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Investigation of the impact of wakes and stratification on the performance of an onshore wind farm

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Abstract

This work investigates the effects of wakes and stratification on the performance of turbines operating in the Bessaker wind farm. The wind farm is located in a highly complex terrain. Most dominant wind directions recorded close to the site are westerly and south easterly and the average wind speed is recorded in the range of $10-15m/s$ implying that the turbines are rarely idle. However, the power production data of individual turbines revealed that a few turbines were almost always under-performing. This matter was earlier investigated using a multi-scale model ([1]) involving meso-scale weather forecasting model providing input to a nested micro-scale CFD code. This previous study hinted at strong thermal stratification as the culprit which causes a channeling effect thus reducing the wind potential available uphill. However, wake effects were completely ignored in those studies. The current work includes an actuator line (AL) model to enable simulation of wake effects along with stratification and terrain effects on turbine behavior. As a result, the model is able to capture the delay in wake recovery during stable stratified conditions and the resultant turbine-turbine interactions leads to the reduced power production at wind-farm. The inclusion of wake effects showed that the current inter-turbine distance of 4 rotor turbine diameter at some locations is not good for wind-farm operation. This effect was not captured by the earlier multi-scale model which lacked the AL model. Further, the work shows some differences in results arising out of two models (current and previous multi-scale model) related to channeling effect. This difference is attributed to difference in thermal stratification level (Froude number) as the current model uses standard atmospheric inlet profiles/initial profiles, while the multi-scale model used inputs from the higher meso-scale weather forecasting model. The overall work indicates the importance of including wake and stratification effects and the importance of downscaling (using inputs from weather-forecasting models) in improving predictions. According to the authors this is the first work of its kind which accounts for stratification, complex terrain and wakes in a single simulation.

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Keywords: Wind Farm, Stratification, Terrain induced turbulence, Wake effects, Actuator line, CFD

1. Introduction

The wind energy has immense potential to contribute towards global energy demand and it will increase further provided the cost of wind-energy (CoE) remains competitive. Over the past decade, the CoE has reduced owing

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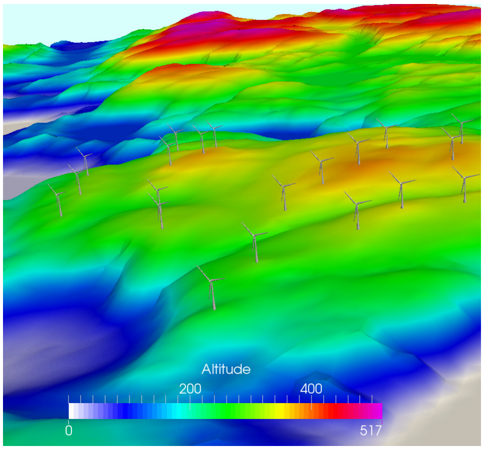
(a) Bessaker wind farm



(b) Digital model (Altitude in m)

Fig. 1. Bessaker wind farm

to significant improvements in turbine technologies (involving longer and lighter blades, efficient blade designs and effective operational control practices). Research continues to be devoted to make wind energy more affordable, which will boost the wind energy contribution and help to create a cleaner and greener environment. In this direction, an accurate estimate of wind resource will help to determine the expected power production and associated cost at a given site. Wind resource within a particular farm-site is influenced by surrounding terrain conditions, atmospheric stratification (which changes during the 24 hrs. day) and wake effects (wherein upstream turbine generated wake influences downstream turbines)[2]-[6]. Most of the numerical wind models used to predict wind conditions/power production over-simplify the actual physics for sake of faster computational time, in at least one of these three ways: by (a) not accounting for a complex terrain geometry and simplifying its effect by using a roughness factor with a flat terrain (b) assuming neutral atmospheric conditions and ignoring stratified conditions and accompanying buoyancy effects (c) using simplified wake models.

These simplified assumptions may give faster results but at the cost of accuracy. In this work, we have developed an advanced numerical model that can account for effects of highly complex terrain, atmospheric stratification and wake effects in a multi-turbine wind farm. The objectives of this work are two folds: firstly to test the predictive ability of this advanced numerical model, and influence of different components (e.g. with/without atmospheric stratification) on wind dynamics in a wind farm and secondly to apply this model on a realistic industrial wind farm for troubleshooting/designing it and encourage usage of advanced models with more physics for industrial wind farms.

This model has been applied on a realistic industrial wind-farm called Bessaker Wind Farm, which is operated by TrønderEnergie AS. The verification of results obtained by the model has been done with the observed power production trends at the Bessaker Wind Farm. The technical aspects about the Bessaker Wind Farm is given in the next section, followed by details of this advanced model, solution methodology, results and discussion and conclusion.

2. Bessaker wind farm and problem statement

Bessaker wind farm (Figure 1) is operated by TrønderEnergie AS, one of the largest energy provider in Norway. The farm is a located in a complex terrain in mid-Norway region near Trondheim. The hilly terrain rises from sea level to a maximum altitude of 500m. The onshore wind farm established on this complex terrain has 25 turbines, which are located at different altitudes in the terrain. The base of lowest turbine is located at 240m above sea level and the highest turbine is located at about 385m above sea level. Rest of the turbines are within the altitude range. All the 3 bladed turbine used in the wind farm have a rated power of 2.3MW, a rotor diameter of 71m and a hub height of 64m with cut-off speed at about 28m/s wind. Generally, most dominant wind directions recorded at this site at 35m above the ground is westerly and south easterly and the average wind speed is recorded in the range of $10-15m/s$ implying