Energy entrainment from low-level jets benefits wind farm performance

Srinidhi Gadde and Richard Stevens[1]

[1] Department of Science and Technology, University of Twente

Low-level jets are the wind maxima in the lower regions of the atmosphere. Due to their significant influence on the power production of wind farms, it is crucial to understand the interaction between low-level jets and wind farms, which we study using large-eddy simulations. We find that the power production in the back of the wind farm is relatively high when the jet is above the wind farm. When the low-level jet is at turbine hub height, the production of the turbines in the back is limited. However, the production of turbines in the back is higher than anticipated when the jet flows under the wind turbines. The reason is that the negative shear of the jet creates a significant upward entrainment flux, which facilitates energy extraction from the jet by downstream turbines. While low-level jets are beneficial from the point of view of power production, our simulations also show that their presence induces significant cyclical variation in aerodynamic loading. This means that low-level jets increase the fatigue loading experienced by the turbines and this can negatively affect the turbine lifetime. Overall, our work underlines the importance of fundamental fluid dynamics research for the understanding of the flow dynamics in wind farms.

Introduction

Wind energy has been used for many different purposes since the Middle Ages, for, among other things, reclaiming land, sawing wood, and grinding grain. The Netherlands have a rich history and a leading role in its development, like, for example, the famous Kinderdijk. In recent decades, wind energy technology has undergone major developments. Today, wind energy is mainly used for electricity generation, and there is great interest in this technology because of its enormous potential as a clean energy source. To achieve the European climate targets, generating much more clean energy is necessary, and wind energy will play a crucial role in this development. However, to realize wind energy potential, many technological and scientific challenges remain. Here we discuss some of our recent work [2, 3] on modeling wind farm flow dynamics, showing the crucial role of fluid mechanics in this development.

Large eddy simulations of wind farms

Studying turbulent phenomena in the atmosphere is of fundamental importance for optimizing the design of wind farms and providing reliable production forecasts [4]. The flow in a wind farm is highly turbulent and strongly depends on atmospheric conditions. Figure 1 shows a visualization of the turbulent flow in a wind farm obtained from a large eddy simulation. The energy extraction by the wind turbines from the incoming flow creates wind turbine wakes, i.e. the low-velocity wind speed regions created behind the turbines. In the figure, these wind turbine wakes are visible as blue 'clouds' behind the turbines. The visualization shows the complex turbulent nature of the wind turbine wakes, which affects the performance of downstream turbines.

Figure 1: Flow visualization of turbine wakes from a large eddy simulation of a wind farm. Wind turbines extract energy from the incoming wind and produce a low-speed wake (blue smoke in the figure). Figure adapted from Gadde (2021) [1].

When downstream turbines operate in the wakes of the upstream turbines, their power production is reduced compared to turbines operating in free stream conditions. The reason for the lower power production, which is also known as 'wake effect', is the velocity deficit in the wake. Naively one would expect that the power production of turbines farther downstream in the wind farm continuously decreases as then there are more upstream turbines that harvest energy from the flow. However, after the first few rows, the combination of wake deficit and high turbulence intensity in the wake creates a downward turbulent entrainment that brings a high energetic flow from above the wind farm towards the wind turbine region. This vertical kinetic energy entrainment counteracts the wake effects and is beneficial for the power production of turbines farther downstream in the wind farm.

Influence of low-level jets on wind farm performance

Under typical atmospheric conditions, vertical kinetic energy transport in a wind farm is downward [5], pulling down the high-energetic geostrophic winds in the higher atmosphere towards the wind farm. However, the direction of this vertical kinetic energy flux depends on the wind shear in the atmospheric boundary layer. Typically, the wind shear at turbine height is positive, i.e. the wind velocity increases with height, which leads to the negative entrainment flux. However, atmospheric temperature variation, also known as thermal stratification, can give rise to negative wind shear situations under stable conditions. The effect of negative wind shear on entrainment flux in a wind farm is hitherto unexplored. Negative wind shear can be created in the atmosphere due to interesting lower-atmospheric phenomena such as low-level jets [6]. Low-level jets can be considered `high-speed atmospheric rivers', which are frequently observed worldwide [7, 8, 9]. Understanding the influence of low-level jets on wind farm performance is crucial as their strong winds provide a crucial contribution to the energy potential of a site. Figure 2 shows a typical low-level jet profile and the three main scenarios we consider, i.e. the low-level jet above, at the middle, or below the turbine rotor swept area. We studied these three scenarios in detailed large-eddy simulations [10], shown in Figure 2, which reveals that the flow physics for these three cases are pronounced differently.

