J. Wind Eng. Ind. Aerodyn. 144 (2015) 146–153

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

The impact of stable atmospheric boundary layers on wind-turbine wakes within offshore wind farms

Martin Dörenkämper*, Björn Witha, Gerald Steinfeld, Detlev Heinemann, Martin Kühn

ForWind – Center for Wind Energy Research, Department of Physics, Carl von Ossietzky University Oldenburg, D-26129 Oldenburg, Germany

ARTICLE INFO

Keywords:
Atmospheric stratification
Boundary layer
Large-eddy simulation
Wind energy
Wind turbine wakes

ABSTRACT

In terms of predicting wind turbine wakes, the stably stratified atmospheric boundary layer (SABL) is taking an exceptional position as wake effects and thus loads on subsequent turbines are stronger. In this study we show the impact of the SABL on power production and wake effects (power deficits) in offshore wind farms by means of measurements as well as large-eddy simulations (LES). Measurements show enhanced wake effects in the SABL compared to the unstable situation. Another influence on the power generation of an offshore wind farm is the distance of the wind farm to the shore. This is accounted for in the LES by a modification of surface characteristics at the coastal discontinuity. In addition to the effect of the coast, the numerical case study also shows the existence of local jets between the turbines of the wind farm.

1. Introduction

The number of wind turbines being connected to the electrical grid worldwide is increasing rapidly. In Europe, the wind-energy capacity is expected to grow up to more than 130 GW within the next decades. Most of the projected and also the already erected offshore wind farms are located in rather small regions like the North Sea and also the Baltic Sea (EWEA, 2014). Further limitations (e.g. shipping routes and nature reserves) lead to very limited areas where hundreds of turbines will be built. Thus, inter- and intra-wind farm wake effects are an important issue for the power output of these offshore wind farms.

Due to its far extension into northern latitudes, the related cooling of the water masses in winter and its proximity to the shores, the atmospheric boundary layer (ABL) over the Baltic Sea is dominated by stable stratification. Smedman et al. (1997) found for locations on the southern Swedish coast that two-thirds of all situations were stably stratified. This is in contrast to the ABL over the North Sea which is predominantly neutrally to slightly unstably stratified (Sathe et al., 2011). The larger probability of stable atmospheric boundary layer (SABL) states also leads to an increased frequency of low-level jets (Smedman et al., 1996).

The atmospheric stability is an important meteorological variable impacting the development of wind turbine wakes in offshore wind farms. This impact has been investigated in several studies within the last years. Barthelmie et al. (2007) showed the dependence of wind speed deficits on stability for the offshore wind farm Nysted in the Baltic Sea. Hansen et al. (2012) reported a strong dependency of the power deficit inside the offshore wind farm Horns Rev on atmospheric stability. They found, based on measurements at an offshore met mast in the North Sea, that offshore stable and unstable conditions are present at wind speeds up to 15 m s^{-1}. Above this wind speed neutral conditions (very small absolute value of the Richardson-number) prevail because the shear production of turbulence dominates over the buoyancy production/consumption. In addition, they reported a dependency of the intensity and the width of wind turbine wakes on atmospheric stability inside an offshore wind farm with the largest deficits for very stable and stable conditions.

One main reason for the impact of atmospheric stability on the power output of offshore wind farms is the size of turbulent momentum fluxes in the atmosphere which act in refilling the wakes. The role of these momentum fluxes for large wind farms has been described in Emeis (2010). More recently, investigations of power data for single offshore wind turbines showed differences of up to 20% between stable and unstable stratification for the same mean wind speed (e.g. Dörenkämper et al., 2014).

The power output in the non-wake case is lower in an SABL for the same hub height wind speed of the ambient flow. Dörenkämper et al. (2014) explain this by the increase in shear in the inflow of a multi-megawatt offshore wind turbine which is not captured by a single hub height inflow measurement. The increase in shear in the lower part of the rotor disk is not compensated in the upper part of the rotor. Furthermore their study showed that low turbulence intensities also lead to a decreased power output for equal inflow wind speeds. In contrast to this study, Wharton and Lundquist

* Corresponding author. Tel.: +49 441 798 5077; fax: +49 441 798 5099.
E-mail address: martin.doerenkaemper@uni-oldenburg.de (M. Dörenkämper).

http://dx.doi.org/10.1016/j.jweia.2014.12.011
0167-6105/

(2010) found a decreased power output for unstable conditions. They did not use a single measurement at the inflow but calculated a "true-flux" equivalent wind speed which then incorporates the impact of shear and turbulence.

Nowadays available computational power and enhanced wind turbine parametrizations allow for detailed studying of wind turbine wakes in offshore wind farms. First numerical investigations of the flow around wind turbines were mainly based on the Reynolds-averaged Navier–Stokes (RANS) solvers through single wind turbines (among others Sørensen and Shen, 2002; El Kasmi and Masson, 2008). These studies lack in resolving important turbulent quantities and a detailed structure of the wake in wind farm simulations. More recently, the development of high-performance parallel computers facilitates simulations of atmospheric turbulence-resolving large-eddy simulations (LES). First studies were limited to single wind turbines (e.g. Jimenez et al., 2007) and/or idealized inflow conditions neglecting Coriolis or buoyancy effects (e.g. Porté-Agel et al., 2011).

