Numerical Study of the Impact of Atmospheric Stratification on a Wind-Turbine Performance

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Abstract. This paper is aimed to obtain a better understanding of how a stably stratified atmospheric condition involving low-level jet, in comparison to neutral condition, affects to a wind-turbine performance. In this work, large-eddy simulation approach in combination with actuator-line model is used to simulate the wake flows in an infinitely long wind farm. Here, numerical simulations of the wind-turbine wakes are carried out under the influence of neutral and stable conditions. The numerical results are compared between the two atmospheric conditions. It has been seen that the wind-turbine performance is highly influenced under the stable conditions. For an infinitely long wind-farm scenario, the power produced by a turbine under the stable condition is smaller by 81\% than that under the neutral condition.

1. Introduction

Diurnal and seasonal variations induce drastic changes to the Atmospheric Boundary-Layer (ABL), which in turn, affect wind energy production. Especially, stably stratified ABL-conditions, typical in wintertime, are a challenge to wind energy production as such conditions are characterized by relatively shallow ABL depth, lower and sometimes intermittent turbulence levels, strong wind shear, and a relatively high wind near the top of the boundary layer. At this height, the local wind becomes super-geostrophic and can form a Low-Level Jet (LLJ). In this way, a LLJ is a localized maximum in a vertical profile of wind speed and that typically occurs at a height between 80–1000 m \cite{1, 2}. This region is very important for wind energy production as modern wind turbines are operating in this region and thus LLJs have a direct impact over the wind turbines performance. As such LLJs can be found in every continent, their occurrences are frequently been reported for example in the mid-latitudes, especially in Southern Great Plains, and in the polar regions \cite{1, 2}. According to the authors \cite{2}, LLJs occur more frequently (70\%) in the cold season than in the warm season. According to \cite{3}, about 75\% of LLJs in the Great Plains occur at nights in summers.

Due to the localized maximum wind velocity in LLJ, stable conditions involving LLJs may provide larger energy potential compared to those of neutral and convective ABLs having the same geostrophic wind speed. However, Stable Boundary Layer (SBL) may induce high deformation strain and great fatigue loads on wind-turbine structure due to strong shear and veer inherited with stable conditions \cite{4, 5, 6, 3, 7}. Further, Coriolis effects associated with the planetary rotation are responsible for changes in wind direction with height (i.e. veering) and
the formation of an Ekman spiral [8]. Such effects can lead to a skewed wind turbine wake and they are more pronounced in stable conditions [9].

This paper is aimed to obtain a better understanding of how a stably stratified atmospheric condition involving LLJ, in comparison to neutral condition, affects to a wind-turbine performance. Previously, several numerical studies [10, 11, 12, 13, 14, 15, 16, 17, 8, 18, 19] attempted to study the influence of thermal and especially stable stratifications on the wind-turbine wakes. However, most of the previous studies [10, 11, 13, 15, 16, 18, 19] have simulated stable conditions in the absence of LLJs. Apart from that, a number of previous numerical attempts [12, 13, 14, 18, 19] made for stable conditions were focused on a single turbine wake, therefore, their findings are only limited to a stand-alone turbine and not to a large wind farm. Nevertheless, some recent studies [8, 14, 17] have focused on wake development under the influence of real-time stable atmospheric conditions, in which, proper representations of LLJs do occur.

In this paper, we carry out Large-Eddy Simulations (LES) for infinitely long wind-farm wakes under the influence of neutral and stable stratifications. To consider real-time stable atmospheric conditions in this study, we have adopted the stably-stratified wind conditions from the GABLS (Global Energy and Water Cycle Experiment Atmospheric Boundary Layer Study) [20] case study. This case represents a typical quasi-equilibrium moderately SBL with a LLJ (at a height between 115–255 m), similar to those commonly observed over the polar regions and equilibrium night-time conditions over land in the mid-latitudes [17, 14]. In this study, firstly simulations are performed without any wind turbine for both, stable and neutral, atmospheric conditions in order to generate their reference cases. Then, the simulations are repeated by including a 5-MW wind turbine. The results from the both conditions are compared against each other to see the impact of the stably-stratified condition with respect to that from the neutral condition. The result comparison is shown into perspective for wind energy applications.

