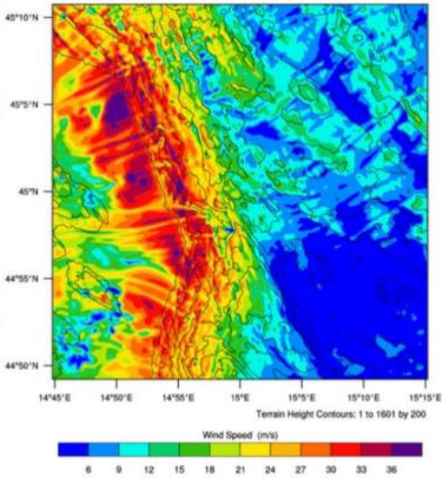

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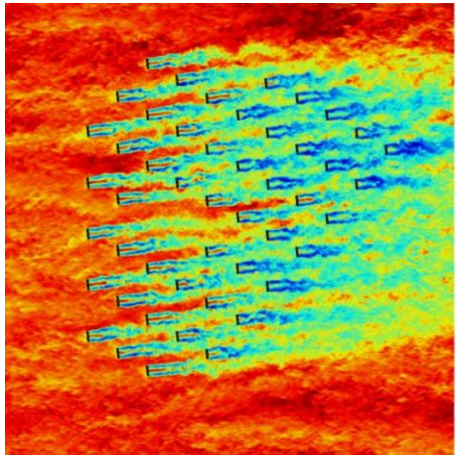
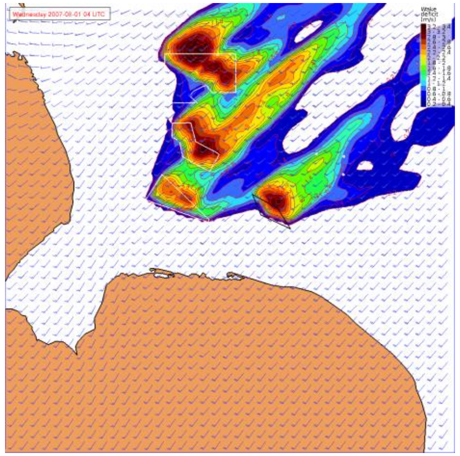




Using WindSim to determine turbine performance due to site specific wind shear

Niklas Sondell

Karlstad Modern Energy AB

Background and experience

Broad experience from all stages of project development from initial wind measurements to post-construction wind farm optimization

ROLF-ERIK KECK

SENIOR SPECIALIST WIND&SITE

Rolf-Erik has a strong background in driving R&D projects and conducting technical calculations from the wind industry and hold s a PhD in wake modelling. During his five year at Vestas he has driven R&D projects targeted at power performance testing, profile aerodynamics, full rotor simulation and wind farm aerodynamics and loads.

The last three years Rolf-Erik has worked as a senior specialist for Statkraft A/S in Oslo where he is responsible for all wind and site activities as well as layout optimization at Fosen wind portfolio which at 1000MW capacity is the largest onshore project in Europe (https://en.wikipedia.org/wiki/Fosen_Vind). In the role as wind & site responsible for Fosen, the main tasks has been focused on analyzing wind measurements to assess production and turbine performance and loading, conducting CFD calculations, optimizing layout based production & loads.

An important part of the reasonability has been to act as the technical expert in the turbine tender process to ensure optimal turbine configuration for local conditions and adequate load assessment.

NIKLAS SONDELL

SENIOR SPECIALIST WIND&SITE

Niklas has a strong background in meteorology and mechanical engineering combined with a solid programming and IT knowledge. This make him a valuable assets as he combines knowledge of large and mesoscale dynamics with detailed knowledge of micro scale CFD and turbine response.

In recent positions within the applied meteorology department at StormGeo and as a Senior Wind Resource Analyst at Statkraft, he has been the main responsible for several internal R&D projects within a wide variety of field such as: wind farm production forecasts, ice prediction & modelling, site specific turbine performance as well as asset analysis and post-construction wind farm optimization.

Within Statkraft Niklas has also served as the main responsible for yield, wind resource, layout and site suitability for the 402MW Dudgeon offshore wind farm (http://dudgeonoffshorewind.co.uk/).

Topics

- Mapping site specific wind shear performance with WindSim using Rotor Eqvivalent Wind Speed (REWS) approach.

- In-house tools for weighting wrg files using three different stabilities and to calculate a REWS wrg files. WRG files for three heights and three different stabilities (total 9 files) is extracted from WindSim and weighted into one single file.

Wind shear correction – rotor equivalent wind speed with veer correction

Q.2 Definition of rotor equivalent wind speed under consideration of wind veer

The rotor equivalent wind speed is the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the vertical wind shear and veer. For the case that at least three measurement heights are available (see Subclause 7.2.5) the rotor equivalent wind speed is defined as

$$v_{eq} = \left(\sum_{i=1}^{n} (v_i \cos(\varphi_i))^3 \frac{A_i}{A} \right)^{1/3} \quad \text{(Q.1)}$$

where

n is the number of available measurement heights ($n \geq 3$);

v_i is the wind speed measured at height i;

φ_i is the angle difference between the wind direction at hub height and segment *I*;

A is the area swept by the rotor (i.e. πR^2 with radius R);

A_i is the area of the i^{th} segment, i.e. the segment the wind speed v_i represents (refer to Clause 9.1.2.1, Equation (6).

