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Why doesn't my wind farm produce what I expected? A guide to wind farm performance assessment

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Summary

A framework for performance assessment of wind farms without quality on-site met data is presented. Over 2 years of SCADA data from an onshore wind farm in continental climate were used for a performance assessment study. The loss contributions from several factors such as wakes, availability, electrical losses, turbine performance, environmental factors and curtailment are addressed and, when possible, quantified.

The pitch, power and temperature measured by individual turbines are used to estimate the wind speed at each turbine position, and the recalculated speeds from selected turbines according to wind direction are used to estimate a free stream wind speed for the wind farm. The contribution from different factors to the overall losses is estimated. Special attention is placed in the results for wake losses. Data is divided according to a rough atmospheric stability classification to address its effect on wakes. The effect of nearby forested areas on wake development is also discussed.

1. Introduction

The final investment decision for a wind farm has to be based on an accurate estimation of the net production. Nevertheless, the accuracy of additional losses used in wind farm production estimates is uncertain. Furthermore, once the investment for a wind farm has been obtained and the project installed, the estimate methodology is rarely reviewed unless severe underperformance occurs. It is of great interest to revisit the estimation methods, find the sources of bias and uncertainty and devise improvement measures.

A methodology for wind farm performance assessment has been devised. A performance assessment study was done for an onshore wind farm with over 2 years of SCADA data and without an on-site met mast. Despite the lack of on-site met data, wind conditions at the site can be accurately assessed by use of the available SCADA database. The disagreement between estimate and observation is broken down and the contribution from different factors is assessed. The approach addresses the most relevant factors in performance assessment and can clearly identify sources of bias and uncertainty given appropriate data.

The method revealed the true loss of energy due to availability and found unreported curtailment which could also be quantified. The method has also proven to be valuable in order to assess wake losses, which were found to be underestimated by WAsP,

especially in conditions associated with stable atmospheric stratification. The effect of nearby forests on wakes was seen to be large and affecting turbines moderately far from them. Finally, the wind index correction was seen to have a major impact when assessing the accuracy of production estimates.

2. Assessing wind conditions at the site

2.1 Data filtering

The raw 10-minute SCADA time series contain several data quality flags. Certain calculations require a stricter quality control. The availability and curtailment cases need to consider data flagged as unusual or non-perfect behaviour in order to correctly describe what happens. Wake losses, on the other hand, should be studied in normal operational conditions. Introducing records where some turbines were not operating would completely alter the wake profile, since the flow would be affected in a different way than it is in normal operation. Finally, the speed recalculation should also be fed with good quality data, since it uses the pitch and power curves in normal operation as a base.

2.2 Effective wind speed

The only sources of wind speed data are the nacelle anemometer records from the turbines, which are immersed in the turbine wake. A more accurate estimation of the wind speed can be made based on the power output, pitch angle, ambient temperature and pressure that are actually felt by the turbine; along with density-specific power and pitch curves.

Air density is calculated from the ambient temperature measurement and the assumption of standard pressure conditions for a site at sea level via the ideal gas equation for dry air. The assumption of a dry ideal gas could be inappropriate for the case, but air humidity measurements are not available.

The turbine power curve is given for several values of air density, while pitch curves for different densities can be obtained from aerodynamic simulations with the appropriate blade and turbine specifications. These curves were provided internally by DONG Energy.

Before pitch regulation begins to act, it is merely the blade aerodynamics that determines the power output at a given speed and air density. Therefore, at power output values lower than a certain threshold, the wind speed can be determined based on the power output and the air density corrected power curve. Similarly, at power output values close enough to rated, the pitch control system starts to take action, and the power output is no longer solely dependent on the wind speed. Linear interpolation is performed to obtain a power or pitch curve at exactly the observed density, and a final interpolation uses this curve and the measured power or pitch to obtain an estimated effective wind speed observation.

2.3 Validation of effective wind speed

An initial validation can be performed by binning observed power and effective wind speed results, creating a power curve and comparing it against the manufacturer power curve and the one obtained directly from measurements. Figure 1 shows the recalculated power curve along with the measured one from filtered records and the manufacturer power curve for the yearly average air density for one of the turbines in the wind farm. A gap is visible between the so called measured power curve and the recalculated one. This gap is broader at low speeds, and makes the measured power curve effectively reach rated power at a higher speed. The behaviour towards the high wind speed bins is due to lack of data at those speeds for this turbine. The fact that the recalculated and the manufacturer power curve coincide almost perfectly throughout the whole domain validates the effective wind speed and it indicates that the speed recalculation accurately describes the wind speed felt by the turbine. The validity of the recalculation as a description of the wind speed experienced by the turbine is expected to hold regardless of whether the turbine is in the wake of another one or not, since the

calculation only depends on the wind turbine aerodynamics and pitch control.
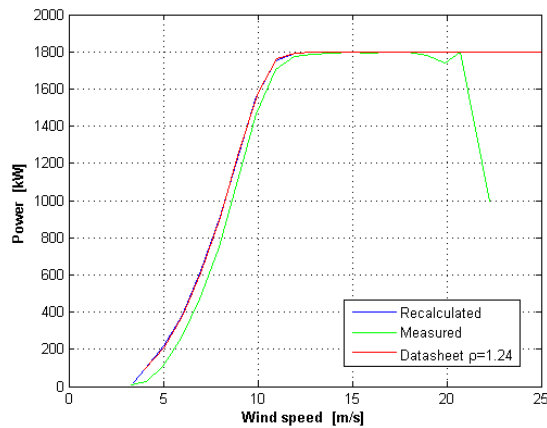

Figure 1: Validation of effective wind speed by comparison of recalculated, measured and manufacturer power curves.

