Wind Turbine Wake Effects on Wind Resource Assessments – a Case Study

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Abstract. This paper describes a case study of wind turbine wake loss effects on wind resource assessment in cold region. One year wind park SCADA data is used. Computational Fluid Dynamics (CFD) based numerical simulations are carried out for wind resource assessment and estimation of resultant Annual Energy Production (AEP). Numerical results are compared with the field SCADA data, where a good agreement is found. To better understand the wind flow physics and effects of wind turbine turbulence wake loss effects, three different wake loss models are used for the numerical simulations, where results with wake model is found in best agreement with the AEP estimation from field SCADA data. A detailed comparison of all wind turbines is also presented with the gross AEP. A preliminary case study about wind park layout optimization has also been carried out which shows that AEP can be improved by optimizing the wind park layout and CFD simulations can be used as a tool in this regards.

1 Introduction

Due to increasing demand of electrical power and need of protecting the environment, there has been increasing needs of rapid expansion and better use of renewable energy resources to cut the toxic emissions. Cold climate regions have good wind resources, but environmental challenges such as atmospheric icing have been recognized as hindrance in proper utilization of these good wind resources. Worldwide, installed wind energy capacity in ice prone cold regions in 2015 was 86.5 GW, which is expected to reach 123 GW in 2020 [1]. In cold climate regions, before selecting a wind park site area for wind resource assessments, it is important to also discuss the factors such as low temperature and icing climate. All these factors gives an idea about estimation of related problems and how to overcome project budget, economical optimization, noise effects on urban areas and health and safety factors of urban population before building a wind park in cold climate regions [2].

The assessment of wind resources at cold climate sites is challenging, but important, as wind energy project development decisions are based on these estimated results. Wind resource assessment of a wind park include aspects such as terrain topology of the sector where the wind farm is to be located, wind behaviour along the time, type of buildings or any other human intervention around the wind farm location that may induce changes in the terrain roughness, as well as, the geometry of the wind turbine and its expected performance in the calculation of the tested scenarios. Low temperatures and icing events make additional challenges for wind resource assessment in cold regions [3]. CFD based wind resource assessment using measurements from wind parks can provides improved agreement with the field measurement, when compared to the analytical flow models under different wake effects. This paper describes a case study of wind turbine wake effects on wind resource assessment in cold climate regions. CFD based numerical simulations are carried out using one year (2015) wind park SCADA data. To better understand the wind turbine wake effects on flow behaviour and resultant power production, CFD based parametric study has also been carried out in this paper, where three different wake loss models are used to calculate the AEP of each wind turbine.

2 Wake loss models

This section provides a description of three wake loss models used for this study. Turbulent structure created behind a wind turbine can affect the wind flow in surrounding of other wind turbines. Wind turbine wake losses can be calculated by using both analytical and numerical methods, however, analytical methods are more attractive as opposed to CFD based numerical simulations, as they are more simplistic in nature and considerably less computationally demanding than CFD methods. These analytical wake loss models can also be used in conjunction with CFD at a later stage in order to make a comparison among them and their impact on energy production. All three wake effect models are based on calculating the normalized velocity deficit, δV, as given in equation (1):

$$\delta V = (U-V)/U \qquad (1)$$

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Where, U is the free stream velocity, and V is air velocity at some point after the turbine rotor. All models are rotational axisymmetric along the x-axis, which imply that reduced wakes will be calculated off hub height. These models are briefly described as follow:

- **Jensen model [4]** is based on momentum deficit theory. This model gives a simple linear expansion of the wake. The wake behind the turbine is assumed to be as big as the diameter of the turbine and spread lineally of function of the distance, determined by the wake decay factor, k. Velocity deficit is defined to be depended only of the distance behind the rotor. The wake decay factor increases with increasing level of ambient turbulence, where a typical range is from 0.04 to 0.075. The problem of interacting wakes is solved assuming the kinetic energy deficit of a mixed wake is equal to the sum of the energy deficit for ach wake at that particular location. In this model the velocity profile inside the wake is considered constant and not as a Gaussian distribution. Due to the constraint of the model itself, the thrust coefficient must be smaller than one. Then the normalized velocity deficit is defined as:

$$\delta V = D(1-\sqrt{1}-C_T)/(D+2kx)^2 \qquad (2)$$

$$K = 0.5/\ln(\frac{h}{Z_n}) \qquad (3)$$

  Where C_T is the thrust coefficient (-), h is the hub height (m) and Z_o is the roughness height (m).