Determination of area segments

The segments (with areas A_i) shall be chosen in the way that the horizontal separation line between two segments lies exactly in the middle of two measurement points. The segment areas are then derived according to Equation (6):

$$A_i = \int_{z_i}^{z_{i+1}} c(z)dz = g(z_{i+1}) - g(z_i) \qquad (6)$$

where

z_i is the height of the i th segment separation line ($H-R<z_i<H+R$), numbered in the same order as v_i (either top down or bottom up).

The rotor width at height z is:

$$c(z) = 2\sqrt{R^2 - (z-H)^2} \qquad (7)$$

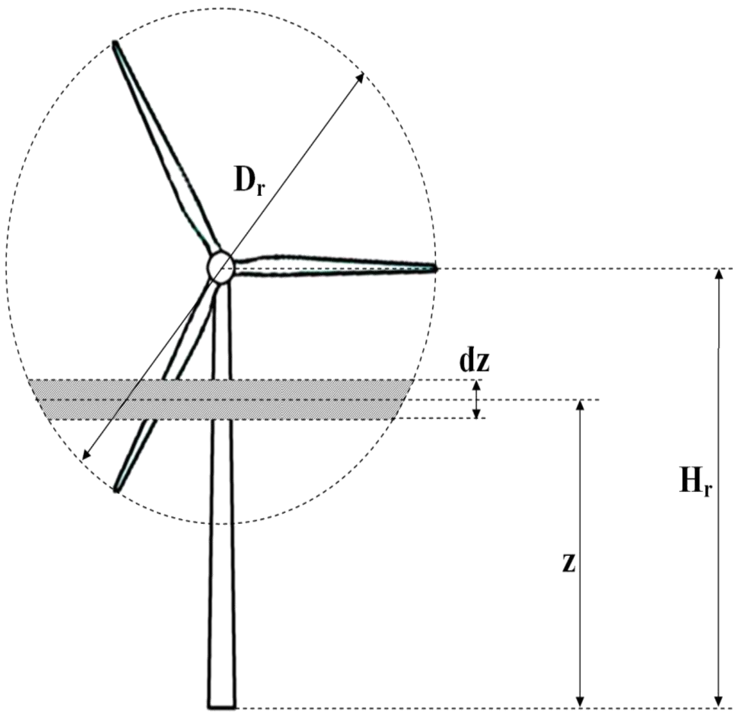
Where

R is the rotor radius

H is the hub height

The integrated function is:

$$g(z) = (z-H)\sqrt{R^2-(z-H)^2} + R^2 Arc\tan\left(\frac{z-H}{\sqrt{R^2-(z-H)^2}}\right) \qquad (8)$$



