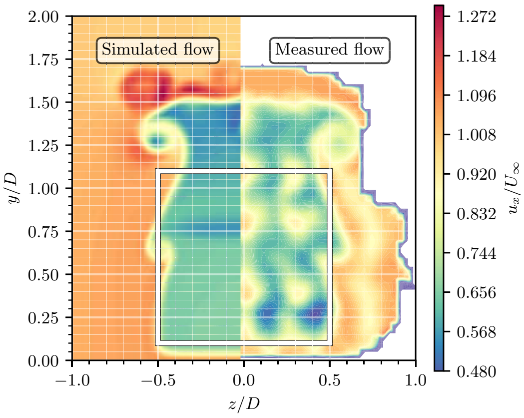

Figure 4. Simulated (left) vs. Experimental (right) velocity fields behind ABL-controlled setups with 2 wings, displaying u_x-velocity colored fields at $x/D = 1$. Setup with $C_T = 0.72$ and $C_W = 0.88$ (vertical loading), featuring two blades. Full work in [Martins et al., 2024]

ABL after extending 40 actuator heights into the wind farm. This analysis was critical for understanding how our simulated wind farm's wake and ABL development compare to those observed in unstable atmospheric boundary layers. A key aspect of this comparison was verifying the similarity of the vorticity mechanisms present in both systems. Although these mechanisms have different origins in our model and in natural unstable ABLs, identifying similarities helps in understanding the dynamics of wind farms and their interaction with the surrounding environment.

The analytical model of the wind farm performance builds upon the foundational model by [Frandsen, 2007] and its adaptations by [Sørensen and Larsen, 2021], our study further extends this modeling approach to encompass the dynamics of vertical momentum advection and its impact on momentum forcing distribution across the ABL. Initially, our model aimed to replicate the ABL's vertical momentum flux by uniformly distributing wind farm loading throughout the ABL's height. However, this method did not adequately address the alterations in the ABL's velocity profile caused by trailing vortices, a phenomenon analogous to the vorticity generated by baroclinic processes due to buoyancy loads in unstable boundary layers. This resulted in an underestimation of the velocity gain at wind turbine height. To address this, we integrated the methodology of [Peña and Rathmann, 2014], which delves into the role of atmospheric stability in wind farm performance and extends the Infinite Wind-Farm Boundary-Layer (IWFBL) model to include the effects of atmospheric stability. This advancement was achieved by incorporating a dimensionless wind shear parameter, based on the stability parameter z/L (where z signifies the height above the surface and L represents the Obukhov length, a key indicator of local atmospheric stability). This crucial parameter is instrumental in capturing the influence of atmospheric stability on wind behavior and efficiency in wind farm models, thereby allowing for a more precise representation of wind conditions

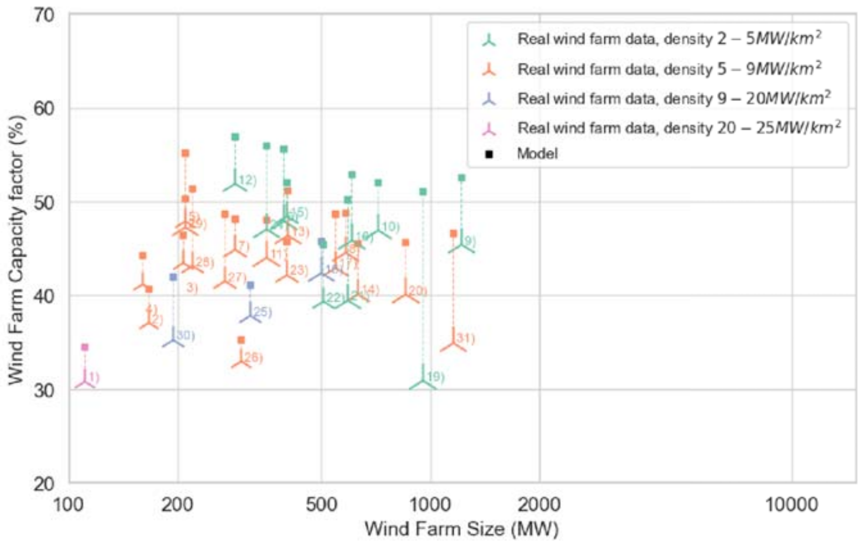

Figure 5. Validation of model predictions against real wind farm data for capacity factor. Colors indicate range of wind farm rated power density. Number labels identify wind farm, using legend in Figure 6.

and their impact on wind farm efficiency. Utilizing the extended model, we calculated the efficiency of the wind farm under varying power densities, following procedures outlined by [Sørensen and Larsen, 2021] and [Sørensen et al., 2021].

