Use of CFD Model for vertical wind extrapolation in complex terrain

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Abstract

In this study, a wind resource assessment was performed on the An Suidhe Wind Farm site which is located in a forested and complex terrain in Scotland. The modeling has been done with the CFD software Meteodyn WT, using a fine resolution grid and activating a forest model. Results have been compared with on site measurements thanks to the availability of multiple met masts.
As sites for wind farm development increasingly extend into areas of complex terrain, wind turbine hub heights are becoming greater. Vertical extrapolation of the wind with height will have an influence on the wind speed and thus on energy production. Furthermore, the uncertainties on the wind speed estimations are higher due to the presence of forests.

Introduction

RWE Npower Renewables Ltd is developing a wind farm project in complex terrain where non-linear flow models reduce the error on expected wind resources.

The wind farm layout covers approximately 2.5 * 3 square kilometers, with two meteorological masts on the forested and complex site. Both masts were equipped with three anemometers (at 20m, 30m and 50m). Distance between the two masts is about 1 kilometer. 15 months of data were collected allowing the wind resource analysis.

The wind farm layout, as well as the characteristics of the two types of the 23 medium power wind turbines which are planned to be installed, have been supplied. These have been analyzed in conjunction with the results of the wind analysis in order to predict the annual energy output of the An Suidhe wind farm.

Altitude variations near the site, highlighting the orographical complexity of the site, are plotted on the following figure.

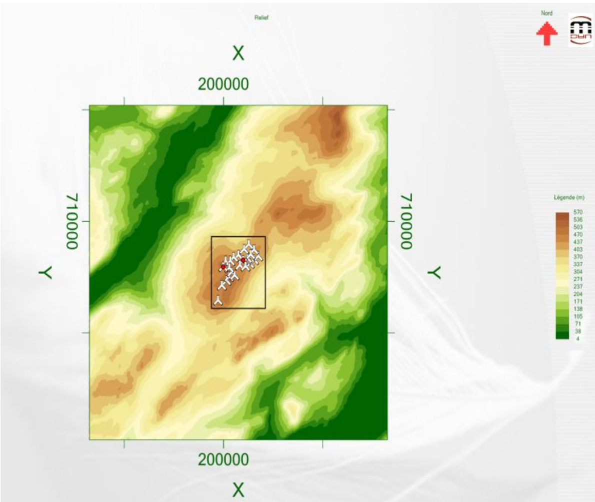


Figure 1: Topography, met masts (red points) and wind turbines location

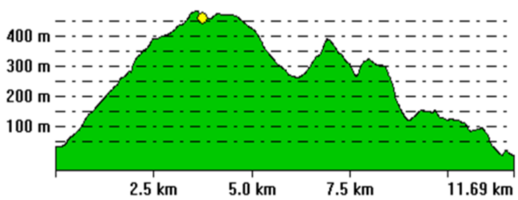


Figure 2: Altitude variation near the site

Values of roughness correspond to water bodies, coniferous forest, moors and headlands, and transitional woodland-shrub and were deduced from CORINE Land Cover 2000 database.

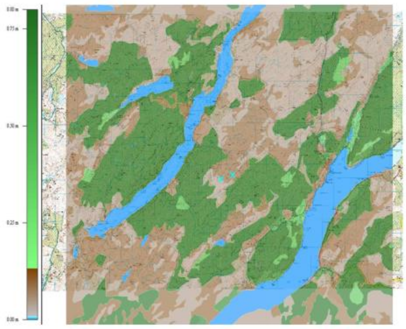


Figure 3: Roughness map derived from CORINE Land Cover 2000 database

Methods

Orographical and roughness data discussed in the previous section are used as inputs for defining the site in the CFD software Meteodyn WT.

A fine resolution grid (4 meters in the vertical direction, 10 meters in the horizontal direction, resulting in 8 - 9.2 million cells depending on wind direction) was used to model wind flow over the site. This fine resolution has permitted the computation of flow over a complex and forested area.

The minimal horizontal resolution drives the horizontal length of calculation cells near the result point location whereas the minimal vertical resolution drives the vertical length of the calculation cells near the ground.