In the wind shear correction function ***dz*** is set to 1 m

IBL – Internal Boundary Layer

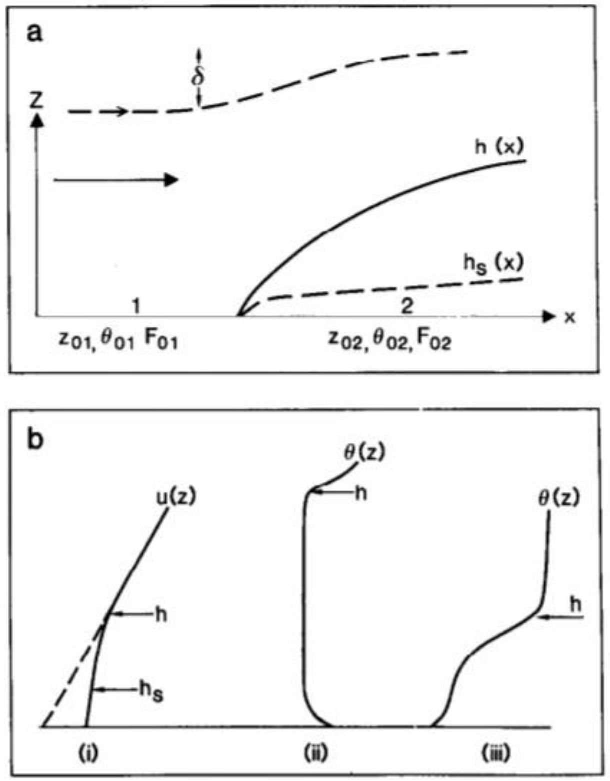
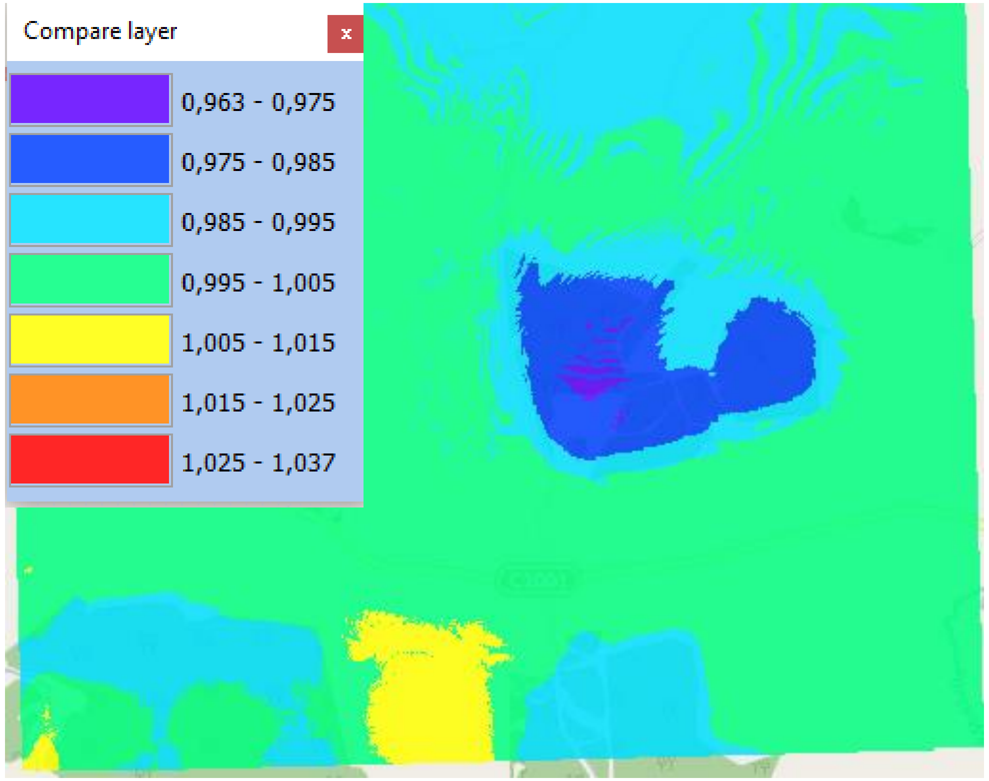
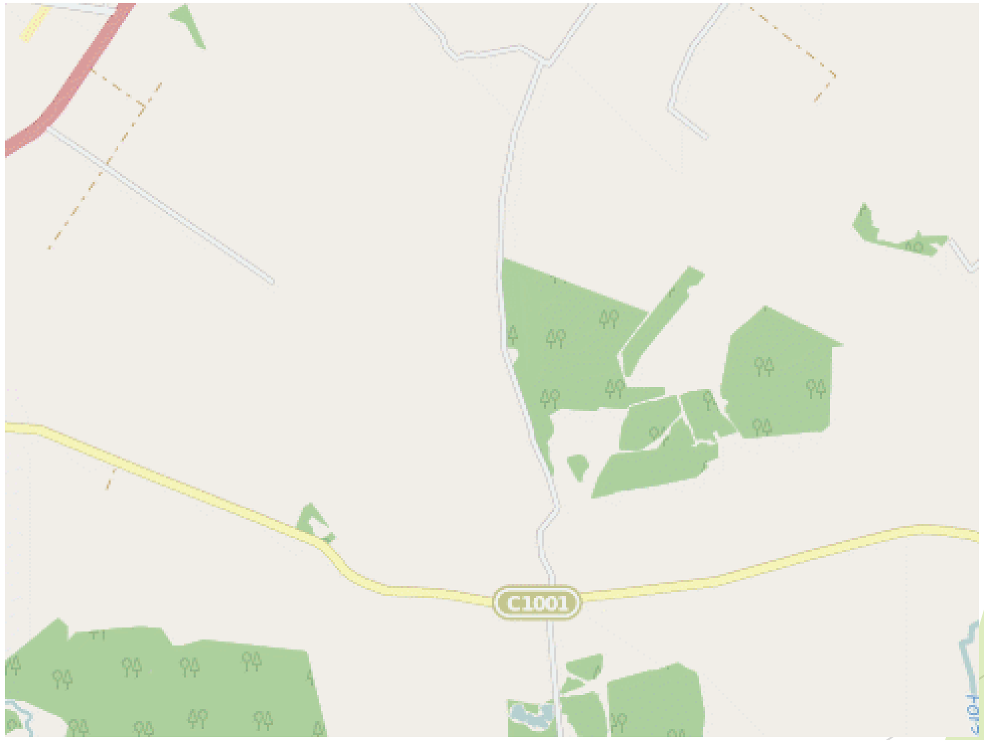


Fig. 2. (a) Schematic representation of the IBL $h(x)$ and inner equilibrium layer $h_s(x)$ downstream of a step change in roughness (z_0), temperature (θ_0) and heat or moisture flux (F_0). Streamline displacement, δ, is also shown. (b) Vertical profiles at a distance x downstream of the discontinuity – (i) wind profile for neutral flow across a z_0 change; (ii) θ profile for an unstable IBL and θ_0 change; (iii) θ profile for a stable IBL and θ_0 change.