LES of entire wind farms in varying atmospheric stratification are currently a subject of investigation. Churchfield et al. (2012) performed a wind farm LES of the entire Lillgrund offshore wind farm with 48 wind turbines in a neutrally stratified ABL including Coriolis force and found an overprediction of relative power by 25–40% compared to field data. The power losses at the Horns Rev offshore wind farm were investigated by Porté-Agel et al. (2013) for different inflow angles in neutrally stratified flow concluding that only small changes in wind direction can have a strong influence on the total power output of the entire wind farm. Most recent studies encompass convective and stable boundary layers in LES of wind turbine wakes (e.g. Aitken et al., 2014; Mirocha et al., 2014).

The objectives of this study are to show the impact of atmospheric stability on wind turbine wakes derived from measured Supervisory Control and Data Acquisition (SCADA) data, followed by a case study of a developing SABL after a coastal passage and its impact on wind turbine wakes within an offshore wind farm.

Section 2 introduces the data and the LES framework used in this study. In Section 3 measured wake effects are presented first before they are further investigated in the LES case study.

2. Data and methods

2.1. Wind farm data

EnBW Baltic 1 (EB1) was by the time of commissioning the first commercial offshore wind farm in Germany. It is located about 16 km north of the Darß-Zingst peninsula within the southern Baltic Sea (Fig. 1(a)). The wind farm consists of 21 pitch-controlled Siemens (SWT-2.3-93) wind turbines, each with a rotor diameter of 93 m (1*D*), a hub height of 67 m (1*H*) and a rated power of 2.3 MW. The turbines are founded on monopiles in a water depth of around 18 m. The wind farm is arranged in a triangular shape (Fig. 1(b)) and therefore it allows for studying multiple wake situations for different wind directions. A SCADA dataset (power, nacelle position, nacelle wind speed, status; among others) of three full years (April 2011–March 2014) was available for this study. The data were filtered for downtimes, curtailments and other non-normal operation data. Afterwards, a power deficit for each turbine of the wind farm was calculated as

$$P_{def} = 1 - \frac{P_{wake}}{P_{free}} \tag{1}$$

with P_{def} the power deficit of each individual wind turbine, P_{wake} the measured power of the wind turbine and P_{free} the power of a reference turbine in the undisturbed flow. As reference turbines, the turbines at the corners of the wind farm were selected, depending on the wind direction. For a wind sector of 0°–120° turbine B01 was selected, for 120°–240° – B06 and for 240°–360° – B21. Wind speed measurements were obtained from the nacelle anemometers. The wind direction was derived from the nacelle position. Comparisons with data from a Light Detection And Ranging (LiDAR) campaign within the wind farm showed only small differences of the average nacelle positions as well as average wind speeds measured on top of the nacelle to the wind direction and wind speed derived from the LiDAR data.

2.2. LES framework

Simulations of the wind farm flow were conducted with the LES model PALM (A PArallelized LES Model) (Raasch and Schröter, 2001). The model uses a staggered Arakawa C-grid which is stretched in vertical direction above the top of the ABL. A fifth order advection scheme by Wicker and Skamarock (2002) was used. Subgrid fluxes were prescribed by the 1.5 order flux gradient subgrid closure scheme following Deardorff (1980). The boundary conditions were defined by a geostrophic wind speed (u_g,v_g), a roughness length (z_0) and a potential temperature profile. The Monin–Obhukhov similarity theory (MOST) was applied between the surface and the first computational grid level.

The simulation chain in this study consisted of pre-runs (PreRun1, PreRun2) without the effect of wind turbines in which the ABL was created and a subsequent main-run (MainRun) that was including the effect of the wind turbines. To initiate the development of turbulence, the pre-runs were initialized with random perturbations. Lateral and longitudinal cyclic boundary conditions were used (PreRun1,2). Afterwards, the actual wind farm simulation (MainRun) was driven by a turbulence recycling method in longitudinal flow direction (Kataoka and Mizuno, 2002). The inflow was realized by Dirichlet (fixed profile), the outflow by radiation boundary conditions. The model has been applied in SABLs in several studies (Beare et al., 2006; Steinfeld et al., 2007, among others).

To model the effect of wind turbines on the ABL, several wind turbine parametrizations of different complexity (based on Calaf et al., 2010; Mikkelsen, 2003; Wu and Porté-Agel, 2011) were adapted and implemented in the code. These parametrizations have been applied and verified in several research projects (e.g. Steinfeld et al., 2010; Witha et al., 2014a, b). The wind turbine model used in this study is described in more detail in Section 2.2.1. To include effects of the coastal discontinuity, a series of simulations was conducted employing the set-up described in Section 2.2.2.

2.2.1. Wind turbine parametrization

For a detailed but computationally efficient representation of the effect of the wind turbines on the flow, the LES model PALM was extended by an "enhanced actuator disk model with rotation" (ADM-R) (similar to the model used in Wu and Porté-Agel, 2011). Within this parametrization, the rotor disk is subdivided into rotor annulus segments on which the resulting lift and drag forces per segment are calculated independently from the actual position of a certain blade at the considered time instance. We are averaging the loads on each rotor annulus segment and project them afterwards onto the grid of the LES. A schematic illustration of the rotor representation in the ADM-R wind turbine parametrization is shown in Fig. 2.

This parametrization has the advantage that the time-step of the simulation is not determined by the rotational speed of the rotor blade but solely by the flow solver itself and is therefore