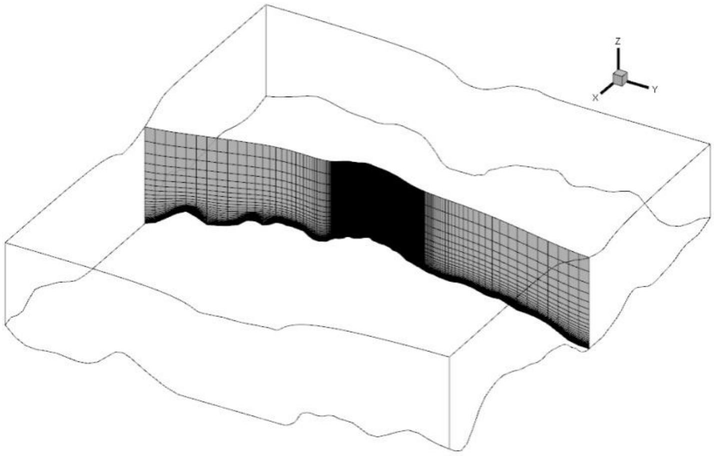


Figure 4: Vertical computation mesh for the 180 deg direction

Directional calculations were performed for 23 sectors, refining the number of directions around the predominant wind sectors.

Synoptic direction (deg)	Number of cells (-)
30	8 854 272
60	8 608 320
80	6 812 640
100	6 812 640
110	8 012 124
120	8 854 272
130	9 289 980
140	9 031 925
150	8 608 320
160	8 012 124
180	6 715 800
210	8 854 272
230	9 289 980
240	8 608 320
260	6 812 640
270	6 715 800

Figure 5: Number of cells for the modeling of each direction

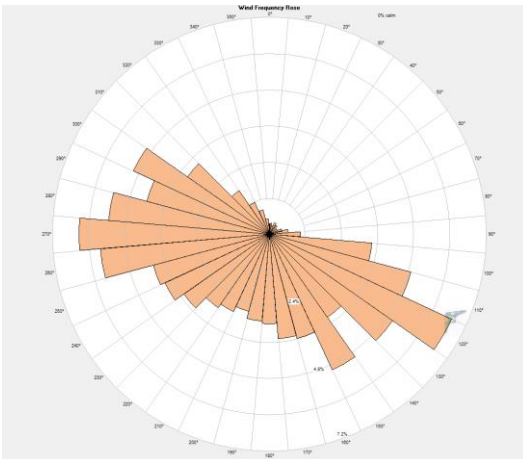


Figure 6: Wind rose at met mast 1

Meteodyn WT solves the steady isotherm uncompressible Reynolds Averaged Navier-Stokes equations.

- Mass conservation: $\frac{\partial \rho \overline{u_i}}{\partial x_i} = 0$
- Momentum conservation: $-\frac{\partial(\rho \overline{u_j}\,\overline{u_i})}{\partial x_j} - \frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \rho\,\overline{u_i^{'}}\,\overline{u_j^{'}}\right] + F_i = 0$

The non-linear Reynolds stress tensor is modeled by a one-equation closure scheme (k-L model, developed by Yamada and Arritt [1], dedicated to atmospheric boundary layer resolution).

The turbulent viscosity is considered equal to the square root of the turbulent kinetic energy multiplied by a turbulent length scale which depends on stability.

$$\upsilon_T = k^{1/2} L_T$$

Where the turbulent kinetic energy represents the kinetic energy of the speed fluctuations in a turbulent flow: $k = \frac{1}{2}\, u_i^{'}\, u_i^{'}$

Perturbations due to forests usually generate a high level of turbulence and strong wind shears. Meteodyn WT takes these parameters into account by incorporating a sink term in the momentum conservation equations and a turbulence production term in the turbulent kinetic energy equation for the cells lying inside the forested areas [2]. The turbulent kinetic energy transport equation is given by:

$$U_j \frac{\partial k}{\partial x_j} = P_k - \varepsilon + \frac{\partial}{\partial x_j}\left[\left(\frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]$$

With $\varepsilon = C_\mu \frac{\upsilon_T}{L_T^2} k$ (dissipation) and $P_k = \upsilon_T \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_j}{\partial x_j}$

The length scale of turbulence L_T as well as the $C\mu$ coefficient are depending on the atmospheric stability through Richardson flux number R_{if} as follow:

$$L_T = \sqrt{2} S_m^{3/2} l$$

Where l is the Monin Obukhov length defined by: $\frac{1}{l} = \left(\frac{1}{l_0} + \frac{1}{\kappa z}\right)$,z = height and κ=0.41, l_0=100 m

$$S_m = 1.96 \frac{(0.1912 - R_{if})(0.2341 - R_{if})}{(1 - R_{if})(0.2231 - R_{if})} \text{ if } R_{if} < 0.16$$

$$S_m = 0.085 \text{ if } R_{if} > 0.16$$

$$C_\mu = \frac{4S_m}{B_1}, B_1 = 16.6$$

The data from both met masts contained some corrupted values. Instead of removing the corrupted wind speed measurements and reducing the quantity of available data, each corrupted sample was re-evaluated from directional correlations between anemometers.