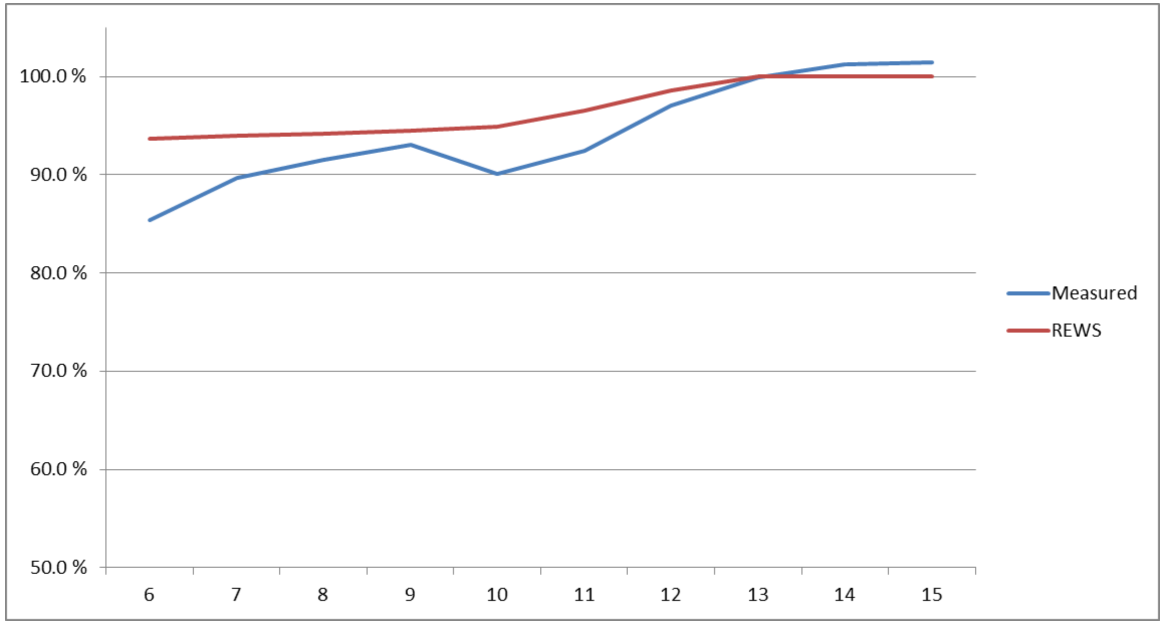
Rotor Eqvivalent Wind Speed (ratio) Forest IBL (Internal Bounday Layer)





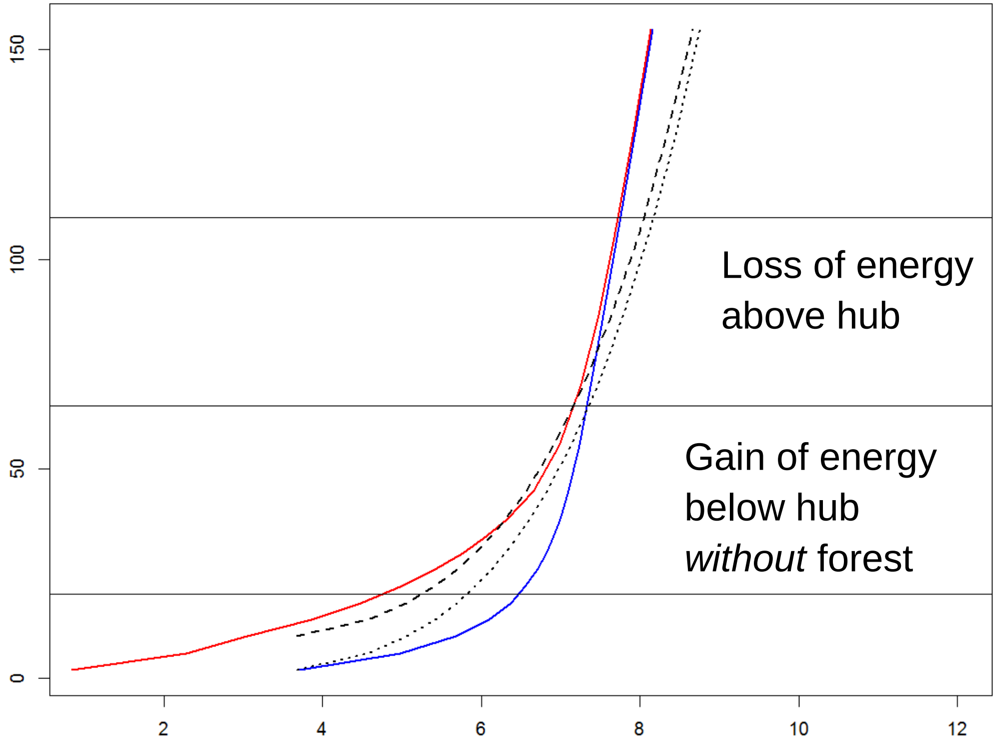
Performance

- The measured performance together with the modelled performance from previous slide.
- REWS explains a lot of the performance loss. Only energy losses are included, although the strange shear profiles will also give areodynamic losses in addition to the energy losses. Wind veer is also neglected / not known.