2. Computational approach

In this work, the incompressible filtered Navier-Stokes equations including the Coriolis and buoyancy forces are solved along with the continuity equation and potential-temperature transport equation. The Boussinesq approximation is used for the buoyancy forces. Further, Lagrangian-Averaged Scale-Independent (LASI) dynamic Smagorinsky model [21] is employed to model the effect of the sub-grid scales. Here, the LES calculations are carried out using the OpenFOAM-based SOWFA (Simulator for On/Offshore Wind Farm Applications) package developed by the NREL (National Renewable Energy Laboratory) researchers [5]. Recently, the SOWFA package has been successfully used in the ABL flow simulations for wind energy applications [5, 14, 22, 23, 24, 25, 26].

Following [8, 14, 17, 24, 27, 28, 23], we have chosen to model the turbine effects into the simulations rather than resolving the turbine geometry. The turbine-induced forces are parametrized in the simulations using the actuator line model developed by Sørensen and Shen [29]. The turbine used in this study is the NREL 5-MW reference turbine [30]. It is a three-bladed horizontal axis wind turbine with a rotor diameter $D$ of 126 m and a hub height $H$ of 90 m. More information on the NREL 5-MW turbine can be found in [30].

The simulations are performed over a computational domain of the size of $7D \times 7D \times 5D$ in the stream-wise ($x$), span-wise ($y$) and vertical ($z$) directions, respectively. Here, $D = 126$ m is the diameter of the rotor. The computational domain is discretized uniformly into $221 \times 221 \times 158$ number of grid-cells in $x$, $y$ and $z$ directions, respectively. This leads to a grid resolution $\Delta x = 4$ m in all directions. This resolution ensures that there are about $31$ finite-volume grid cells within the rotor area, which indicates finer grid resolution than those utilized in many previous studies [8, 17, 28, 15, 27, 13, 31]. It is obvious that one would desired to use even finer grid resolutions than what we used here, such as up to 1 m in the wake region.
However, due to higher CPU resources requirement we limited our grid resolution to 4 m. Also, Basu and Porté-Agel [32], who simulated the same stable condition (the GABLS case), showed that it is sufficient to have grid resolution of 4 m to simulate this particular stable condition.

To simulate an infinitely long wind farm, periodic boundary conditions are utilized in both horizontal directions in all simulations. The turbine was placed in the middle of the computational domain. Such arrangement implies a seven diameter (7D) distance between individual turbines in horizontal (stream-wise and span-wise) directions. The stably stratified condition simulated here is adopted from the GABLS case [20] in order to examine the influence of especially LLJ to the wind-turbine performance. In all simulations, the flow is driven by fixing a pressure gradient force which adjusts a desired geostrophic wind $U_g$ near the domain’s top boundary. For this reason, in all simulations the height of the computational domain is kept high (at $z = 5D = 630$ m), so that the flow at the height where the $U_g$ is fixed is not affected by the turbine wakes.

In the stable case, the geostrophic wind is specified as $U_g = (8.0, 0.0, 0.0)$ m/s at $z = 628$ m, and a cooling rate of 0.25 K/h is specified at the surface boundary. The velocity is initialized to the geostrophic wind throughout the domain. From the surface to up 100 m, the potential temperature $\theta$ is initialized to 265 K, and above that a capping inversion with a strength of 10 K/km is applied. Also, below 100 m, random fluctuations with amplitudes of 0.15 K and 0.5 m/s are added to the initial potential-temperature and horizontal-velocity fields, respectively. The reference temperature $\theta_0$ is set to 263.5 K. Using these initial and boundary conditions, the stable case attains a quasi-steady state in roughly 8–9 h with a boundary-layer depth ranging between 190–200 m.

