POWER PREDICTION AND SITING – WHEN THE TERRAIN GETS ROUGH

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ABSTRACT: As erection of wind turbines in complex terrain becomes more and more common, the need for accurate power prediction and optimal siting in complex and semi-complex terrain has been highlighted. This project presents a numerical method for wind field simulations, optimal siting and power prediction. The numerical method has been embedded in the software package WindSim. Recently WindSim has run several "blind test" validations. Findings from one "blind test" validation in a semi-complex terrain in Denmark will be presented herein. Production statistics show that power production from different wind turbines varies up to 25%, even though the variation in ground elevation is only 7 meters. We estimate that a redesign of the wind farm layout based on simulations would give a 10% increase in the power production.

Keywords: Navier-Stokes Equations, Numerical Methods, Siting, Wind Field Simulations

1 INTRODUCTION

Most power predictions are still obtained by running linearised flow models, which do not take into account the correct response from a complex terrain. As local variations in the wind speed can be very significant the accurate prediction of the wind field is of great interest for project developers. This fact is very important since the energy content in a wind field is proportional with the wind speed in the third cube. Accurate flow simulations make it possible to optimise the energy production, and also to reveal unwanted effects such as areas with high turbulent intensity and vertical loading.

We have established a method for power prediction and optimal siting in complex terrain based on the solution of the 3D Reynolds Averaged Navier-Stokes equations. The development of the method started in 1997 and is today embedded in the simulation package WindSim.

1.1 Norwegian Wind Atlas

From 1998 to 2001, WindSim was used in the assessment of wind resources along the Norwegian coast [1]. The "Norwegian Wind Atlas" contains more than 100 detailed numerical models taking into account terrain elevation, roughness variation and local wind climatology obtained from available weather stations with long-term wind statistics. Before publishing of the "Norwegian Wind Atlas" we performed several validations of the method against measurements in both complex and semi-complex terrain, see table I. The "Norwegian Wind Atlas" was undertaken in co-operation with the Norwegian Meteorological Institute and financed by the Norwegian Water Resources and Energy Directorate.

Table I: Validations in connection with the publishing of the "Norwegian Wind Atlas", 1999 - 1998

Year	Grid (m)	Location
1999	100x100	Stadt, Sogn, Norway
1999	100x100	Jaeren, Rogaland, Norway
1998	Various	Torsnesaksla, Troms, Norway [2]
1998	Various	Askervein hill, UK [3]

1.2 "Blind test" validations – Micro-siting

Based on the experiences from the "Norwegian Wind Atlas" the method has been developed further towards power prediction and optimal micro-siting. Since mid 2000 several validations from sites around the world has been performed in co-operation with turbine manufacturers and project developers. All tests have been performed as blind tests, where only a limited part of the measurements were made available as the testing started. The remaining measurements, which typically were wind speeds at additional mast or power production data from wind turbines was made available after the wind field simulations were delivered. Table II summarizes the blind test validations of wind farms and sites under development. Typically, the area of interest is in the order of 10 km². At sites with complex terrain the accuracy of the wind field simulations will require a similar accuracy in the resolution of the terrain elevation. The grid resolution for sites in complex terrain should be in the order of 10x10 meters. In some of the cases the grid resolution was too coarse. In such a case the wind field simulations did not resolve the length scales observed in the measurements and the validation case had to be disregarded.

Table II: Blind test validations at wind farms and sites under development, 2002 - 2000

Year	Grid (m)	Developer/Location
2002	20x20	Energi- og Miljødata/Denmark
2001	50x50	Renewable Energy Systems/UK
2000	50x50	Natural Power/UK
2000	50x50	Renewable Energy Systems/US
2000	30x30	Enercon/Portugal
2000	10x10	Ecotecnia/Spain
2000	10x10	Norwegian Met. Inst./Norway [4]

2 TORRILD A SEMI-COMPLEX SITE IN DENMARK

The sites summarized in table II range from gently smooth to very complex terrain. We will present results from the site in Denmark where the terrain is rather smooth. Although the gradients in the terrain are

moderate, terrain induced speed-ups are still significant, which is clearly observed in the measured power production.

2.1 Digital terrain model

The digital terrain model for Torrild with elevation and roughness data is presented in figure 1 and 2. The cylinder represent a 30 meters high measuring mast, whereas the triangles marks the position of the 15 wind turbines, all of the same type with a nominal effect of 150 kW and a hub height of 30 meters. There are 118 meters in row distance and 155 meters between rows, which in terms of rotor diameter is 5.1 RD and 6.7 RD respectively.
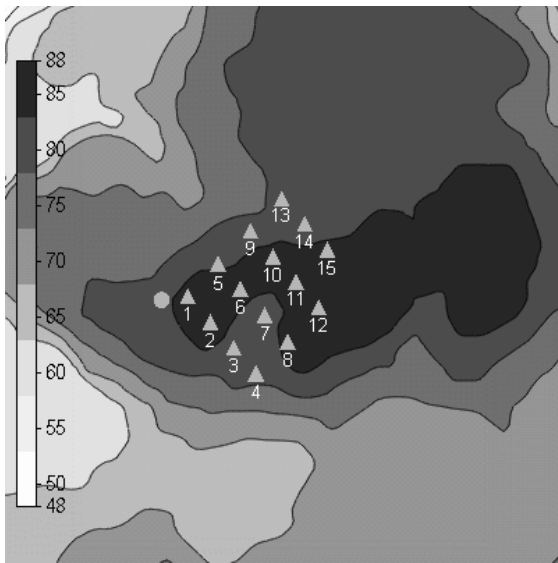

