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Physical Colloquium

„Large Eddy Simulations of Wind Farm–Atmosphere Interactions“

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Colloquium on

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Wind energy is Europe’s largest source of renewable energy. However, achieving the International Energy Agency’s Net Zero Emissions scenario requires wind energy production to increase more than tenfold by 2050. Meeting this demand calls for innovative approaches. Wind turbine performance is strongly influenced by atmospheric turbulence, which governs the vertical transport of kinetic energy and replenishes the energy extracted by turbines. High-resolution large-eddy simulations (LES) provide crucial insights into wind farm-atmosphere interactions. The figure presents a flow visualization illustrating this interaction. In this presentation, I will discuss how we use LES to improve our understanding and develop analytical models to quantify the effects of atmospheric processes on wind farm performance and wake recovery.

For very large wind farms, farm-scale losses caused by the atmospheric response to the entire wind farm become the dominant limiting factor. In contrast, turbine-scale losses arise from internal flow interactions within the array. This suggests that optimizing wind farm layout has limited potential to enhance performance in extended arrays. The wind energy industry primarily relies on computationally efficient engineering models for wind farm design, often focusing on wake effects between turbines. However, to fully understand wind farm performance, it is essential to further develop models that accurately capture energy entrainment and the broader wind farm–atmosphere interaction.

This presentation introduces a new analytical model for fully developed wind turbine arrays in conventionally neutral atmospheric boundary layers. The model accounts for free-atmosphere stratification, Coriolis effects, wind farm layout, and turbine operating conditions. Derived from physical insights obtained through LES, it extends the geostrophic drag law (GDL) from flow over flat terrain to fully developed wind farms. The presence of a large wind farm significantly increases friction velocity compared to flow over flat terrain, which we model using updated GDL coefficients. Our model accurately captures the vertical wind speed profile within the farm and reproduces power production trends observed in simulations. Results show that normalized wind farm performance decreases with increasing free-atmosphere thermal stability or decreasing Coriolis force. Additionally, we find that optimal wind farm performance occurs at a lower thrust coefficient than the Betz limit, suggesting that the optimal operating conditions for turbines in a wind farm differ from those of a single turbine.

We also examine how baroclinicity—caused by horizontal temperature gradients in the atmosphere—affects wind farm performance and wake recovery. Baroclinicity modifies turbulence intensity at turbine height, influencing power generation in the entrance region of a wind farm. Further downstream, it alters wake recovery by changing the kinetic energy available for entrainment above the wind farm. Our findings indicate that wake expansion is governed by atmospheric turbulence intensity, while an upward shift in the wake velocity deficit is driven by vertical velocity shear. These insights have guided the development of a novel engineering model to predict large-scale wake recovery in both barotropic and baroclinic conditions.

Host: Prof. Dr. Kerstin Avila