In the neutral case, the geostrophic wind (at $z = 628$ m) is adjusted such that in the absence of the turbine, the wind speed at hub height is the same as that in the stable case. This condition insures that in the absence of the turbine there is a similar amount of potential power (due to the similar wind-speeds at hub height) available in both atmospheric conditions. Like in the stable case, the velocity is initialized to the geostrophic wind in the entire domain with 0.5 m/s of random fluctuations.

In all simulations, the aerodynamic roughness length $z_0$ is set to 0.1 m, and all the simulations take place at 73° north latitude. The LASI sub-grid scale model requires to solve two partial-differential equations for the model quantities: $\mathcal{L}_{LM}$ and $\mathcal{L}_{MM}$. These quantities are initially set to $\mathcal{L}_{LM} = 2.56 \times 10^6$ m$^4$/s$^4$ and $\mathcal{L}_{MM} = 1.0 \times 10^4$ m$^4$/s$^4$ throughout the entire domain such that the Smagorinsky constant $C_s$ is 0.16. The boundary conditions for $\mathcal{L}_{LM}$ and $\mathcal{L}_{MM}$ quantities are zero normal-gradient at the surface and top boundaries.

Following [8, 17], who carried out wind-turbine wake simulations using the GABLS case, the simulation with stable condition is run for 9 h of flow physical time, and the turbine was introduced in the simulations only during the last two hours, i.e. from the 7th hour on-wards till the end of 9th hour. The same is also done in the neutral case. The numerical results are time averaged over the last hour and they are also space averaged in the horizontal directions.

3. Numerical results and discussions

We start this section by briefly discussing the validation of especially the stable simulation from the reference cases, that it, in the absence of the wind turbine. After that we discuss the impact of the two (stable and neutral) atmospheric conditions in the reference simulations as well as in the turbine simulations.

3.1. Validation of the simulations

Figure 1 shows the LES predicted vertical profiles of the time-and-space averaged $x$-directional velocity $U_x$ (a, b), $x$-directional velocity fluctuations $\sigma_x$ (c) and potential temperature $\theta$ (d). The figure also compares the predicted results with their corresponding reference data. To
validate our stable case we have chosen to compare our results with another LES data by Basu and Porté-Agel [32]. For the neutral case, we compare the $x$-directional velocity $U_x$ with the standard logarithmic law: $U = \frac{u^*}{0.4} \ln \left( \frac{z}{z_0} \right)$. Here $u^*$ is the frictional velocity. In both cases, the results generally agree well with their respective reference data. In the stable case, the boundary layer shows the existence of a LLJ between $z = 115–240$ m. The upper height of the LLJ from our LES is slightly shorter (by 10 m) than that in [32]. Both LES profiles show the same magnitude of the maximum velocity in the LLJ region. The boundary layer height ($\delta$) and the Obukhov length ($L$) from our stable simulation are 190 m and 118 m, respectively. These parameter are also in close agreement with the reference LES [32].

![Figure 1](image-url)

**Figure 1.** Vertical profiles of the LES results (dashed lines) of the $x$-directional wind-speed $U_x$ (a, b), $x$-directional velocity fluctuations $\sigma_x$ (c), and potential temperature $\theta$ (d) obtained from the reference cases (without turbine). The solid lines represent their corresponding reference data for validating the simulations.

