Calculation of depleted wind resources near wind farms

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Introduction

Wake losses between neighbouring wind farms are both important for developers of new farms and for owners of existing farms. Planning authorities will usually keep inter-farm wake-losses at an acceptable level by reserving turbine-free zones around each wind farm. This wind farm separation should however not be too large, as this could mean wasting limited areas with favourable conditions for wind energy. This presentation will demonstrate a new computationally efficient method for mapping the wind-resource depletion in the vicinity of wind farms.

Approach

Linear wake models allow us to use a new algorithm based on Fourier transformation, for computation of the wake-affected velocity field near a wind farm cluster. As usual, the wind resource map is calculated by probability-weighted integrals of the local energy density, or production of a sample turbine, at all wind conditions. The difference is that we include wake effects.

The new method is illustrated by an examination of the atmospheric stability effect in the Fuga model, and the effect of a variable wake-decay factor in the Park model, also known as the Jensen-Katic model.

Main body of abstract

The main idea of the new algorithm is to construct maps of wakes from multiple turbines by a convolution of the velocity field behind a single turbine and maps of thrust-related influence factors for all turbines. This convolution is done by Fast Fourier Transformation (FFT), which is more efficient than direct computation. The influence factors depend on wind conditions and they are evaluated just like in a traditional annual energy production (AEP) calculation, where we first sort turbines after wind direction, estimate the wakes from upwind turbines, and progressively calculate sheltered wind speeds and thrust of turbines further downwind in the wind farm. The calculation time is equal to that of the usual AEP algorithm plus extra time needed for convolution of wakes and influence factors. The time used for Fourier transformations does not depend on the number of turbines, only on the number of turbine types.

The FFT-based solutions are cyclic, so the convoluted field needs a buffer-zone to avoid wrap-around effects of wakes crossing boundaries of the map part of interest. The extent of the buffer zones is optimized for each wind direction. The FFT calculations are further optimized by use of the FFTW algorithm and by simultaneous transformation of pairs of real fields stored as real and imaginary parts of a complex field.

The method should work for all linear wake models, i.e. models where we can add solutions from several turbines and scale fields of velocity deficits by factors depending on turbine thrust. The method has been implemented for two models - Fuga, based on linearized CFD, and the Park model, which is part of WAsP. The Park model is not linear, since it evaluates the combined wake effect from multiple turbines by the root of the sum of squared wake contributions. For this model, we modify our method by squaring single-wake fields and maps of influence factors before convolution and finally take the square root of the sum of fields for all turbine types.

A linear wake model can be applied for flow in complex terrain in an approximate way. The thrust coefficient of a wake-shedding upwind turbine is evaluated at a wind speed corrected for terrain-induced speed up as well as local wake corrections. In addition, the wake velocity deficit is scaled at the site of prediction by the same speed-up factor as the ambient wind. In the present model we evaluate the thrust of each turbine at a wind speed corrected for the speed up relative to the reference site. The combined wake effects found by the FFT-based convolution applies to a wind speed at the reference site, which may differ from local wind speeds. When predicting the wake effect at a new site we therefore interpolate in a set of intermediate solutions for a range of winds at the reference site. In the context of resource modelling this does not increase the work load significantly, since we already have to evaluate wake effects for multiple wind speeds. We just have to ensure that the range of reference-site wind speeds is wide enough to enable wake estimates for the range of turbine operation at all positions in the map.

Fuga is developed for offshore wind energy and assumes flat terrain and uniform surface roughness. Surface roughness and atmospheric stability are input parameters which determine the ambient wind profile and eddy diffusivity, which are uses to model the wake development. The Park model does not make any assumptions on the terrain, and the expanding wake is simplified to a cone parameterized by a wake decay factor, defined as the tangent of half the opening angle. It is recommended to select a smaller wake decay factor for offshore projects than for onshore projects.

Figure 1 compares different predictions of the wind resource reduction around the Rødsand offshore wind farm with 90 turbines. The wind climate is predicted by a WAsP resource grid, which provides frequency of occurrence and Weibull wind speed distributions in twelve wind sectors at every point at 102x35 grid nodes with 200m resolution. Maps of wake-velocity deficits are calculated for 360 wind directions and 27 wind speeds, and a map of the AEP of sample turbine, of the same type as the neighbouring wind farm, is calculated with and without wake effect using the wind-climate predictions of the WAsP resource grid. When using a Windows PC with an i7-2760QM CPU, the calculation time for one of the computations shown in the Figure 1 becomes 865 sec by direct computation and 27.8 sec by the suggested FFT-based method. The performance ratio of the two methods will depend on the dimensions of the resource grid and on the number of turbines.

