The consideration of atmospheric stability within wind farm AEP calculations

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1 Introduction

The atmospheric stability largely affects the flow conditions in the atmospheric boundary layer (ABL) relevant for both off-shore [1] and on-shore [2] wind energy sites. The stratification driven by temperature gradients and buoyant forces has strong impact on the generation of turbulence and thus the wind turbine wake recovery. It also determines the amount of mixing between different layers of air, and hence it is crucial for the transport of energy into the wind farm from above (and below).

In this contribution we include the effect of atmospheric stability into the calculation of the annual energy production (AEP) of an existing on-shore wind farm for the year 2011. The time series of inflow wind and stability conditions are obtained from a mesoscale simulation with the Weather Research and Forecasting (WRF) model [3]. Then, two AEP calculation methods are compared, one is the weighted sum of steady computational fluid dynamics (CFD) simulations, the other a result of the wind farm modelling software flapFOAM [4–7] by Fraunhofer IWES. For the latter we present a new simple wake transformation model that represents thermal stratification effects of wind turbine wake deficits. The results of both methods are compared to one another and measured SCADA data.

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2 Approach

We consider an on-shore site with 20 Nordex wind turbines, for which a WRF simulation with three nested domains and high vertical resolution (60 levels) for the entire year 2011 is carried out. From the local results at the site the time series of wind speed, wind direction and Obhukov length (MOL) are extracted. From this data a representative set of states is selected, with the according statistical weights.

The AEP is then evaluated by two different methods. First, Reynolds-Averaged-Navier-Stokes (RANS) equations are solved in three dimensions with CFD methods and the open source software OpenFOAM [8]. The wind turbine rotors are modelled by actuator disks in this approach. The turbulence model is an extension of the k-ϵ model that includes thermal stratification effects, also the wall functions have been modified accordingly. Furthermore, the boundary conditions are generated automatically and self-consistently, by a one-dimensional cyclic precursor CFD simulation run, fed with parameters like wind speed and MOL from WRF. The precursor run yields the thermal wind shear profiles and the corresponding turbulence model inflow conditions.

Second, the wind farm modelling software flapFOAM is used to calculate the AEP. It is a wake modelling framework which is based on single-wake superposition. As shown at EWEA 2011 [4], this software is capable to use pre-calculated CFD results as single-rotor wake models, besides classic wake models like the Jensen model [9], the Ainslie model [10] and others. For the effect of stratification on wakes we present a new model that is independent of the choice of wake model. It can be understood as a simple phenomenological transformation rule for the wake deficit, that depends on the MOL parameter and the distance from the disk. The latter is derived from CFD RANS simulations of a single rotor for 9 different values of MOL.

The results of both approaches are finally compared to each other and to SCADA data from the site, provided by Nordex.

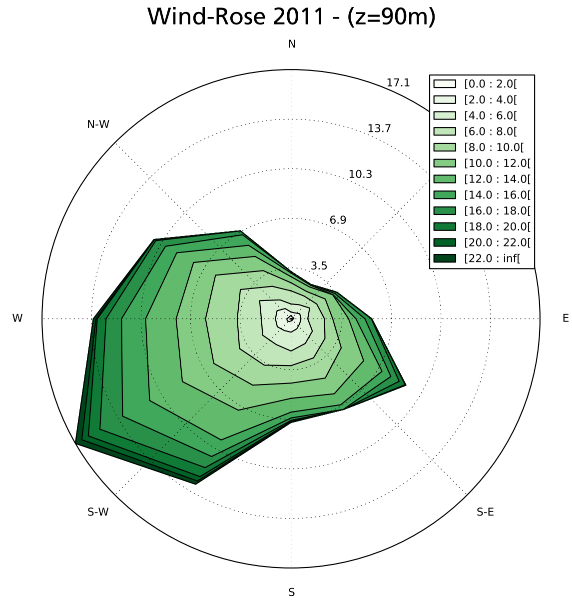

Figure 1: Wind rose from one-year WRF simulations at hub height (z = 90 m) in bins of 30°.

3 Main body of abstract

The wind speed and stability (90 m/MOL) distribution derived from the WRF simulations and are presented in Figs. 1 and 2, respectively. The figures shows distinct westerly winds with the highest wind speeds being associated with winds from the southwest.

The stability distribution over the wind direction shows that these south-westerly winds are associated with stable stratification (90m/MOL>0.2). The comparatively rare (<15 %) events of unstable stratification (90m/MOL<-0.2) are associated with westerly winds. Easterly winds are strongly connected with stable and very stable (90m/MOL>0.8) stratification.

For the inclusion of stratification effects into flapFOAM, a uniformly loaded actuator disk model was simulated for MOL values $L = \pm120, \pm180, \pm240, \pm480$. The corresponding spanwise wake deficits are shown in FIg. 3 for a downstream distance of 8D. As expected, the wake recovers faster in the unstable case compared to neutral stratification, and the stable case wake deficit is stronger. As illustrated by Figs. 4 and 5, for fixed downstream distance x, it is possible to model the deficit induced by stratification

$$\Delta_{\text{deficit}} \equiv (\text{wake deficit}) - (\text{neutral wake deficit})$$

by a dimensionless function of the form

$$\Delta_{\text{deficit}}\left(\frac{z_h}{L}, \frac{x}{D}\right) = a\left(\frac{x}{D}\right)\sqrt{\left|\frac{z_h}{L}\right|} + b \qquad (1)$$

where z_h is the hub height, L the MOL, $a(x/D)$ an explicitly known function and b a constant. The above expression is a simple model for stratification effects that can be applied to arbitrary wake models.