- **Larsen model [5]** is derived from the turbulent boundary layer equations. It considers the axial velocity into consideration to increase the order of magnitudes of terms in the equation of motion neglected by first order equations. Solution is achieved as the Prandtl's is used by expressing velocity as function of the distance power -1/3, as the boundary layers behaves. Then the normalized velocity deficit is defined as:

$$\delta V = \frac{1}{9}\sqrt[3]{\frac{C_T \pi D}{4x^2}}$$

$$\left[\frac{4}{\left(3C_1^2 C_T \pi D x\right)^{1/2}} - \left(\frac{35}{2\pi}\right)^{3/10}\left(\frac{1}{3\,C_1^2}\right)^{1/5}\right] \qquad (4)$$

  Where C_T is the thrust coefficient (-), D is the rotor diameter and the parameter and C_1 is a constant related to the mixing length and the position of the rotor respect to the coordinate system, defined as function of diameter as turbulence intensity at hub height.

- **Ishihara model [6]** takes into account the effect of turbulence on the wake recovery, which is not constant and depends on the distance from the wind turbine, and the turbulence generated by the rotor and the atmospheric turbulence. For large thrust coefficients, the rate of wake recovery increases. Introduces a turbulence depending rate of wake expansion. The velocity profile is assumed to have a Gaussian profile, then the normalized velocity deficit is defined as:

$$V = 1{,}1812\sqrt{C_T}\left(\frac{x}{D}\right)^{-6(I_a+I_w)}$$

$$exp\left(\frac{r^2}{\left(0{,}3241 C_T^{1/4} D^{(1-3(I_a+I_w))} x^{3(I_a+I_w)}\right)^2}\right) \qquad (5)$$

  Where C_T is the thrust coefficient (-),D is the rotor diameter, I_a is the ambient turbulent intensity at hub height and I_w is the turbulent intensity at the location.

3 Numerical methodology and wind park layout

Wind park used for this study is located in the Arctic region of Norway and consists of 14 wind turbines. One year (2015) SCADA data has been collected and sorted for this study. Wind park terrain is hilly and is mainly covered by grass in summer and snow in winter. Figure 1 shows the wind park layout and wind rose map.

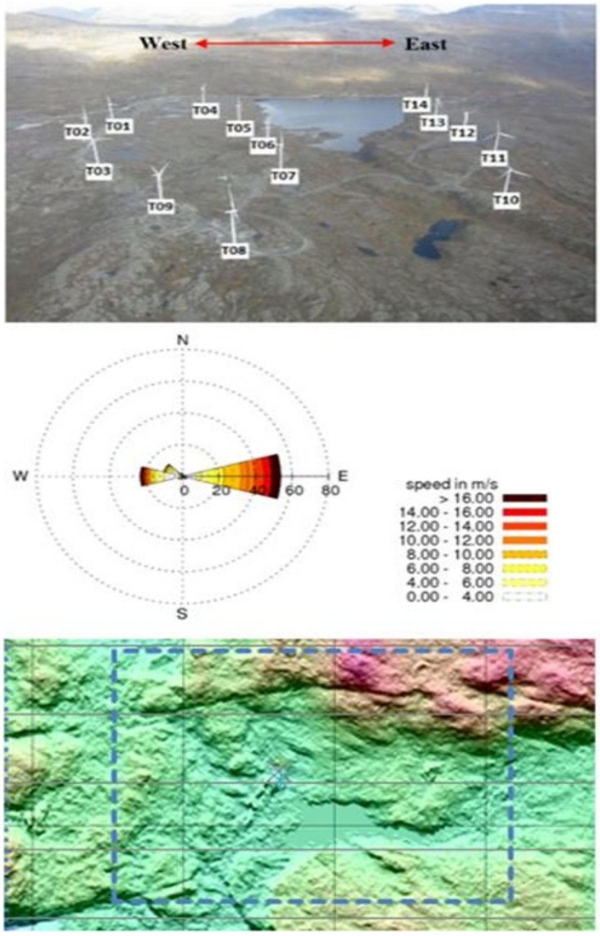

Fig. 1. Wind park layout & wind rose map.