The left-hand side of Figure 1 shows a significant effect of atmospheric stability in the Fuga predictions. The stability variations are not extreme, as the Monin-Obukhov numbers are L=333m for the stable case and L=-200 for the unstable case. It should be said that it is unrealistic to use the same stability at all wind speed, but it is difficult to obtained reliable joint statistics of wind speed, direction and stability.

The right-hand side of the Figure shows calculations by the Park model with variable wake-decay factor. A similar effect is observed, and it is tempting to consider the wake-decay factor as a kind of stability parameter. That approach is tested in Figure 2, which shows the lost AEP along an East-West transect through the middle of the neighbouring Nysted wind farm. The Park model wake effect decays faster with distance in than that of Fuga, so it is not possible to match the results of the two models for all distances.

Figure 3 shows resource maps for a small wind farm in complex terrain. As expected, we observe larges wind resource near each of the turbine sites and smaller reductions far from the wind farm. Most sites have a bi-modal wind distribution with the most frequent winds near 150° and 300°. This wind-rose orientation is reflected in the depleted AEP map.

Conclusion

A new method for calculating maps of wake effects from multiple turbines is presented. It is sufficiently fast to calculate maps of AEP with wake effects, i.e. maps of the depleted wind resource near wind farms and wind farm clusters. The method has been used for a comparison of the Fuga and Park wake models. Fuga is shown to be sensitive to atmospheric stability, and Park is sensitive to its empirical wake-decay factor. It is not possible to select a wake-decay factor, which will match the Park model with Fuga for all distances.

Learning objectives

- to calculate wake effect of a large number of wind turbines efficiently
- to calculate wind resource maps with wake effects
- to compare the Fuga and Park wake models