We find that our CFD approach captures well the effects of thermal stratification, also when comparing the individual simulations to met mast data at the site. It is clearly observed that flow over complex terrain has stronger tendency to separate in the unstable case, and that wakes are more pronounced in stable situations. The wake modelling approach with flapFOAM has convincing results compared to

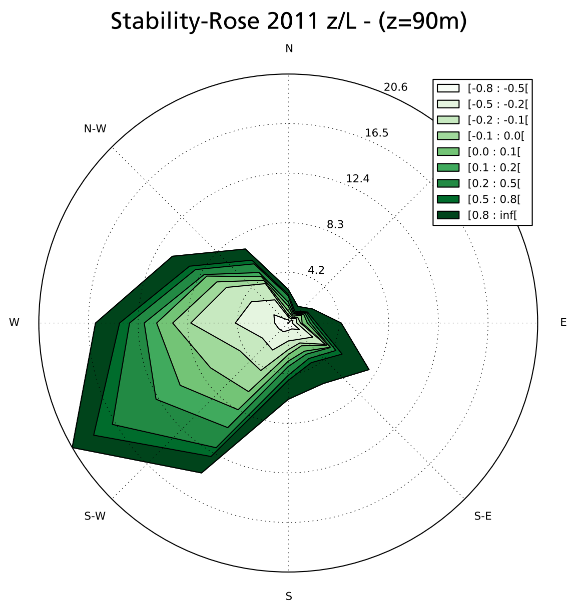

Figure 2: Stability rose (90 m/MOL) from one-year WRF-simulations in bins of 30°.

CFD in flat terrain cases. It is possible to obtain good agreement of wake deficit fields using the introduced wake transformation for wake models.

4 Conclusion

In this paper we calculate the AEP of an on-shore wind farm based on a representative set of meteorological states that include the thermal stratification parameter MOL. These states are obtained from a mesoscale simulation with WRF for the year 2011, they serve as input data for two different approaches to calculate the AEP.

One consists of computationally expensive explicit CFD simulations of the RANS equations with OpenFOAM for the selected set of states. For the representation of thermal stratification effects the solver, the boundary conditions, the turbulence model and the wall functions have been adopted. The method yields good agreement with met mast data in the in-

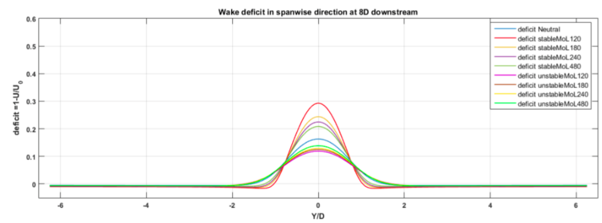

Figure 3: Spanwise wake deficit CFD RANS results for 9 different MOL.

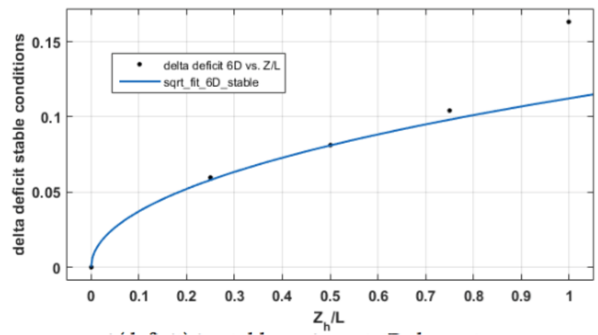

Figure 4: Change of wake deficit compared to the neutral case as a function of hub height z_h over MOL L, for stable stratification. The blue curve is the wake transformation model. We exclude the very stable result $z_h/L = 1$ for the model fit.

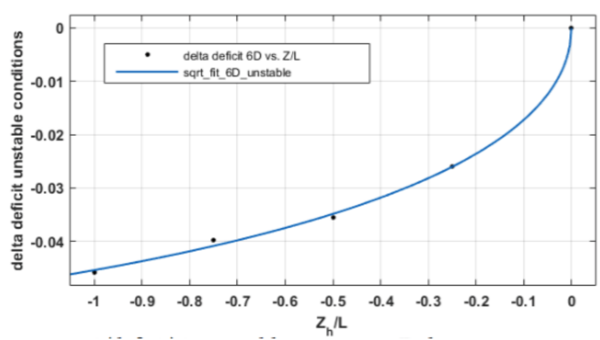

Figure 5: Change of wake deficit compared to the neutral case as a function of hub height z_h over MOL L, for unstable stratification. The blue curve is the wake transformation model.

dividual simulations of the considered set of meteorological states.

The second method is a fast AEP calculation based on the modelling software flapFOAM, an inhouse development by Fraunhofer IWES. In order to include stratification effects into the latter we developed a new simple wake transformation model that has been deduced from CFD RANS simulations of a single rotor. The method is capable to reproduce CFD wake deficits in stratified flow in flat and almost flat topography.

We compare the outcome of these different approaches, and validate against SCADA data. This clarifies the usability of the proposed methods and models. Due to its simplicity, especially the engineering wake model approach is a practical improvement to existing modelling tools, and may be a valuable step towards the inclusion of thermal stability effects into wind farm planing.

5 Learning objectives

- Calculation of wind farm AEP including stratification effects, using WRF results as input data
- CFD-RANS AEP simulations including stability for existing on-shore wind farm
- Transformation of engineering wake models due to stability effects according to a new simple model
- Comparison of CFD and flapFOAM results with SCADA data

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