### 3.2. Impact of stratifications on the reference (without turbine) wind conditions

Here we first compare and study the impact of stratifications on the reference (without the wind turbine) wind conditions. In the following, Figure 2 compares various wind statistics from the reference cases of the two conditions. The vertical profiles of the normalized horizontal wind-speed $U$ calculated as $U = \sqrt{U_x^2 + U_y^2}$ are shown in Figure 2(a). Here, $U_x$ and $U_y$ are the mean-velocity components in $x$ and $y$ directions, respectively. The results are normalized with the hub-height velocity $U_H$. It can be observed that the upper-half area of the rotor seems to be in high influence of the LLJ. However the center of the LLJ appears at $z \approx 2H$, and it is just outside of the rotor area. The boundary-layer height in the stable case is about 190 m ($z/H \approx 2.1$), which is only the 30% of the neutral boundary-layer height. Because the neutral boundary-layer grows up to the top boundary, the wind-speed increases with height. As a result, the geostrophic wind in the neutral case is higher by 22% compared to that of the stable case.

Figure 2(b) shows the horizontal turbulence intensity $I_M$ for the two cases. Here, $I_M$ is the magnitude of the turbulence intensities from the two horizontal directions, and it is calculated as

$$I_M \text{ (in \%)} = 100 \sqrt{\left( \frac{\sigma_x}{U_H} \right)^2 + \left( \frac{\sigma_y}{U_H} \right)^2}$$

where, $\sigma_x$ and $\sigma_y$ are the root-mean-square of the velocity fluctuations in $x$ and $y$ directions, respectively. The negative heat-flux in stable stratification has a tendency to reduce the turbulence level. As a consequence the turbulence intensity is smaller thoroughly in the stable boundary layer as compared to that in the neutral boundary layer. At the hub height, the
intensity in the stable case is smaller by 48% compared that from the neutral condition. Figure 2(c) explains that the change in the wind direction (wind veer) is stronger in the stable case compared to that in the other case. The wind direction changes about 19° across the rotor diameter in the stable case, while only 4° of change is observed in the neutral case. This indicates asymmetric load to wind turbine under the influence of stable condition.

Figure 2(d) presents the wind shear $\alpha$, and it is calculated as $\alpha = \frac{H}{U_H} \left( \frac{dU}{dz} \right)$. It is observed that in the neutral case the shear is 0.52 at the rotor-lowest position and then decreases to 0.11 at the rotor-highest position leading to the reduction of 79% within the rotor. The shear reduction in the stable case is 65% within the rotor area. Importantly, the shear observed especially in the stable case, is too high for safe turbine operations according to the IEC (International Electrotechnical Commission) standards [33]. For example, IEC suggests $\alpha = 0.2$ as one of the design criteria for the strongest class of wind turbines [33]. The shear values at the hub height are found to be 0.17 and 0.37 in the neutral and stable cases respectively. Thus the IEC design criterion for even the strongest class of wind turbines is exceeded under the stable condition. Generally high shear is very likely the case in almost all stable conditions. The increased shear in the stable case is likely to affect the pitching angle of the turbine. Also, the high wind veer under the stable condition are expected to affect power production and to increase the yawing moments with possibly harmful consequences for turbine lifetime.

3.3. Impact of stratifications in the presence of the wind turbine

Next we look the results from the turbine simulations. Figure 3 shows the contours of the time-averaged velocity magnitude at a horizontal ($x-y$) plane at the hub height from the two cases. Because the wind directions at the hub height are different in both cases, the turbine yaw-angles were aligned to their respective wind directions at the hub height, which were known from their reference cases. The velocity distributions in Figure 3 explain that the stable stratification has a significant impact on the wind-turbine wake. The wake is stronger under the influence of the stable condition, as it prolongs longer as well as the hub-height wind speed is smaller in the entire domain compared to that in the neutral case. These findings are in agreement with other studies [10, 13, 18, 19, 16]. Due to less vertical turbulent mixing in stable conditions in general, the wake recovery is slower in stable condition than for example in convective or neutral conditions. In addition, the wake is also triggered by the use of periodic boundary conditions in the horizontal directions (infinitely long wind farm) and the effects are more profound in the
stable case due to less turbulent mixing.