Figure 3(a) shows the row-averaged power normalized by the first row's power production for the three cases. When the low-level jet is above the turbines ($z_{jet} > z_h$), the relative power production for turbines farther downstream in the wind farm is relatively high. The reason for this is the strong downward vertical kinetic energy flux that transports energy from the jet towards the turbines and thereby counteracts the wake effects. When $z_{jet} \approx z_h$, the power production continuously reduces towards the rear of the wind farm. The corresponding wake recovery shows that the velocity continuously drops in the downstream direction, which indicates that the wake recovery is negligible. Interestingly, when the jet is below the turbines ($z_{jet} < z_h$), the power production of the second row is severely affected due to the absence of turbulence in the wake of the first turbine row. However, the power production increases farther downstream due to wake-generated turbulence, and it shows an upward trend towards the back of the wind farm. For this case, the wake turbulence becomes significant behind the second turbine row, and subsequently, the turbines entrain high-momentum wind from the low-level jet below the turbines.

Energy budget analysis

To further understand the power production of downstream turbines, the planar-averaged vertical turbulent flux of streamwise momentum $\langle \overline{u'w'} \rangle$, normalized with the $\langle \overline{u'w'} \rangle$ value at the wall, is plotted in Figure 3(b). When the low-level jet is above the turbine rotor swept area ($z_{jet} > z_h$), there is a significant negative (downward) momentum flux, which extracts the jet's momentum and eliminates it towards the rear of the wind farm. However, when the low-level jet is below the turbines ($z_{jet} < z_h$), the turbines operate in the negative shear region, and a significant positive entrainment flux is created. As a result, the jet's energy is entrained towards the turbines, and the power production shows an upward trend towards the end of the wind farm, see Figure 3(a). In essence, when the low-level jet is below the turbine rotor swept area, the momentum deficit by the turbines in combination with the negative shear creates a significant positive turbulent flux from the low-level jet towards the turbines.

Essentially, we identified two main scenarios in which wake recovery is enhanced due to the entrainment from energy from the jet. For continuous production of turbulence, $\langle \overline{u'w'} \rangle (\partial \overline{u}/\partial z)$ should be negative, where $\partial \overline{u}/\partial z$ is the wind shear. Therefore, in the presence of positive shear ($\partial \overline{u}/\partial z$ is positive), $\langle \overline{u'w'} \rangle$ should be negative to produce turbulence. However, when the shear is negative ($\partial \overline{u}/\partial z$ is negative), $\langle \overline{u'w'} \rangle$ should be positive to sustain turbulence. The velocity deficit in the turbine wakes tends to create a positive entrainment flux below the hub height and a negative entrainment flux above the hub height. This leads to the following two scenarios:

1. When the low-level jet is above the turbine rotor swept area ($z_{jet} > z_h$), the low-level jet energy is pulled towards the turbines due to the momentum deficit created by the turbines. This creates a significant downward entrainment flux that benefits the production of turbines further downstream in the wind farm. In this case, $\langle \overline{u'w'} \rangle$ is negative, and the horizontally averaged $\partial \overline{u}/\partial z$ is positive, and this creates a net downward vertical flux towards the turbines.
2. When the low-level jet is below the turbine rotor swept area ($z_{jet} < z_h$), the high momentum low-level jet with the positive entrainment flux from below aid power production. The turbines extract the low-level jet energy transported by the positive entrainment fluxes. In this case, $\langle \overline{u'w'} \rangle$ is positive and the horizontally averaged $\partial \overline{u}/\partial z$ is negative. The negative shear created by the wind turbine wakes contributes to the negative shear already present above the low-level jet, which amplifies the effect.

An energy budget analysis of the turbulent entrainment flux over a control volume surrounding each turbine row provides the conclusive evidence of the phenomena described above. Figure 3(c) shows the development of the turbulent kinetic energy flux as a function of the positions in the wind farm. The solid lines represent the energy flux entering the control volume below, and the dashed lines represent the energy flux entering the control volume above. We can observe that the turbines operate in a positive shear region when the low-level jet is above the turbines. The downward flux is strong, and the vertical entrainment flux is enhanced in the presence of low-level jets. However, the net entrainment is severely limited when the low-level jet is in the middle of the turbine rotor swept area, which prevents turbines downstream in the wind farm from benefiting from the jet's energy. Furthermore, the figure shows that a positive entrainment flux is created when the low-level jet is below the turbine rotor swept area, i.e., in the negative shear region of the jet. This new mechanism extracts energy from the low-level jet. Figure 3(d) shows the integrated net entrainment flux as a function of the downstream location in the wind farm. The figure clearly shows that the energy entrainment from the jet is significantly higher for the cases $z_{jet} > z_h$ and $z_{jet} < z_h$ than when $z_{jet} \approx z_h$. In essence, we discovered an interesting turbulent phenomenon wherein the high-energy wind is pulled up (or down), aiding the wind farm power production, when the low-level jets are below (or above) the turbines. This hitherto unknown effect is critical for wind resource planning in areas where low-level jets events are frequent [2]. Therefore, installing turbines with heights slightly above the low-level jet height in wake recovery is advisable. Otherwise, the wake recovery of the downstream turbines is severely affected, increasing the so-called `wake losses.'