On the next figure, the effect of the correction process on mast 2 is highlighted. On the left side, we can observe the monthly mean wind speed before the correction, which is wrongly evaluated in September because of the amount of corrupted data. Right side shows the effect of the correction.

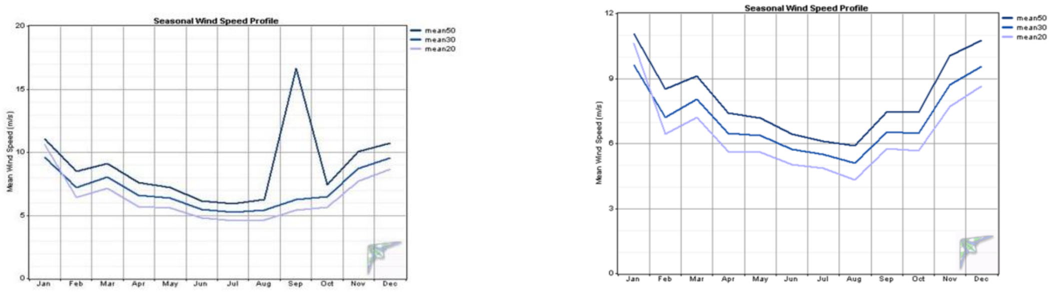


Figure 7: Monthly mean wind speed before (left side) and after (right side) the data correction

After analyzing the wind shear variation and because of strong mean speed (around 8m/s at 50 meter high), the modeling focused on a neutral stability class.

Results

Orographical and roughness data discussed in the previous section are used as inputs for defining the site in the CFD software Meteodyn WT.

The 6 anemometers are defined as single result points. Only two of them will be used as reference points when running the wind extrapolation process (one for each mast). The other measurements heights will only be used in order to check the accuracy of the model.

The 23 wind turbines are defined. The site is centered on the wind farm. The radius has been set at 7.5 km in order to take into account the main altitude variations near the site.

Directional results

For each met mast, the measured climatology is applied on the highest measurement point (which become the reference point, in this case at 50 meter high) and then extrapolated from the reference point toward all the result point locations, based on the directional characteristics calculated in previous step.

In order to remove completely any thermal effect, a high wind speed condition filter is applied on the highest anemometer: each collected sample with a 10 minute average wind speed lower than 10 m/s is not taken into account.