The time-and-space averaged results from the turbine simulations are presented in Figure 4. The results from the turbine simulations (solid lines) are also compared with their reference cases (dashed lines). The horizontal wind speed in Figure 4(a) suggests that due to the stronger wake effects in the stable case the mean wind is smaller by 46% at the hub height than that in the neutral case. This was however expected from the velocity distributions in Figure 3. In the mean wind-speed (Figure 4(a)), the wake effects extend vertically till $z = 3.4H$ and $z = 5.1H$ under the stable and neutral conditions, respectively. In both cases, the turbulence intensity in the wake is found to be increased thoroughly in the boundary layers. In the neutral case, the turbulence intensity does not vary significantly across the rotor, whereas in the stable case it increases from 7.7% at the lower-tip to 10.2% at the upper-tip, and it maintains till $z = 2.9H$.

In both cases, the wind veer changes from their respective reference conditions, however the changes are not significant in the neutral case according to Figure 4(c). The veer across the rotor has been reduced from $19^\circ$ in the reference case to $15^\circ$ in the wake for the stable case. For the neutral case, the reduction is from $4^\circ$ to $2^\circ$. Despite having the large difference (112% at the hub height) between the two shear values of the two reference cases (neutral and stable), the shear values from the turbine cases seem to close to each other at the hub height (Figure 4(d)).

Apart from that, the shear behaves differently between the two cases. Table 1 summarize the hub-height values of the various wind statistics from the reference and turbine simulations. The table also reports differences between the two simulations for each atmospheric condition.

Next we discuss the velocity deficit. Figure 5 shows the velocity deficit $\Delta U$ profiles for the two cases and compares with another LES results of Porté-Agel et al. [8]. The deficit $\Delta U$ is calculated using the spaced-averaged velocity as $\Delta U = (U - U_{\text{ref}})/U_{\text{ref}}$, where $U_{\text{ref}}$ is the velocity from the reference case. In [8], they simulated wind turbine wakes using the same stable condition (i.e. the GABLS case) for infinitely long wind farm case with two arrangements: $5D$ and $8D$ distance between individual turbines in the horizontal directions. In our case, the corresponding distance is $7D$. It has to be mentioned that Porté-Agel et al. [8] used different turbine than what we have used in this work. They used so-called V112-3.0MW wind turbine with a hub height of 119 m and a rotor diameter of 112 m. Apart from that their turbine’s aerodynamic properties are much more different than the turbine (NREL-5MW) used here. Therefore, a direct comparison is not possible between the present results and the results from [8], rather we use their results as a qualitative validation.
Figure 4. Vertical profiles of the normalized horizontal wind-speed $U/U_H$ (a), horizontal turbulence intensity $I_M$ (b), wind direction $\gamma$ (c), and wind shear $\alpha$. The solid lines represent results from the turbine simulations and the dashed lines from their respective reference cases. The light-gray background depicts the rotor area.

Table 1. Wind statistics from the reference and turbine simulations at the hub-height. The difference is calculated with respect to their reference values. The sign, + or −, in the difference shows either increment or decrement in the respective value.

|                | Neutral reference | wake | difference | Stable reference | wake | difference |
|----------------|-------------------|------|------------|------------------|------|------------|
| $U$ (m/s)      | 7.5               | 6.8  | −9 %       | 7.5              | 3.7  | −51 %      |
| $I_M$ (%)      | 11.8              | 19.3 | +64 %      | 5.9              | 9.5  | +61 %      |
| $\gamma$ (°)   | 6.7               | 5.2  | +22 %      | 22.6             | 30.9 | +37 %      |
| $\alpha$       | 0.17              | 0.12 | −29 %      | 0.36             | 0.14 | −61 %      |

