Sensitivity of wind flow to atmospheric stability for a complex site with multiple masts

C. Montavon\(^1\), C. Rodaway\(^2\), P. Housley\(^2\), I. Jones\(^1\)

\(^{1}\) ANSYS UK Ltd, \(^{2}\) SSE Renewables

Abstract

Site complexity, both in terms of terrain and forestry, determines the speed, turbulence intensity (TI) and shear exponent factor (SEF) of the wind flow that will be experienced by turbines located on the site. Atmospheric stability conditions, and in particular diurnal cycles affecting the site, play a significant role in modulating these parameters. Understanding how the stability conditions affect the wind flow is important for turbine suitability and energy yield assessments. When modelling is based on the assumption of a neutral atmosphere, these assessments may not capture key site specific wind flow characteristics. This contribution investigates the sensitivity of the SEF and TI to surface stability conditions for a site of moderate terrain complexity with complex forestry. A CFD analysis of the site is performed for varying stability conditions, the results of which are compared to data from masts on site. Finally the simulation results are aggregated with site wind speed data and mesoscale hindcast data to derive the sensitivity of the predicted wind speed distribution on site to the assumptions in the simulation conditions.

Site description

The site, located on the west coast of Ireland, shows a terrain elevation range between 0 and 340m. It is equipped with 4 met masts, with anemometers measuring wind speed at approximately 15m, 50m, 65m and 81m (direction measured at 79m). Concurrent data at the masts is available for 13 months. A short data set (4 months) from a LIDAR VAD scan, located at the base of the hill from mast M1, is also available for validation.

A detailed distribution of forest canopy height in the immediate surroundings has been obtained from LIDAR scans at a horizontal resolution of 1m. The resulting canopy height distribution in the model, as shown in Fig.1, has been interpolated to the model resolution (typically 25m) from the 3 nearest data point in the LIDAR scan data set. Away from the central region, where no scan data is available, forest canopy height has been derived from coarser resolution roughness data.

Site data – sensitivity to stability conditions

Without stability data measured on site, as a first attempt to differentiate between stable and unstable surface conditions, the data was binned by night (mostly stable) and day (mostly unstable) time. An example of the sensitivity of the SEF and TI to diurnal binning is shown in Fig. 2 for mast M2 (mast located further south in a clearer, surrounded by forested patches with heights of typically 10-14m). This shows a clear trend towards increased SEF and reduced TI at night time and the opposite trend for day time, a clear indication that surface stability effects significantly affect the wind conditions on the site.

To be able to quantify the frequency of occurrence of the various surface stability regimes at the site, hindcast data from a WRF simulation covering the same period as the mast data [1] was analysed. The frequency distribution of the gradient Richardson number was derived overall and for 3 broad wind speed ranges (centred around 5, 10 and 15 m/s).

The resulting probability distribution of the Richardson number for the site suggests that stable conditions dominate slightly over the unstable conditions.

CFD model

CFD simulations of the site are carried out with ANSYS’ WindModeller [2]. Forest canopies are modelled with the Katul resistive forestry model [3] using a loss coefficient of 0.05 m\(^{-1}\), modelling the forest canopy to the full tree height. Atmospheric stability is modelled via a transport equation for the potential temperature, assuming an ISO standard potential temperature gradient above the boundary layer.

Surface stability conditions are specified through a potential temperature offset at the ground.

Simulation results & aggregated wind speed prediction

The sensitivity of the simulated SEF and TI at mast M2 to the surface stability conditions is shown in Fig. 5, for the most frequent wind directions. The observed trend in SEF and TI with direction is very well captured. For the SEF, the typical observed range around the average appears to be well reproduced when using surface temperature only as input. The range of variation in TI is well captured for the stable cases, but appears underestimated for the unstable cases, which could be accounted for by the resolved transient fluctuations that develop at low wind speed when working with unstable surface conditions. The average measured TI and SEF appear to lie between the adiabatic and stable results, which agrees with the WRF results analysis, hinting at average conditions slightly dominated by stable cases.

A comparison between measured and simulated WSR is shown in Fig. 6, for the most frequent wind directions. The WSR from the CFD have been obtained in three different ways: Firstly, results obtained from several simulations with stability and aggregating the WSRs by direction with weighing them with the frequency of occurrence of their wind speed/stability bin (inferred from the WRF data set), from one set of simulations using ‘average stability conditions’ derived from the aggregation method. For most sectors and mast pairs, accounting for stability trends to reduce the error in the estimation of the WSR. The aggregated results from several sets of simulations with varying stability conditions do not always deliver improved accuracy over those from one set of simulations with an ‘average’ stability condition. This is quite possibly associated with the strong transients that develop at low speed in unstable conditions, which introduce a large uncertainty in the predicted WSR. This will be addressed in future work by establishing the WSR from transient averaged results.

The relative difference in wind speed between turbine and mast is plotted in Fig.7 vs the elevation difference to associated mast for three different type of simulations. While both WAsP and the CFD predict a trend of reducing wind speed with reducing elevation, the trend is most pronounced when using the CFD simulations including stability effects. This trend is consistent with the observations that the contrast between the wind speed modelled near hilltops and valleys is enhanced in simulations accounting for stability effects. Accounting for tree growth over a period of 20 years, the CFD predicts a reduction of about 5% in average wind speed.

Conclusions

Comparing the trends by direction between the observations and model results shows that the inclusion of stability effects in the simulations accounts for the variability seen in the observation of the SEF and TI by direction, variability not otherwise explained by purely neutral simulations. Compared to the site analysis with WAsP, the analysis based on CFD including stability effects predicts a stronger reduction of wind speed with elevation below the reference mast. As a direction of future work, we can expect that when performing a site energy assessment from masts located near hill tops, the CFD including stability effects is likely to be more conservative than WAsP.

References

1. WRF Mesoscale Results, Carried out by Vortex, 2013, Private Communication, SSE.