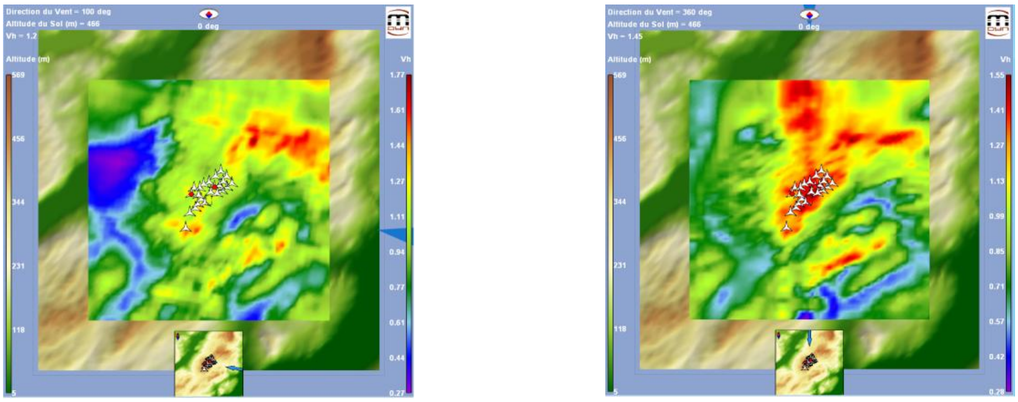


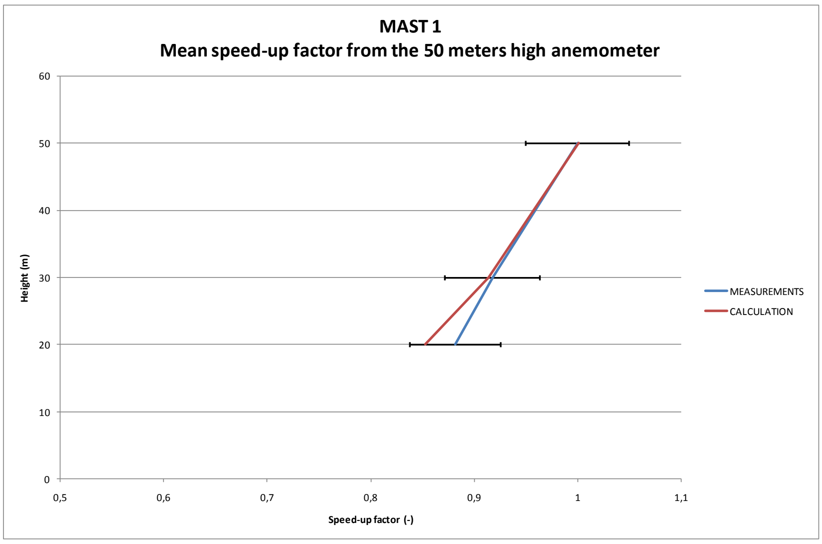
Figure 8: Speed up factor at 55 meters high for 100° (left side) and 360° (right side)

Then the accuracy of the wind extrapolation using the CFD computations is checked by comparing computational results to measured data at the met masts.

Extrapolation

Mean vertical profiles and extrapolation errors are given on the following tables and figures. The table presents the error on the mean speed up factors (normalized by mean wind speed measured at 50 meters) for both mast 1 and 2.

Height (m)	Error Mast1 (%)
50	0.14
30	-0.47
20	-3.33



Height (m)	Error Mast2 (%)
50	0.14
30	2.75
20	5.38

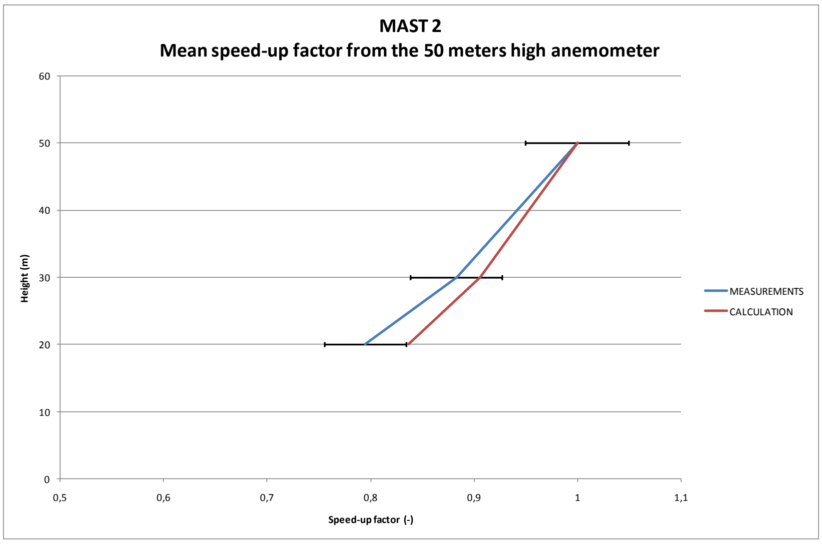


Figure 9: Error on mean speed up factor

For mast 1, mean wind speed is very well estimated. For mast 2, we can note that the error at 20 meters is around 5%. This is due to orographical data that are not fine enough to catch all of the complex altitude variations on the site.
However, as the used measurement height (50 meters) are very close to the hub height (55 meters), there is likely to be minimal vertical extrapolation inaccuracies and therefore little impact on the energy production estimation.

A wind extrapolation can be made from the directional results including the complete range of wind speeds. In this case, the vertical profiles show an error similar to the ones observed previously (at 30 meters -0.6% for mast 1, +3.1% for mast 2).

Eventually, the accuracy of the horizontal extrapolation is evaluated. In this case, the chosen reference point is the mast 1, at 50 meter high. The modeled wind speed at mast 2 at 50 meter high anemometer is compared with measurements.

Mean reference wind speed (m/s) Mast1 – 50 m	Mean calculated wind speed (m/s) Mast2 – 50 m	Mean measured wind speed (m/s) Mast2 – 50 m
7.99	8.089	8.108

Figure 10: Comparison of the measured and extrapolated wind speeds at mats2 50 meters high anemometer

The corresponding error is particularly small, equal to 0.23%.

Conclusion

The standard error on the mean wind speed estimations is around 5%.
The results of An Suidhe wind farm are satisfying and highlight the fact that non linear flow models are adapted to perform well in complex and forested terrain.
The expected energy production as well as the expected wake losses were computed for 23 wind turbines of two different types.

References

[1] P. J. Hurley (1997); *An evaluation of several turbulence schemes for the prediction of mean and turbulent fields in complex terrain*
[2] A.N. Ross, S.B. Vosper; *Neutral Turbulent flow over forested hills*