According to Figure 5, the velocity deficit at the hub height in our stable and neutral cases are 51% and 9%, respectively. In the results of [8], the deficit at the corresponding hub height for $5D$ and $8D$ cases are 41% and 31%, respectively. This suggests that the wake deficit for infinitely long wind farm scenario is generally higher (more than 30%) under stable stable conditions. Further, the deficit seems to be so sensitive to the wind farm arrangement (the distance between
turbines), as there is already 10% difference between the two cases of [8]. In our stable case, the
deficit is even higher by for example 10% compared to their 5D case and 20% compared to the
8D case. This difference can be justified by the bigger turbine that we have used here, which has
33% of bigger rotor area than the turbine used in [8]. Bigger rotor area is also responsible for
higher vertical expansion of the wake in our case. In addition to that different turbine and its
aerodynamic properties, such as airfoil profile, twist angle, chord distribution, tip-speed ratio,
yaw angle, etc., should also be responsible at a certain level for the higher velocity deficit (i.e.
stronger wake) in our case.

3.4. Power output and losses
In this sub-section, we discuss the power output and the associated statistics from the present
work. Figure 6 shows the time series of the power $P$ produced by the turbine during the last
1-h of the flow time in both cases. At first, it is observed that the power production under
the stable condition is far smaller than that under the neutral condition. The last 1-h time-
averaged powers from the two cases are 1.37 MW and 0.26 MW in the neutral and stable cases
respectively. In other words, the mean power output in the stable case is 81% smaller than that
in the neutral case.

Table 2 gives the statistics on the power output and power loss (deficit) for the neutral and
stable cases. The table also reports the difference between the two conditions for each statistics,
which is calculated with respect to the neutral condition. Following [34, 35], we define the power
loss as

$$P_{\text{loss}} \text{ (in \%) } = 100 \left( \frac{P_{\text{avail}} - P}{P_{\text{avail}}} \right) ,$$

which is a loss in the mechanical power with respect to the total-available power $P_{\text{avail}}$ from the
reference wind (potential power). Here the total-available power $P_{\text{avail}}$ is calculated as [34, 35]

$$P_{\text{avail}} = \frac{1}{2} \rho \pi R^2 U_{\text{avail}}^3 ,$$

Figure 5. Vertical profiles of the velocity deficit $\Delta U$ compared with another LES results of [8].
The black dashed lines in the gray background shows the turbine-rotor area of the turbine used by [8].
Figure 6. Time series of the power produced by the turbine during the last 1-h of the flow time.

in which $U_{3 \text{ avail}}$ is defined as

$$U_{3 \text{ avail}} = \frac{1}{2R} \int_{H-R}^{H+R} U^3(z)dz,$$

where $R = D/2$ is the radius of the rotor.

Table 2. Wind-turbine power and related statistics: total-available power ($P_{\text{avail}}$), power output ($P$), power loss ($P_{\text{loss}}$) and standard deviation ($P_{\text{std}}$) of the power from the neutral and stable cases. The difference between the two conditions is calculated with respect to the neutral case.

|              | Neutral | Stable | difference |
|--------------|---------|--------|------------|
| $P_{\text{avail}}$ (MW) | 3.19    | 3.15   | -1%        |
| $P$ (MW)     | 1.37    | 0.26   | -81%       |
| $P_{\text{loss}}$ (%) | 57      | 92     | +61 %      |
| $P_{\text{std}}$ (MW) | 0.39    | 0.04   | -90%       |

From the table one can see that despite having the negligible difference (of 1%) between the total-available powers of the two conditions, the actual (mechanical) power ($P$) produced by the turbine under the stable condition differs by 81% from the power obtained in the neutral case. Further it is noticed that the stable condition loses 92% ($= P_{\text{loss}}$) of its total-available power, while in the neutral case the power loss is 57%. Moreover, the standard deviation from the last 1-h of power output $P_{\text{std}}$ is 0.39 MW and 0.04 MW from the neutral and stable cases, respectively. The standard deviation is smaller (by 90%) in the stable case than in the neutral case which suggests that the power fluctuates less (due to the less turbulent fluctuations in wind) and that the load is more uniformly distributed in time in the stable case than in the neutral case.