CFD based numerical simulations of wind resource assessments are carried out by using WindSIM software, which is a modern Wind Park Design Tool (WPDT) that helps to assess the wind park energy production by using non-linear mathematical methods. For CFD simulations, three wake models (Jensen wake model, Larsen wake model and Ishihara wake model) are used. The Jensen wake model based on momentum base theory and gives simple linear expression of wake determined by the wake decay factor. Larsen model is derived from the turbulent layer boundary and Ishihara wake model used the turbulent depending rate of wake expression. A digital terrain model containing elevation and roughness data is established for the wind park terrain area. The wind park terrain complexity depends on the changes in elevation and roughness. The complexity in elevation is visualized by the inclination angles which is a derived quantity expressing the first order derivatives of the elevation. The digital model represents the computational domain whereas the Reynolds averaged Navier–Stokes equations have been numerically solved. Table 1 describes the CFD solver settings used for this study.

Table 1. Solver setting of CFD model

Height of boundary layer (m)	500.0
Speed above boundary layer (m/s)	10.0
Boundary condition at the top	Fix pres.
Potential temperature	No
Turbulence model	RNG k-e

4 Results and discussion

4.1 Wind resource assessment & wake model study

CFD based numerical simulations with respect to three different wake loss models are carried out. The purpose of this categorization is to better understand the wake effects on the power production. The gross energy production is the energy production of the wind farm calculated by predicted free stream wind speed distribution at the hub height of each turbine location and the turbine's power curve provided by manufacturers. Wind turbines extract energy from the wind. The wind speed downstream from the wind turbine is changed. As the flow proceeds further, the wake is spreading and recovers towards free stream conditions. The wake effect is calculated and then the potential energy production is obtained by taking into account the wake losses.

Table 2. Comparison of three wake models AEP production using CFD.

Wake loss model	Gross AEP from SCADA (GWh/y)	Gross AEP without wake loss using CFD (GWh/y)	Gross AEP with wake losses using CFD (GWh/y)
Jensen	88.49	95	87.7
Larsen			91.9
Ishihara			87.8

Table 2 shows the CFD numerical simulation results of three wake models. The gross AEP from SCADA data is 88.49 GWh/y. Jenson wake model AEP with losses is 87.7 GWh/y almost same with Ishihara wake model but Larsen wake model has the maximum AEP (annual energy production) which is 91.9 GWh/y. The detailed comparison of 14 turbines with wake losses is shows in Figure 2.

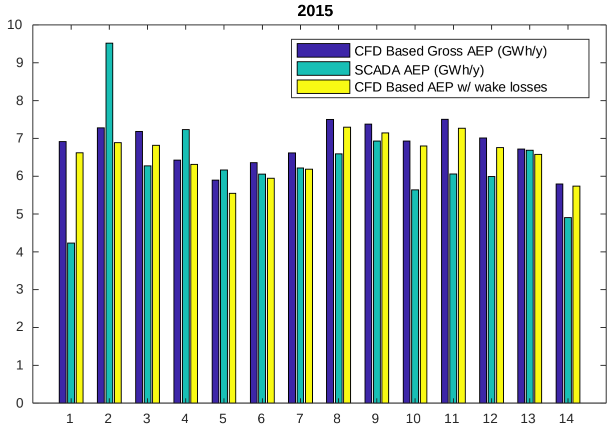

Fig. 2. AEP comparison of 14 turbines.