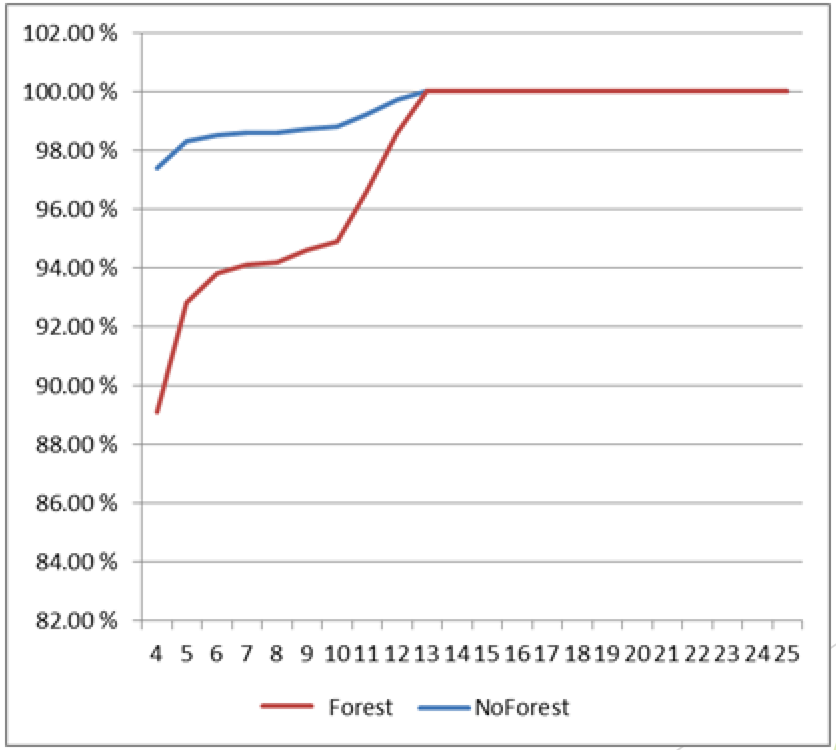


Change in wind profile when removing the forest

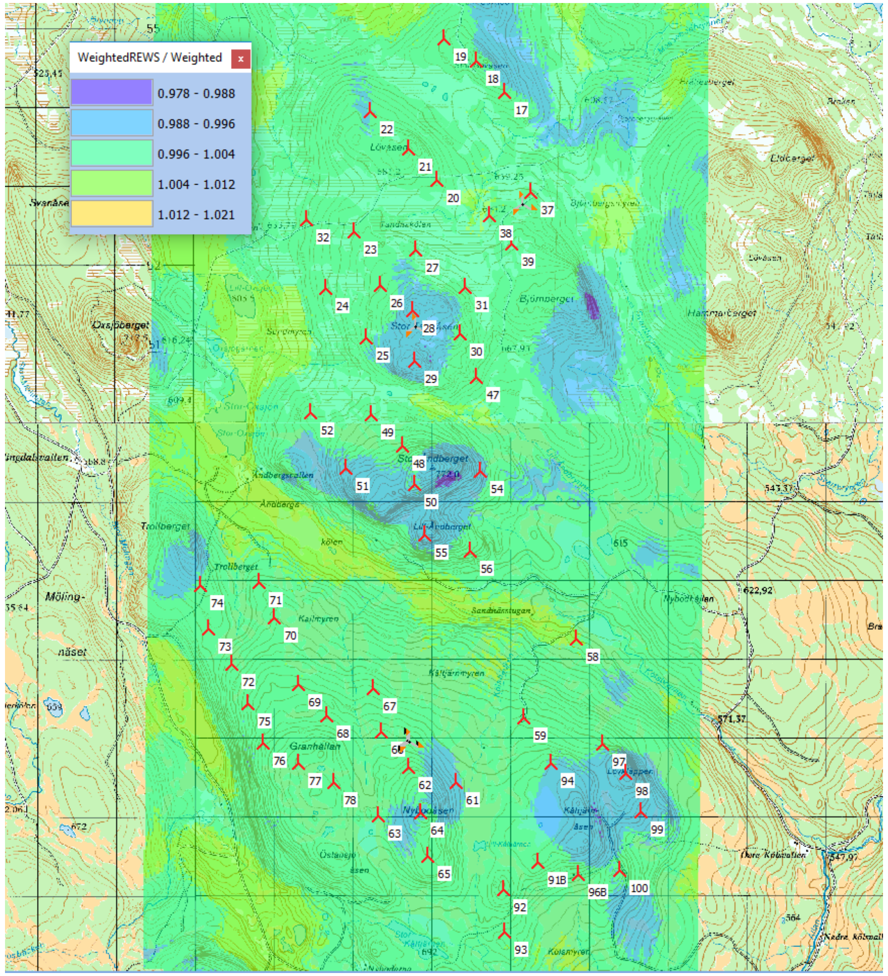
Modelled profiles, sector 240. Blue line without forest, red line with forest. Black dotted line standard shear profile with alpha=0.2. Black dashed line is similar but with a zero displacement height of 8 m (to match the forest case).