Figure 1: Digital terrain model with elevation data in meters, extension of the area is 2x2 km with a grid resolution of 20x20 meters. Triangles represent turbine locations and the cylinder represents the measurement mast.
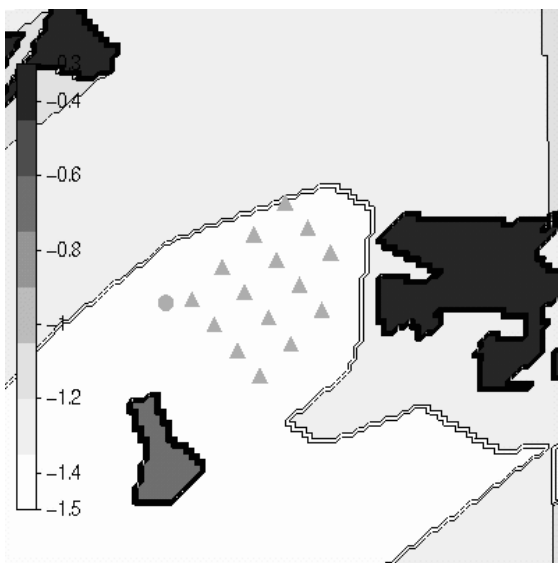

Figure 2: Digital terrain model with roughness heights in meters, the legend is given with a log scale.

2.2 Climatology

In this study climatology data from the period February to October 2000 is used. The mean wind speed at 30 meters height is 5.6 meters. The dominant wind directions are from the W and WSW direction, as can be seen from the wind rose in figure 3. Details for the climatology are given in table III. Sector 1 is headed towards north.
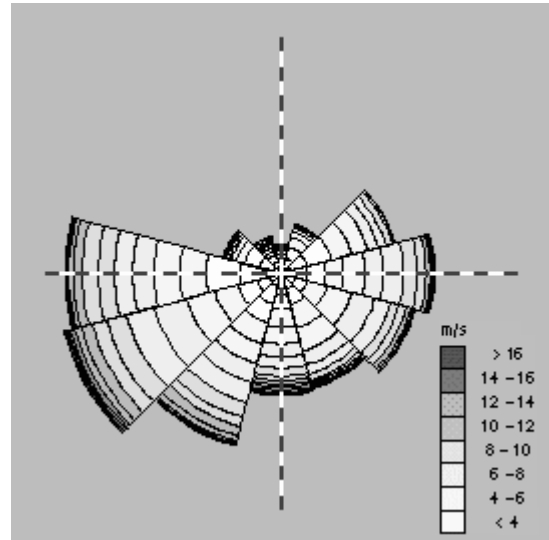

Figure 3: Wind rose for Torrild.

Table III: Climatology data versus sector, frequency of occurrence, mean wind speed and Weibull parameters

Sector	1	2	3	4	5	6
Frequency (%)	2.0	3.5	8.1	10.6	9.6	8.2
Mean (m/s)	4.2	4.1	4.6	5.8	6.0	5.4
Weibull k (-)	1.64	2.11	2.20	2.42	2.54	2.14
Weibull A (-)	4.60	4.58	5.09	6.61	6.74	5.94
Sector	7	8	9	10	11	12
Frequency (%)	8.4	12.3	15.5	14.9	4.2	2.7
Mean (m/s)	6.0	6.0	6.6	5.7	4.0	4.7
Weibull k (-)	1.80	2.25	2.31	2.04	1.46	1.66
Weibull A (-)	6.52	6.86	7.48	6.32	3.97	5.18

2.3 Wind field simulations

One wind field simulation has been performed from each of the twelve sectors. A nesting technique has been used, where the initial and boundary conditions are found from a coarse model, covering an area of 20x20 km and with a grid resolution of 200x200 meters. In the coarse model the inlet profiles are specified according to the log-law from ground level and up to 500 meters height, above this level the profile is set constant. In the vertical direction the grid extends 1000 meters above the point with highest elevation. Two different grid distribution with 20 and 40 cells were tested, both with a refinement towards the ground. There were no significant differences in the results at 30 meters height due to the vertical grid refinement. For the actual terrain a resolution of 20 cells seems to be satisfactory.