The data for capacity factor of real wind farms was calculated from energy generation data of the listed wind farms provided publicly by the *Office of Gas and Electricity Markets* (UK), *Danish Energy Agency* (Dk), *energy-charts.info* and *energynumbers.info*. The wind data is provided by the Global Wind Atlas database. The simulation model is the one developed by [Sørensen and Larsen, 2021].

3. Results and Discussion

3.1. Validation of wind farm performance model with wind farm production data

In this section we present the results of the comparison of the results of the model proposed by [Sørensen and Larsen, 2021] against the capacity factors of 31 wind farms in the North Sea and Baltic Sea. Figure 5 shows a comparison of the values of capacity factor predicted by the model and the real wind farm values. The x-axis indicates the wind farm size. The model over-predicts the real wind farm data. It is relevant to notice that the model does not account for losses due to operation and maintenance, losses in transmission, curtailment and other sources of loss of performance. The largest differences occur with wind farms that have experienced significant curtailment and other operational challenges.

Figure 6 presents capacity factor as a function of equivalent wind farm density, assuming wind farm size 10GW. In this result, the model of [Sørensen and Larsen, 2021] is used to extrapolate the real wind farm data to values for an equivalent wind farm with 10GW of installed capacity. The results are compared with the solution of an infinite wind farm in the North Sea, equipped with the IEA 15MW reference wind turbine. A curve with a 10% loss is also shown for reference. The results show that the values scaled from real data follow the theoretical trend, and the difference to the 10% loss curve can be related to wind turbines used and specific locations of each wind farm.

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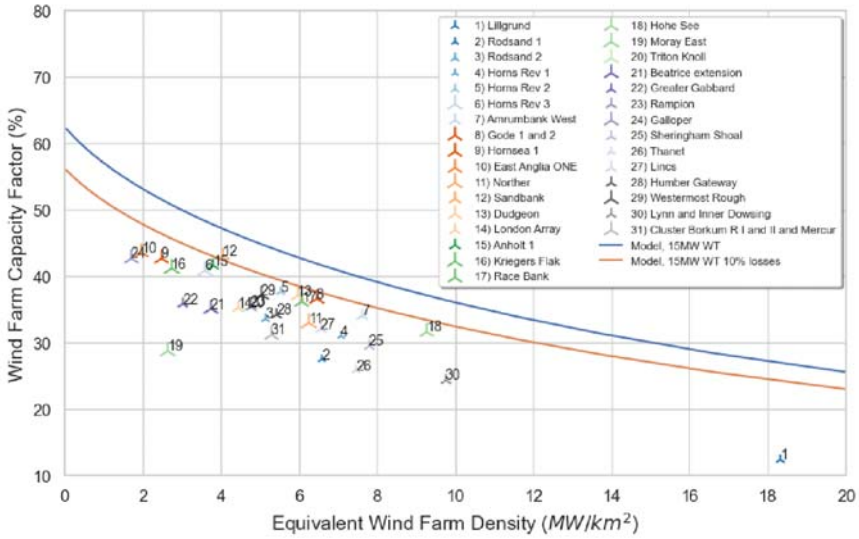

Figure 6. Capacity factor as a function of equivalent wind farm density, assuming wind farm size 10GW.

3.2. Results for the case of regenerative wind farming

In Figure 7, the modified Atmospheric Boundary Layer (ABL) profile is depicted, showcasing changes in the velocity profile beyond a distance of $x > 40D$, where D represents the reference length scale of the actuator. This alteration in the ABL profile is primarily attributable to the vertical flux induced by trailing vortices generated by the lift systems. The noteworthy aspect of this profile is its resemblance to those observed in unstable boundary layers, a similarity stemming from the vertical fluxes. These fluxes, although generated through mechanical means in our model, mimic the natural processes that occur in unstable boundary layers, leading to similar alterations in the velocity profile. This comparative analysis is significant as it provides an understanding of how engineered systems, such as our wind farm model, can replicate and harness natural atmospheric phenomena to optimize wind energy extraction and efficiency.