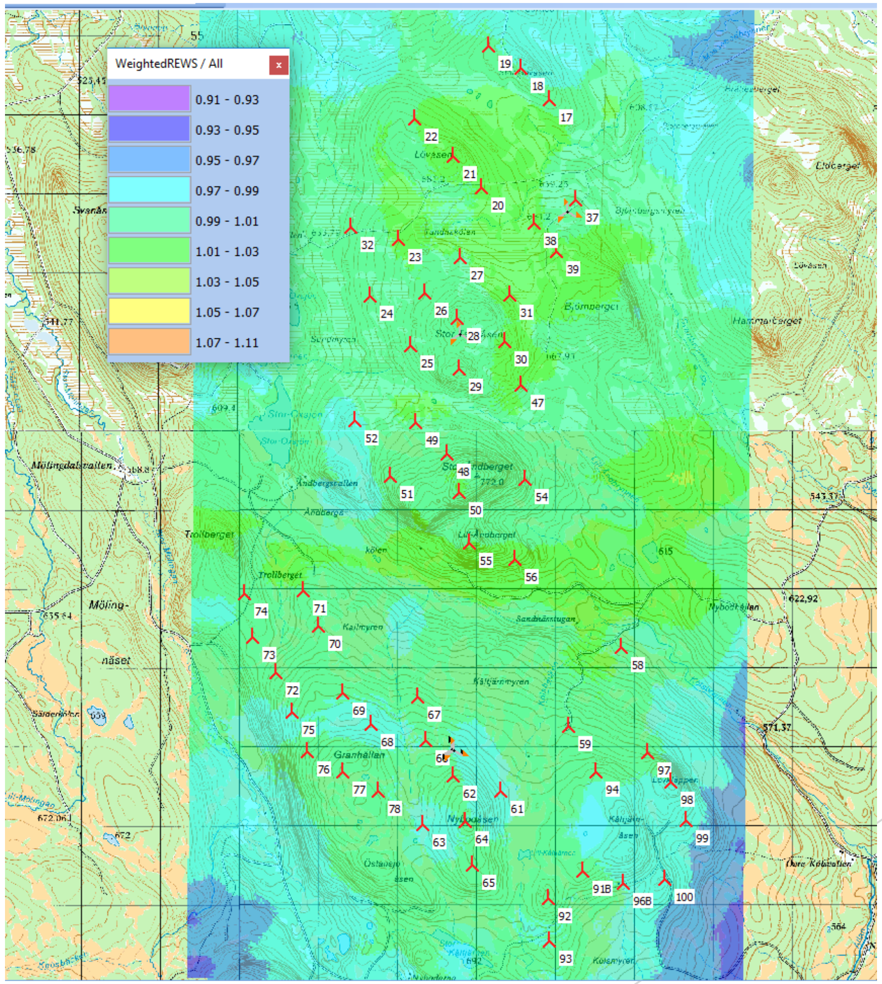


The REWS performances for the two different cases are shown below. The speed-up below hub height gives an increase in performance for the case without forest.

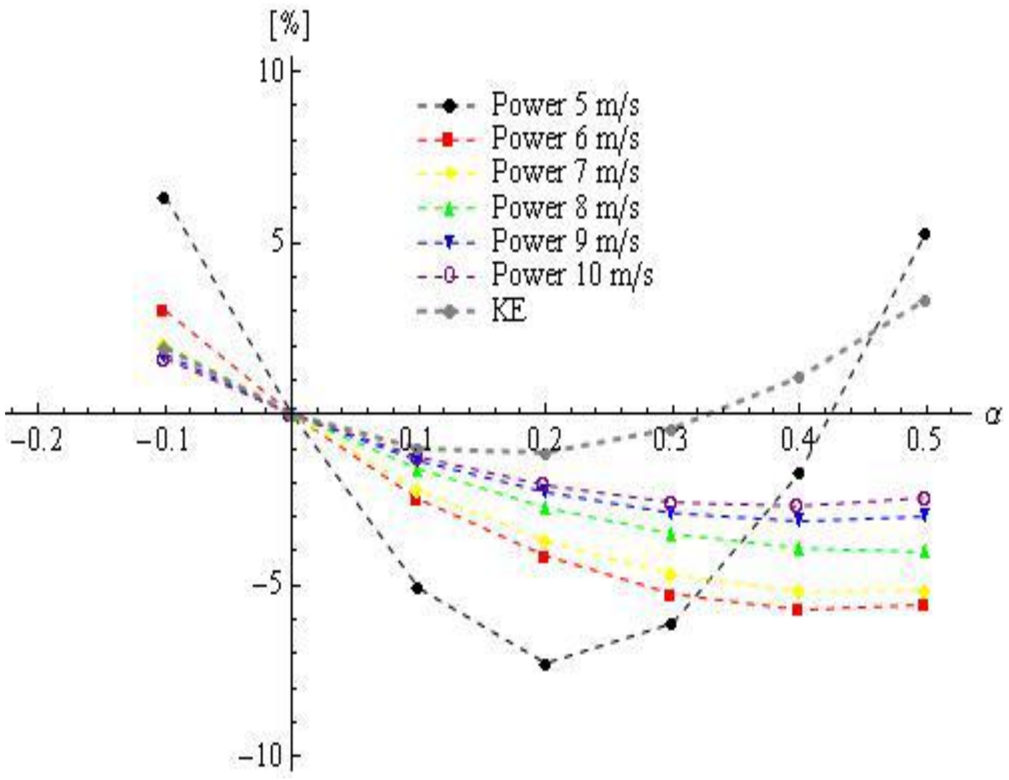


Results from wrg weighting tool





Aerodynamic losses increase with increasing alpha at moderate wind speeds



Simulation of shear and turbulence impact on wind turbine performance
Wagner Rozenn, Courtney S. Michael, Larsen J. Torben,
Paulsen S. Uwe
Risø-R-1722(EN)
January 2010