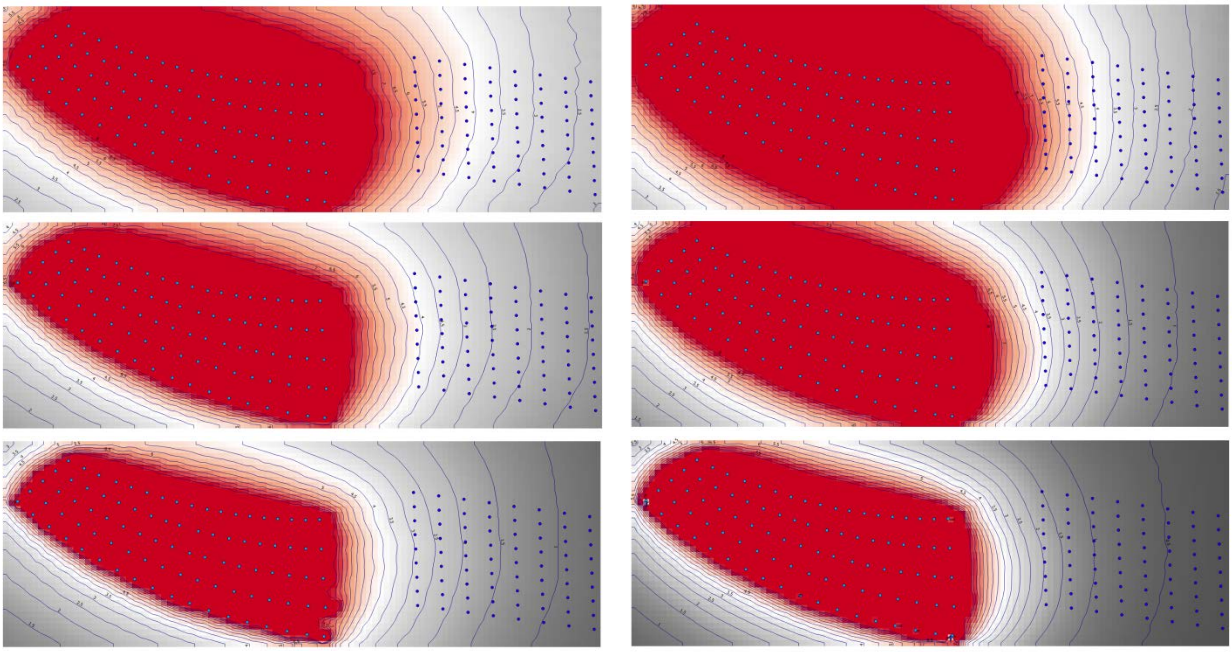

Figure 1: Lost AEP [%] around Rødsand windfarm predicted by the Fuga (left) and Park (right) wake models. Turbine sites are indicated by blue dots and the color scaled for the AEP loss runs from 0% (dark grey), white (4%) to red (8% and above). Results by the Fuga model are calculated for a fixed surface roughness of z0=1e-4 and weakly stable (z0/L=3e-7, top), neutral (middle) and weakly unstable (z0/L=-5e-7, bottom) ambient atmospheric stability. The results by the Park model are calculated for different wake decay factors, i.e. very low (k=0.02, top), a common offshore value (k=0.04, middle) and a common onshore value (k=0.075, bottom).

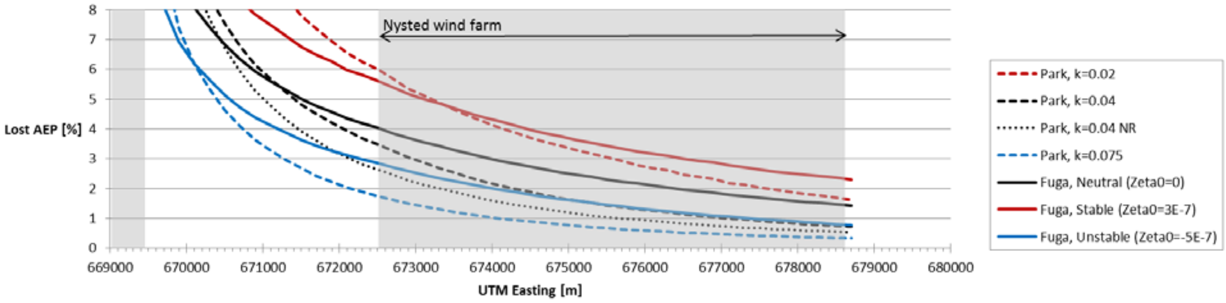

Figure 2: Lost AEP [%] around Rødsand windfarm along an East-West transect trough Nysted wind farm. Grey shades indicate the position of the two wind farms.

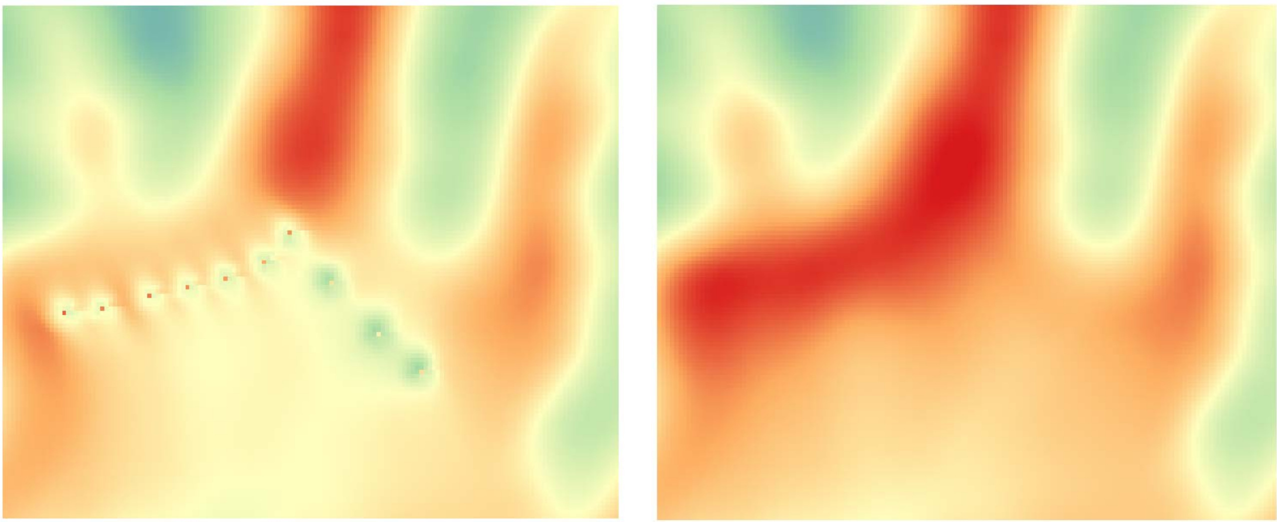

Figure 3: AEP in complex terrain with (left) and without (right) wake effects.