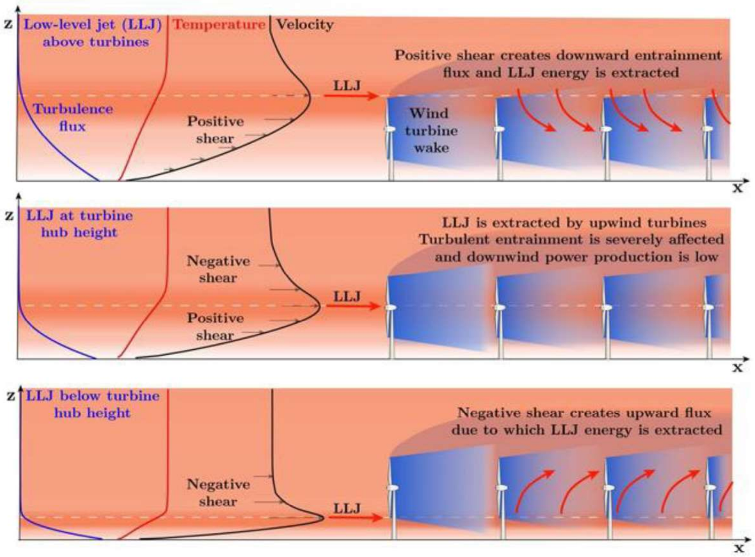

Figure 2: Schematic showing the interaction between a low-level jet, i.e. the wind maximum in the lowest regions of the atmosphere, with a wind farm. Three scenarios are considered. In the upper figure, the jet is above the wind turbines. In this case, a downward vertical kinetic energy flux is created, which benefits the production of the turbines further downstream in the wind farm. In the middle figure, the low-level jet is roughly at the turbine height, and in this case, only the leading rows can harvest the jet's energy. The lower figure shows a jet below the turbine. In this case, the wake generated turbulence created a vertical kinetic energy flux that is directed upwards, and this again benefits the turbines downstream. Figure adapted from [2].