In Figure 8, we illustrate the Atmospheric Boundary Layer (ABL) profile as determined by our vortex model, which now accounts for both the impact of the lift systems used for wake deflection and the presence of actuators with a thrust coefficient (C_T) of 0.8. This configuration represents a more comprehensive scenario where both lift-induced wake deflection and the thrust forces from the turbines contribute to the ABL dynamics. The inclusion of a non-zero C_T value introduces an additional layer of complexity to the ABL profile, as it combines the effects of the vertical fluxes from the trailing vortices with the horizontal thrust forces. This combined effect creates a more nuanced and realistic representation of the ABL profile in the vicinity of a functioning wind farm. The figure demonstrates how the ABL is altered in response to the integrated impact of both vertical and horizontal forces, offering critical insights into the interaction between wind farm components and the surrounding atmospheric environment.

In Figure 9 we see the ABL profile as a function of stability length scale L calculated using the approach by [Peña and Rathmann, 2014], as an analogy the vertical flux due to the trailing vorticity system. We can compare these results to those of the vortex model to the observed ABL profiles. The figure illustrates how the velocity profile, influenced by trailing vortices and devoid of actuator thrust ($C_T = 0$), aligns with those observed in unstable boundary layers. This similarity supports the application of the Monin-Obukhov Similarity Theory

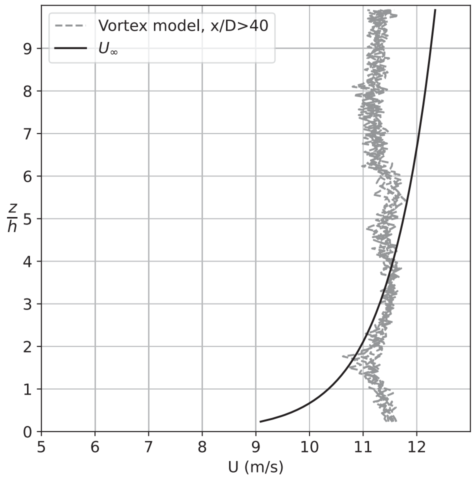

Figure 7. ABL profile calculated by the vortex model, accounting only for the effect of the lift systems for wake deflection but actuators with thrust coefficient $C_T = 0$.

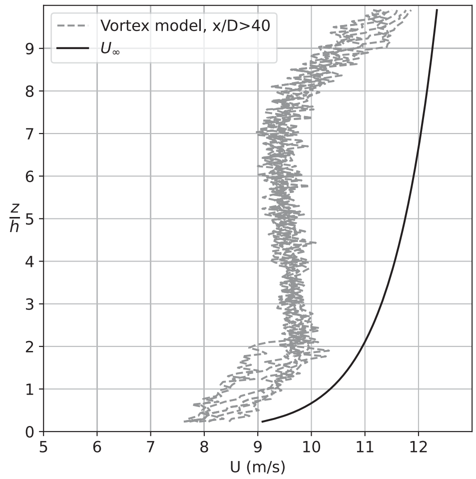

Figure 8. ABL profile calculated by the vortex model, accounting both for the effect of the lift systems for wake deflection and actuators with thrust coefficient $C_T = 0.8$.

(MOST) approach in our ABL model, utilizing it as a foundational concept for determining a range of mixing length scales. Although in our approach the vortices are lift-driven rather than buoyancy-driven, as typically seen in natural unstable ABLs, the resemblance in the velocity profiles validates our approach. The use of the MOST framework, adapted from [Frandsen, 2007] as modified by [Peña and Rathmann, 2014], provides a theoretical basis for understanding and quantifying the effects of these lift-induced vortices on the ABL. This connection reinforces the validity of using lift-driven mechanisms to replicate the dynamics typically associated with buoyancy-driven processes in unstable atmospheric conditions.

In Figure 10, we observe the Atmospheric Boundary Layer (ABL) profile which accounts for both the effects of trailing vortices and the presence of actuators with a specified thrust coefficient (C_T). This representation highlights how the ABL adapts when influenced by both vertical and horizontal forces.

When we compare this with Figure 8, which also includes actuators with a thrust coefficient ($C_T = 0.8$), a harmonious agreement in terms of the modified velocity profile is evident. Figure 8 demonstrates the comprehensive ABL profile under the influence of active thrust forces from the actuators, alongside the vertical fluxes caused by the trailing vortices.