4.2 Wind park layout optimization

To further optimize the annual energy production of the wind park, a preliminary numerical case study is carried out to optimize the existing wind park layout. WindSIM Park Optimizer is used for this purpose. Park optimizer is a numerical tool coupled with WindSIM that helps to maximize the wind farm profitability by optimizing the wind farm layout locating turbine. Park optimizer uses two types of optimization approaches, *1) basic optimization, 2) WFD (wind farm design) optimization*. The basic optimization is based on heuristic algorithm which gives near optimal results. Algorithms such as genetic algorithm, simulated annealing and similar trial-and error algorithms for wind park layout design also provide good results but they are slow in process and do not provide information about quality. The WFD optimizer is highly innovation approach based on formal research operation methods and is derived from state of art optimization solver. For this case study, we used

WFD optimizer. Results from WindSIM simulations of year 2015 presented in previous section are used as input to the WFD optimizer, where WFD optimizer optimally relocated the wind turbines with respect to highest average wind speed where we can assess the highest wind energy. Larsen wake loss model is used. To verify how much AEP is increased after optimization of wind park layout, CFD based numerical simulation of new coordinates is carried out using WindSIM, shows as Figure 3. Table 3 shows the new and increased AEP of the wind park.

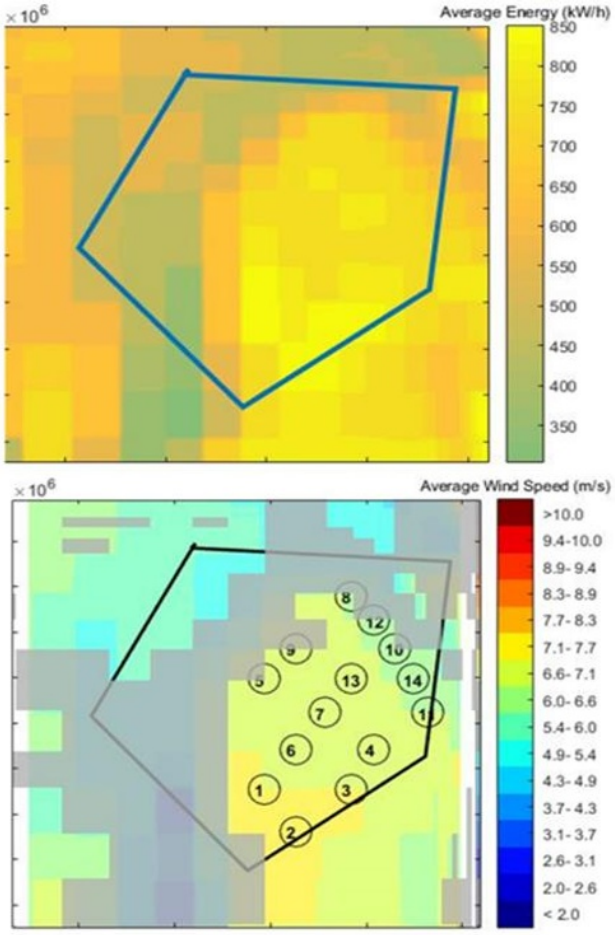

Fig. 3. Wind park layout comparison.

Table 3. Comparison of AEP for optimized layout of the wind park.

Hub Height (m)	80.0
No. of turbines	14
Gross AEP (GWh/y) from SCADA with existing layout	88.49
AEP from CFD with wake losses (GWh/y) with existing layout	91.9
AEP from CFD with wake losses (GWh/y) after layout optimization	99.3

5 Conclusion

One year SCADA data analysis and CFD simulations were carried out for a wind park in cold region. SCADA data AEP results are compared with CFD simulations where a good agreement is found. To better understand the wake effects on AEP, three wake models were tested, where the results show that CFD results with the use of wake loss models are in good agreement with the SCADA data. As an overall a good comparison is found between SCADA data and CFD simulations results. A preliminary case study about wind park layout optimization shows that AEP can be optimized by optimizing the wind park layout and CFD simulations can be used as a tool in this regards.

Conflict

The authors declare no conflict of interest.

Author Contributions

Jia Yi Jin has contributed substantially in the proposal of research idea, literature review, SCADA data analysis and writing this paper; Rizwan Ghani has contributed in modelling, CFD simulation and writing this paper; Muhammad S. Virk has contributed in the proposal of research idea and modified this paper. All authors had approved the final version.

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