The poor power production is a direct consequence of the stronger wake effects associated with the stable case. This reduces the wind speed more in the stable case than in the neutral case. According to Table 1, the wind speeds at the hub height in the wake simulations are 6.8 (m/s) and 3.7 (m/s) in the neutral and stable cases, respectively. Nevertheless, if one would take the power curve of the NREL-5MW turbine [30] into the account, the difference in the powers
between the two conditions is acceptable. For example, according to the NREL-5MW turbine data (e.g. power curve) the rotor powers at the wind speeds of 3.7 (m/s) and 6.8 (m/s) are about 0.15 MW and 1.2 MW, respectively [30], leading to a difference of 87% itself in the turbine’s power curve. This difference is in the close agreement with the difference (81%) obtained by our simulations. In terms of power production, this turbine looks very sensitive with the wind speed variation, as the power is varying from 0.043 MW to 4.8 MW (approximately 110 times) within the wind-speed variation from 3 (m/s) to 11 (m/s) [30]. This also indicate that this turbine is generally not efficient at lower wind speeds (less than 6 m/s) as the power is too small compared to its rated power.

Of course the question is why the wind speed is too low in the wake simulation of the stable case? There can be a number of reasons for this. Firstly, less turbulence mixing due to the negative buoyancy flux in the stable case which does not allow the wake to recover faster, and hence the wake is stronger (i.e. lower wind speed) compared to that in the neutral case. Recently, Abkar and Porté-Agel [11] studied the effect of free atmosphere on a large wind-farm power output. They pointed out that 10 times stronger stratification in the free atmosphere can decrease the power up to 30%. The second reason is the use of periodic boundary conditions (infinitely long wind farm). With respect to a single turbine, the wake effects in an infinitely long wind farm are always stronger as the wake gets stronger towards infinite number of turbines and the effects are more profound in the stable conditions for the above mentioned reason.

4. Conclusions
In this paper, we carried out LES calculations for an infinitely long wind-farm wakes under the influence of neutral and stable stratifications. The stable condition simulated here is characterized by a low-level jet, which appears at a lower ABL depth (115-240 m) in which modern wind turbines are operating. The turbine is modeled using actuator line model, which parametrizes the turbine-induced forces (e.g., lift and drag) into the governing equations. For the both atmospheric conditions, the simulations are also carried in the absence of the wind turbine in order to generate their reference cases. The LES results from the both atmospheric conditions are compared against each other in order to study the impact of the stably-stratified condition with respect to that from the neutral condition.

The results from the reference cases (in the absence of wind turbine) demonstrated that for the similar wind speed at the hub height the stably-stratified wind condition provides lower (e.g. by 35%) turbulence intensity but higher wind-shear (by 112% at the hub height) than that observed under the neutrally-stratified wind condition. The results from the wake simulations show that the stable condition has significant impact on the turbine wake and power statistics. The wake under the stable condition is far stronger than that seen under the neutral condition due to the less turbulent mixing associated with the stable condition. The velocity deficit in the stable case is higher by 47% compared to that in the neutral case. In the wake, the vertical variation of the wind statistics within the rotor is also high in the stable case, while the profiles in the neutral case are vertically less profound (weaker vertical variation). With respect to the neutral case, the vertical expansion of the wake is smaller by 33% in the stable case, as the negative buoyancy flux acts against it. Due to the wake, the boundary-layer depth in the stable case is increased by 35% compared to its reference case.

Concerning the power statistics, we noticed that the power production under the stable condition is 81% smaller than the power obtained in the neutral case. With respect to the total-available power, the power loss (deficit) is higher in the stable case. The power loss is found to be 57% and 92% in the stable and neutral cases respectively. However, for the obtained wind speeds in the wake simulations, the power statistic (production and losses) obtained in this study is in agreement with the turbine’s power curve. In the future, we will extend this work by simulating a single-turbine wake as well as finite-size wind farm using the same atmospheric
conditions and the results will be compared with the existing results. This comparison will bring further insight into the impact of stable conditions involving low-level jets on the wind turbine performance.

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