The congruence between these figures is significant, as it indicates a consistent and realistic portrayal of the ABL's response to the combined effects of vertical and horizontal forces in a wind farm setting. The agreement in the modified velocity profiles across these figures validates the effectiveness and accuracy of the modeling approach in capturing the complex dynamics of wind farm interactions with the ABL. This consistency is crucial for understanding the full spectrum of ABL modifications and for optimizing wind farm design and operations to enhance efficiency and performance.

The results in Figure 10 extend to Figure 12, examining different turbine separation scales s. These results facilitate the calculation of a power density ratio U_h^3/U_∞^3 as a function of wind farm density, expressed by s, and varying scales of vertical ABL mixing, defined by the turbulent mixing length scale L.

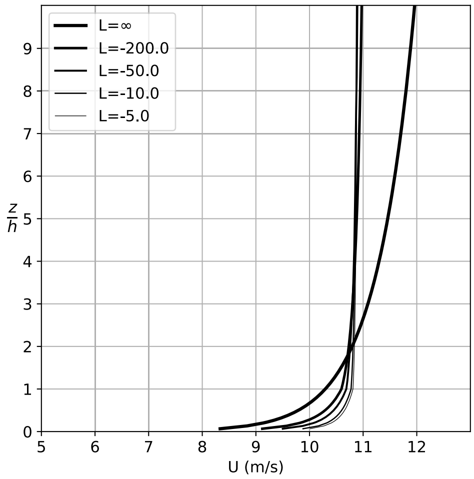

Figure 9. ABL profile as a function of stability length scale L calculated using the approach by [Peña and Rathmann, 2014], as an analogy the vertical flux due to the trailing vorticity system.

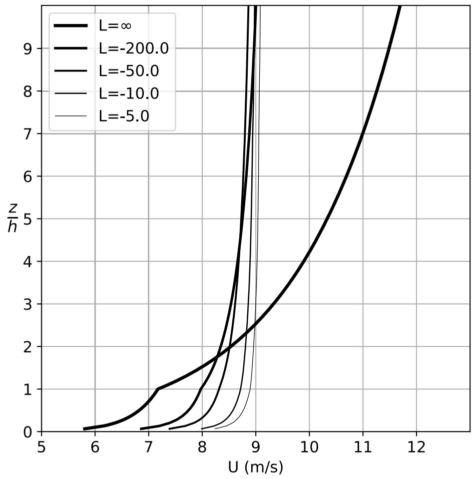

Figure 10. ABL profile as a function of stability length scale L, integrating the effects of trailing vorticity and actuators with thrust coefficient C_T.

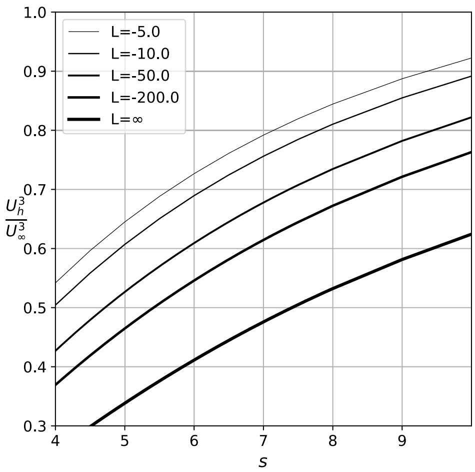

Figure 11. Efficiency as a Function of Density and Stability in the ABL.

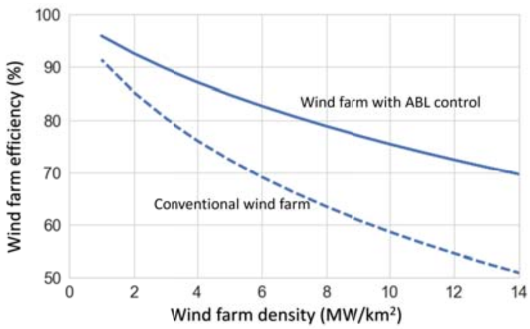

Figure 12. Comparison of wind farm efficiency as a function of power density between a conventional wind farm and one with ABL control.

Figure 12 compares wind farm efficiency as a function of power density for conventional wind farms and those with ABL control, following the procedure proposed by [Sørensen and Larsen, 2021]. The calculations assume rated power density of the actuator turbine of $330W/m^2$, hub height of $150m$, and diameter $240m$. Wind farm density is defined in MW/km^2 of rated capacity, with wind conditions akin to the North Sea, and reference wind speed of $10.4m/s$ at $100m$. The efficiency gains in Figure 12 result in significant increases in annual energy production.