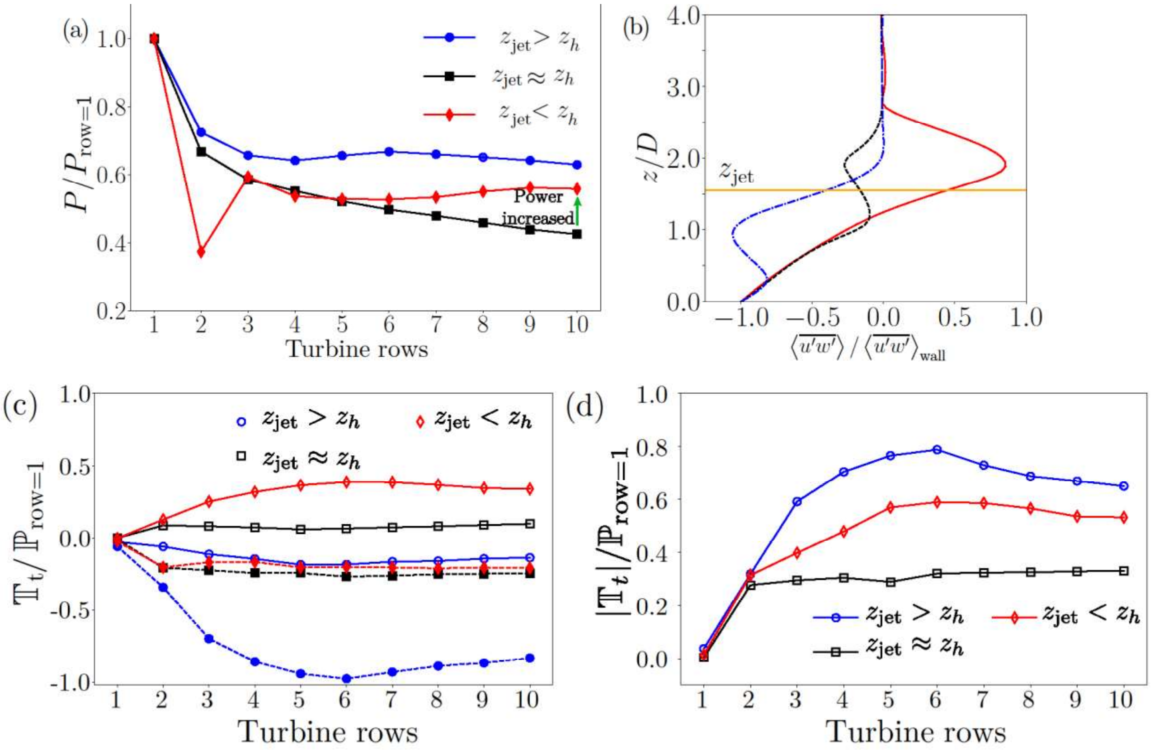

Figure 3: (a) The row-averaged power normalized with the power production of the first row. (b) Planar-averaged streamwise vertical momentum flux versus height. (c) Turbulent kinetic energy flux as a function of the downstream location. The solid lines indicate the energy that enters the control volume around the respective turbines from below. The dashed lines indicate the energy that comes from above. (d) Net energy flux as a function of downstream position. Figures adapted from Gadde and Stevens (2021) [2].

Effect of low-level jet on aerodynamic blade loading

So far, we focused our discussion on the large-scale interaction between the wind farm and the low-level jet. However, it is also crucial to understand how the low-level jet affects the fatigue loading experienced by the turbines. To study this we analyzed the influence of the low-level jet height on the external aerodynamic blade loading of the turbine blades for the three scenarios considered above [3]. Figure 4 shows that the flow structures created behind a stand-alone turbine are significantly affected by the low-level jet height. The wakes are mostly turbulent with weak tip and root vortices when the low-level jets are above the turbine. However, with decreasing low-level jet height, the strength and stability of the root and tip vortices increase, and this can cause higher fatigue loads on the downstream turbines. Overall, our study shows that the turbines are subjected to higher aerodynamic loads in the presence of low-level jets than in typical scenarios without low-level jets. This means that the influence of low-level jets needs to be considered in the life-cycle analysis of wind turbines. These new insights can help to design wind turbines and wind farms.

Outlook

In our recent studies [2, 3, 11] we focused on the influence of low-level jets on wind farm power production. However, in more realistic situations, the atmospheric boundary layer contains mesoscale advection tendencies, and baroclinicity [12] due to complex terrain or land-to-sea transitions. While there have been preliminary studies on the effect of baroclinicity on wind farm performance [13], the combined effect of baroclinicity and thermal stability is largely unexplored. For example, low-level jets are enhanced by baroclinicity and differential heating [14] and the influence of this phenomena on wind farm performance needs further investigation. Future studies should focus on incorporating atmospheric mesoscale effects in studies of wind farms, which will be crucial in designing futuristic wind farms.