Figure 13.6. Normalised difference in kinetic energy flux and in power output between shear case and uniform case as function of the shear exponent, for various wind speed at hub height.[39]

When to look for decreasing shear alpha with height

- Onshore
  - Very stable surface layer. Winter or nighttime connected to surface temperature inversions and quasi frictionless laminar flow above the low stable boundary layer. Can be connected to low level jets.
  - IBL (Internal boundary layers). Steep roughness changes and especially step changes in surface temperatures which changes surface stability.
  - Very unstable. Profiles might be steeper than predicted by power law when the atmosphere is unstable.
- Offshore
  - Mostly connected to IBL's and low level jets when warm air is advected offshore from warmer land areas which gives a stable atmospheric surface layer. This is much more seasonal offshore than onshore, although this effect is enhanced during daytime in spring and summer when land areas are warmed up.

The non-theoretical wind shear, meaning not following the power law profile over the rotor disk seems to have the largest impact on performance. With wind shear alpha decreasing with height there is a clear performance loss.

Additional comments

- Using roughness instead of direct forest modelling sometimes looks more correct when verifying only against wind speed at hub height, but might be worse when verifying against the whole wind profile.
- Using stable atmospheric stratification as part of the model results is needed to get correct wind shear in northern countries.
- Pure neutral and MO=10000 gave completely different results for a UK site. MO=10000 gave by far the most correct results.
- WindSim can only deal with IBLs created by roughness changes and forest forces, not changes in heat flux.
- **It is the total energy over the rotor disc that matters!**

ADDITIONAL

Ekman spiral

- The Ekman spiral is used to find the veer between hub height and a specific height along the rotor disc. The Ekman spiral is defined as

$$U = -Ge^{-\beta}\sin\beta,\ V = G(1 - e^{-\beta}\cos\beta),$$

where G is the geostrophic wind speed, $\beta = z(f/2K_M)^{1/2}$, f is the Coriolis parameter, and K_M is the eddy viscosity.

- Based on the veer between two different vanes at two different heights the eddy viscosity K_M is determined and then used in the ekman spiral Equation to determine the veer between two specifc heights.

Terrain/stability dependence

- Based on 10m/s above BL => 7-8m/s at hub height
- Binned in 24 sectors of 15deg
- The effect of atmospheric stability in WindSim is a 0 to 20% variation based on topography