4. Conclusions

This research aims to contribute to advancing the efficiency of large-scale offshore wind farms. Departing from conventional methods focused on horizontal wake interference, our study centers on the active control of vertical momentum entrainment within the Atmospheric Boundary Layer (ABL). Utilizing Multi-Rotor Systems with Lift-Generating Wings, we aim to replicate dynamics observed in highly unstable ABLs, albeit through different mechanisms. Our methodology demonstrates a notable improvement in wind speeds at turbine hub height and potential to increase wind farm density without sacrificing efficiency.

The relevance and need for "regenerative wind farming" was demonstrated by the collection of real wind farm data and validation of the analytical model proposed by [Sørensen and Larsen, 2021]. The results demonstrate the significant losses as wind farms become larger and denser.

The congruence between experimental, simulation, and analytical findings, especially concerning the three-dimensional vortex models and infinite wind farm models, underscores the robustness of our approach. However, it is essential to recognize the distinctions between our generated vorticity and vertical flux systems and those in natural unstable ABLs. The need for precise scaling of these phenomena highlights a direction for future research.

In summary, our study not only affirms the feasibility of enhancing wind farm efficiency through innovative ABL manipulation techniques but also lays a solid foundation for further research. The potential to significantly increase wind farm densities without compromising efficiency offers a promising path for the sustainable and profitable growth of wind energy. The alignment between our experimental, simulation, and analytical approaches serves as a benchmark for future studies in refining and scaling these models for practical wind energy applications.

References

[Broertjes et al., 2024] Broertjes, T., Bensason, D., Sciacchitano, A., and Ferreira, C. (2024). Lift-induced wake re-energization for a vawt-based multi-rotor system. In *Accepted for Torque 2024*.

[Calaf et al., 2010] Calaf, M., Meneveau, C., and Meyers, J. (2010). Large eddy simulation study of fully developed wind-turbine array boundary layers. *Physics of Fluids*, 22(1):015110.

[Distelbrink et al., 2023] Distelbrink, L., Fetecau, M., Gonzalez, L., Jemioł, B., Rizk, M. K., Tapia, M. P., Porcescu, I., Pudāns, J., Roth, J., and Tuğtekin, M. (2023). 30mw multi-rotor turbine block design - design synthesis exercise bsc aerospace engineering. Technical report, Delft University of Technology.

[Dupont et al., 2018] Dupont, E., Koppelaar, R., and Jeanmart, H. (2018). Global available wind energy with physical and energy return on investment constraints. *Applied Energy*, 209:322–338.

[Frandsen, 2007] Frandsen, S. T. (2007). *Turbulence and turbulence-generated structural loading in wind turbine clusters*. Doctoral thesis. ISBN: 9788755034587 Publication Title: Turbulence and turbulence-generated structural loading in wind turbine clusters.

[Huang, 2023] Huang, M. (2023). *Wake and wind farm aerodynamics of vertical axis wind turbines.* PhD thesis.

[Martins et al., 2024] Martins, F., Ferreira, C., and van Zuijlen, A. (2024). Numerical investigation of atmospheric boundary layer control in wind farms with multirotor systems. In *Accepted for Torque 2024*.

[Meyers and Meneveau, 2012] Meyers, J. and Meneveau, C. (2012). Optimal turbine spacing in fully developed wind farm boundary layers. *Wind Energy*, 15(2):305–317. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.469.

[Peña and Rathmann, 2014] Peña, A. and Rathmann, O. (2014). Atmospheric stability-dependent infinite wind-farm models and the wake-decay coefficient. *Wind Energy*, 17(8):1269–1285. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.1632.

[Pryor et al., 2021] Pryor, S. C., Barthelmie, R. J., and Shepherd, T. J. (2021). Wind power production from very large offshore wind farms. *Joule*, 5(10):2663–2686.

[Sørensen and Larsen, 2021] Sørensen, J. N. and Larsen, G. C. (2021). A Minimalistic Prediction Model to Determine Energy Production and Costs of Offshore Wind Farms. *Energies*, 14(2):448. Number: 2 Publisher: Multidisciplinary Digital Publishing Institute.

[Sørensen et al., 2021] Sørensen, J. N., Larsen, G. C., and Cazin-Bourguignon, A. (2021). Production and Cost Assessment of Offshore Wind Power in the North Sea. *Journal of Physics: Conference Series*, 1934(1):012019.