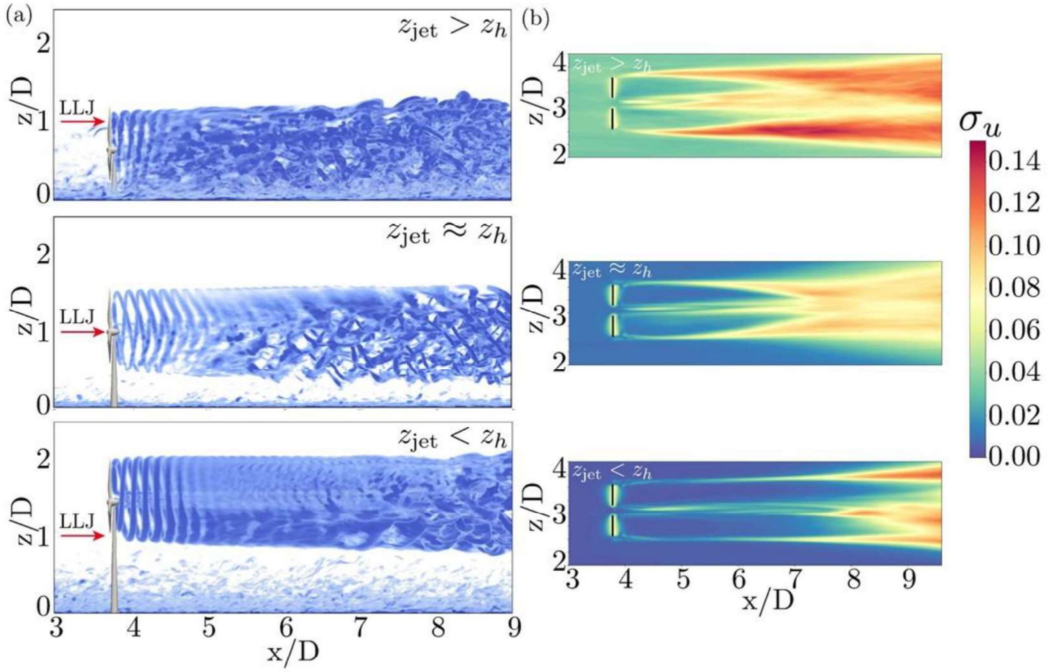

Figure 4: (a) Visualization of vorticity magnitude Ω_{mag} for three different scenarios. From top to bottom: low level jet is above, in the middle, or below the rotor swept area, and (b) corresponding streamwise turbulence intensity $\sigma_u = u'/u_{hub}$ at hub-height, where u' represents the fluctuating streamwise velocity. Figures adapted from Gadde et al. [3].

References

1. Gadde, S.N. (2021). Large Eddy Simulations of Stratified Atmospheric Boundary Layers and Wind Farms. PhD Thesis, University of Twente, doi:10.3990/1.9789036551809.
2. Gadde, S.N., Stevens, R.J.A.M. (2021) Effect of turbine-height on wind farm performance in the presence of a low-level jet. *J. Renew. Sustain. Energy* **13**, 013305, doi:10.1063/5.0026232.
3. Gadde, S.N., Liu, L., Stevens, R.J.A.M. (2021). Effect of low-level jet on turbine aerodynamic blade loading using large-eddy simulations. *J. Phys. Conf. Ser.* **1934**, 012001 (2021), doi:10.1088/1742-6596/1934/1/012001.
4. Stevens, R.J.A.M., Meneveau, C. (2017). Flow structure and turbulence in wind farms. *Annu. Rev. Fluid Mech.* **49**, 311 (2017), doi:10.1146/annurev-_uid-010816-060206.
5. Calaf, M., Meneveau, C., Meyers, J. (2010). Large eddy simulations of fully developed wind-turbine array boundary. *Phys. Fluids* **22**, 015110, doi:10.1063/1.3291077.

6. Blackadar, A.K. (1957). Boundary layer wind maxima and their significance for the growth of nocturnal inversions, *Bull. Am. Meteorol. Soc.* **38**, 283 (1957), doi:10.1175/1520-0477-38.5.283.
7. Prabha, T.V., Goswami, B.N., Murthy, B.S., Kulkarni, J.R. (2011). Nocturnal low-level jet and 'atmospheric streams' over the rain shadow region of Indian Western Ghats, *Q. J. R. Meteorol. Soc*. **137**, 1273, doi:10.1002/qj.818.
8. Kalverla, P.C., Duncan Jr. J.B., Steeneveld, G.-J., Holtslag, A.A. (2019). Low-level jets over the North Sea based on ERA5 and observations: together they do better, *Wind Energy Science* **4**, 193, doi:10.5194/wes-4-193-2019.
9. Wagner, D., Steinfeld, G., Witha, B., Wurps, H., Reuder, J. (2019). Low level jets over the Southern North Sea. *Meteorol. Zeitschrift* **28**, 389, doi:10.1127/metz/2019/0948.
10. Gadde, S.N., Stieren, A., Stevens, R.J.A.M. (2021). Large-eddy simulations of stratified atmospheric boundary layers: Comparison of different subgrid models. *Boundary-Layer Meteorol.* **178**, 363–382, doi:10.1007/s10546-020-00570-5.
11. Gadde S.N., Stevens, R.J.A.M. (2021). Interaction between low-level jets and wind farms in a stable atmospheric boundary layer. *Phys. Rev. Fluids* **6**, 014603, doi:10.1103/PhysRevFluids.6.014603.
12. Floors, S. E. G. R. , Peña, A. (2015). The effect of baroclinicity on the wind in the planetary boundary layer. *Q. J. R. Meteorol. Soc.* **141**, 619, doi:10.1002/qj.2386.
13. Pedersen, J.G. (2013). Large-eddy simulation of the atmospheric boundary layer: Influence of unsteady forcing, baroclinicity, inversion strength and stability on the wind profile. PhD Thesis, DTU Wind Energy, ISBN:978-87-92896-70-4.
14. Gebauer, J.G., Shapiro, A. (2019). Clarifying the baroclinic contribution to the Great Plains low-level jet frequency maximum. *Mon. Weather Rev.* **147**, 3481, doi:10.1175/MWR-D-19-0024.1.