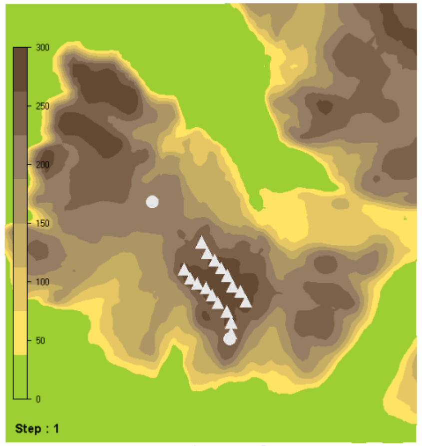
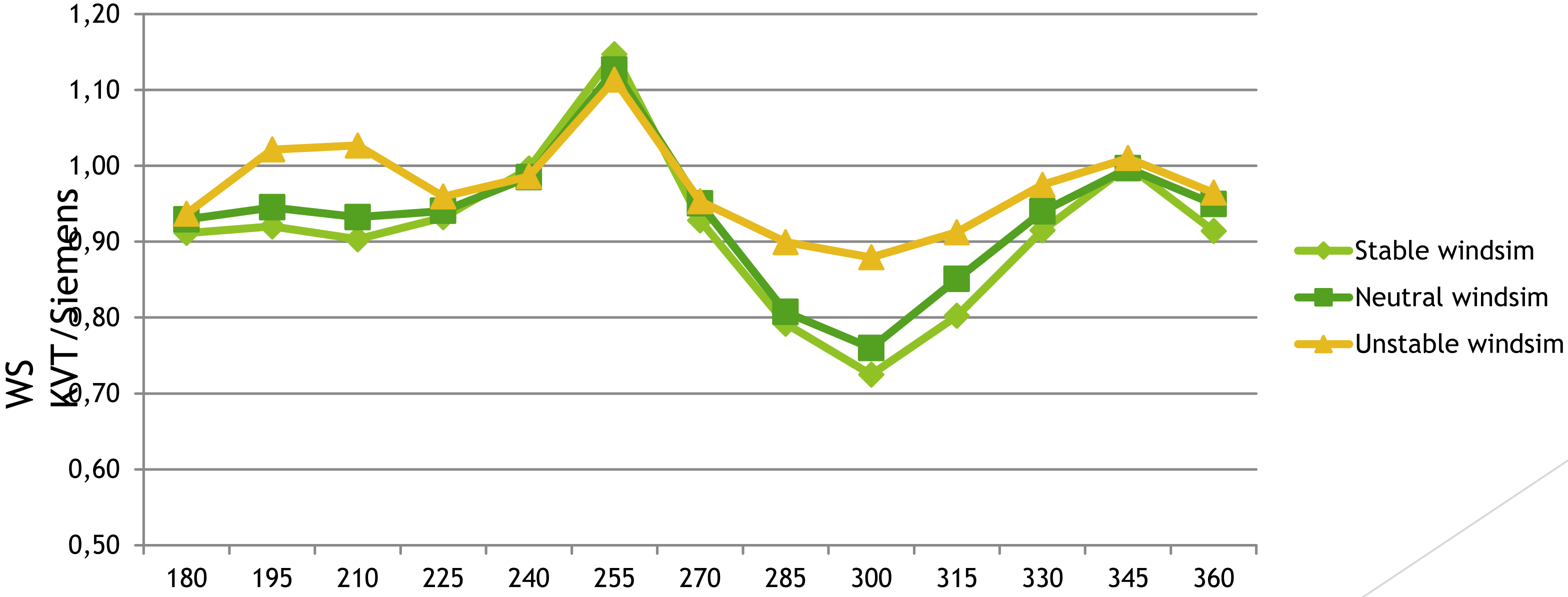
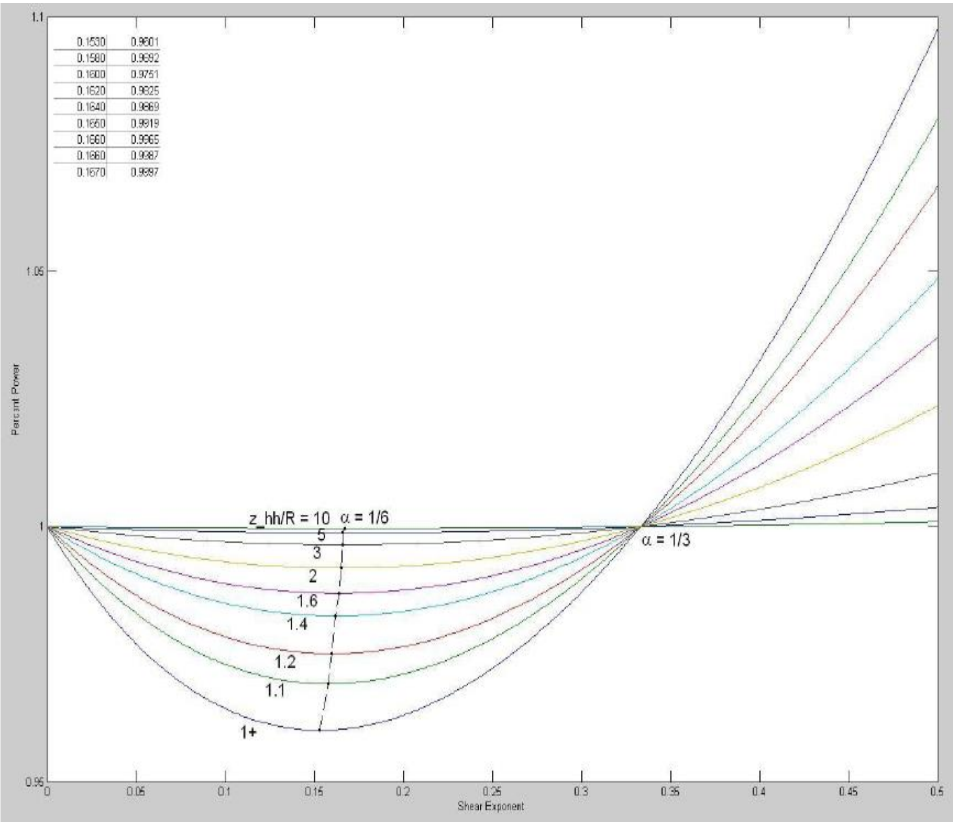


Fig 1. Digital terrain model with objects ▲ Wind turbine ● Climatology station



Available energy in the air at different wind shear alphas



Relative to a flat profile (shear exponent equal zero) the % of the available power varies with the shear exponent. Even in the case of well-defined shear profiles, the hub height (HH) wind speed relation to the power available within the rotor disk varies. Conclusion: The wind shear influences the power available and needs to be measured. z_hh is hub height and R is rotor disc radius.

Modern Energy at a glance

Modern Energy is a boutique consultancy with a strong focus on high quality wind resource analyses and site suitability studies. We consider our detailed knowledge and know-how from all aspects of flow modelling to turbine response, which has been gathered from numerous years of experience, to be our strongest competitive advantage. Modern Energy has highly skilled employees with experience from some of the largest and most complex sites in Europe, both on and offshore, with in-depth knowledge of ice performance in Scandinavia.

Regardless of whether you are a developer, lender, operator or investor we focus on giving you the most accurate analysis using sophisticated methods for both pre- and post construction estimates. In particular we have noticed that site suitability, load assessment and turbine performance are often neglected and/or not fully understood. We have developed high fidelity in-house tools to capture the true physics of turbine performance due to site specific flow conditions, in order to include turbine performance also when optimizing the layout.