2.4 Wind resources

Combining the wind field simulations with the

climatology gives the wind resource map at 30 meters height presented in figure 4. Similar information obtained with the linear model WAsP is given in figure 5.
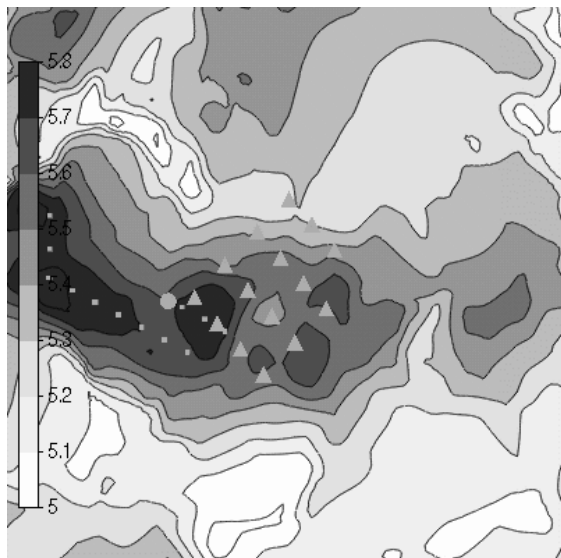

Figure 4: Wind resource map with annual mean wind speed at 30 meters height, simulations with WindSim. The small squares represent an alternative placement of the wind turbines.
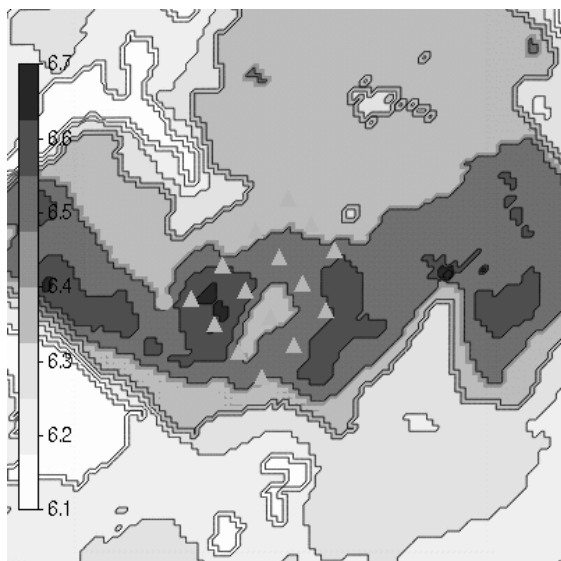

Figure 5: Wind resource map with Weibull A-parameter at 30 meters height from the period February to October 2000, simulations with WAsP.

The mean wind speed variation within the wind farm is easily detected. Both models spot the wind farm area on the hilltop as a windy area, although there is no simple coincidence between the high wind speed areas and the high altitude areas. According to the WindSim simulations the area west of the wind farm is even better suited for wind energy production. In this area we find terrain gradients more or less perpendicular to the main wind directions, giving significant speed-ups.

2.5 Energy production

In terms of energy production the wind field variation within the wind farm is even more pronounced, giving a 25% difference between the turbines with minimum and maximum energy production. The measured production data is given in figure 6 along with the results from the simulations. The wake effects in a wind farm like Torrild will certainly affect some of the turbines. There will also be a certain wake effect from the wind farm affecting the measuring mast situated in the southwest corner of the wind farm. Due to sheltering the measurement mast will give too low wind speeds, resulting in an underestimation of the simulated energy production. On the other hand mutual wake effects between the wind turbines will tend to reduce the energy production of the wind turbines situated in the interior of the wind farm. No attempt has been done to eliminate the wake effects; therefore one should expect to find a general underestimation of the energy production for all turbines due to underestimation of the wind speed from the measurement mast, further an overestimation of the energy production of the sheltered wind turbines.
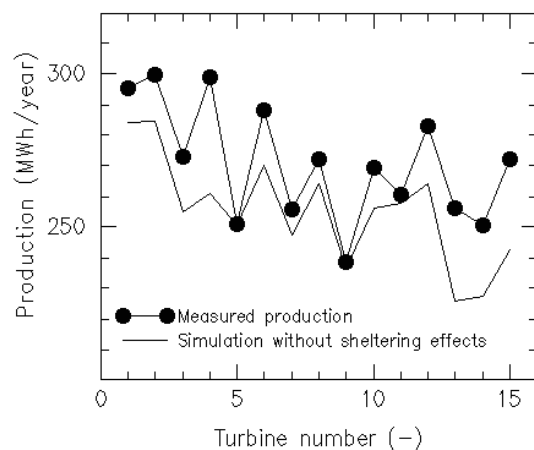

Figure 6: Annual production from each turbine in the Torrild wind farm, compared against simulations without wake effects.

2.6 Energy optimising

A relocation of the turbines in rows south and west of the current position, marked by squares in figure 4, would increase the power production from 3829 MWh/year to 4226 MWh/year, which is a 10% increase in the energy production. Terrain induced speed-up effects will be even more pronounced in complex terrain, although the effects is reduced with the height above ground. The Torrild wind farm is situated in a rather smooth terrain, still the terrain-generated speed-ups are significant at a hub height of 30 meters.

3 SUMMARY AND CONCLUSIONS

• A method for accurate energy calculations and micro-siting optimising in complex terrain has been set forth.
• It has been demonstrated that even at a site in semi-complex terrain the variation in power production between the turbines in the wind farm is as high as 25%, the method reproduces the characteristic features.
• A redesign of the wind farm layout based on simulations would give a 10% increase in the energy production.

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