So far, the algorithm does not account for turbulence or other factors, so it is not exactly a free stream wind speed, but rather an equivalent wind speed that the turbine feels according to its power curve calibration; and its validity is thus subject to the same framework as the power curve measurement test. Therefore, it should not be expected to fully represent the flow at hub height and in front of the turbine if the conditions are out of the framework in the power curve determination test, which would most likely be the case when the turbine is in the wake.

2.4 Free stream wind speed

The wind farm reference wind speed is calculated as the average of the recalculated speeds in the frontline turbines, which are not affected by wakes and are thus expected to have closer conditions to those in the power curve verification test.

Selection of a group of frontline turbines per direction is done in an iterative way, starting with the intuitive turbine selection according to the layout, computing the free stream wind speed from them and calculating the deviation from the individual turbine speed records. If the errors for a particular turbine are not normally distributed around zero, it is removed from the reference group and the process is repeated until all reference turbines comply with the condition of normally distributed errors.

2.5 Validation of free stream wind speed

The reconstructed wind speed and direction time series were compared against data from a wind atlas for the area, which was obtained from an external provider. The reconstructed time series was seen to be qualitatively consistent with the speed in the wind atlas, with different scales but similar trends, and consistent qualitatively and quantitatively with the direction records.

3. Assessing losses

3.1 Overall

Once the wind conditions at the site have been estimated, the loss contribution from several factors can be estimated by the procedure illustrated in Figure 2. First, a no-loss power production time series is obtained by using density specific power curves along with the recalculated wind conditions. The actual total wind farm power production is subtracted from this figure to get an overall energy loss. Data is filtered according to different criteria to treat and assess the contribution to this overall loss from different sources.

3.2 Various operational losses

If the total production is to be compared to the initial production estimate, external reference data such as a wind index should be first used to scale the power production during a certain period of time according to the wind index. Interannual variability of the wind resource is the factor with the heaviest influence on the uncertainty of production estimates, and so this correction can suggest whether the figure for actual annual production is in a normal range.
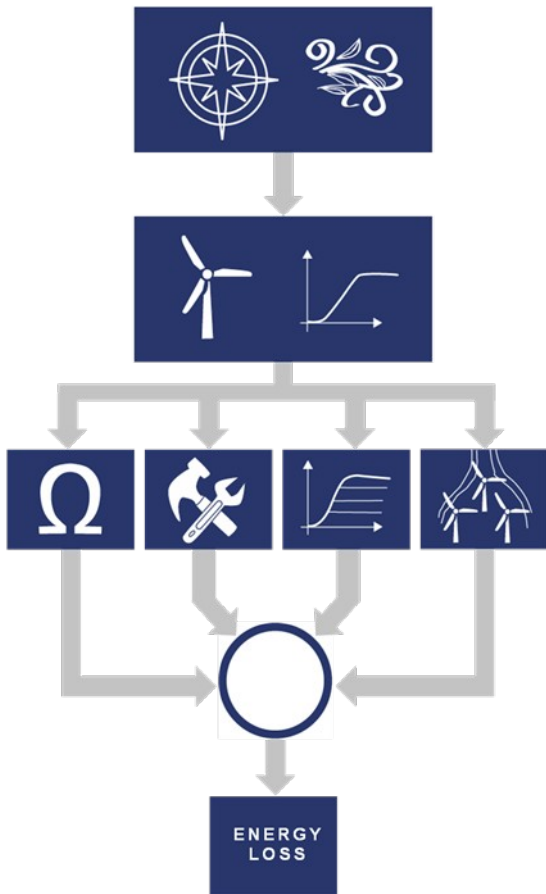
Figure 2: Flowchart of the procedure for estimating loss contributions.

The wind index can also be used as a diagnosis tool. Plotting the monthly wind index along with monthly wind farm production allows a clear visualization of periods when losses are not entirely due to wind conditions. Periods with low availability, for example, can be spotted in this way prior to performing a deeper analysis.

Electrical losses are quantified with the difference from all turbine power records and wind farm substation power measurements. Availability losses are calculated from service and downtime indicators in the database along with the recalculated wind speed for those periods. It is worth noting that the historic availability records are usually given in time basis and do not necessarily scale linearly to energy loss, but with this approach a direct availability-related energy loss can be estimated.

In cases where a clear record of control signals is not available, periods with production limits being applied to the turbines can be identified by examining the pitch curves. Figure 3 shows the pitch curve for a normal operating period along with that for a period with suspected curtailment.

Finally, losses related to environmental factors such as icing or to turbine performance cannot be accurately assessed with the kind of data available. It is only possible to indicate periods with a risk of these situations happening. However, due to the way in which different losses are isolated, this is not expected to affect other parts of the analysis.
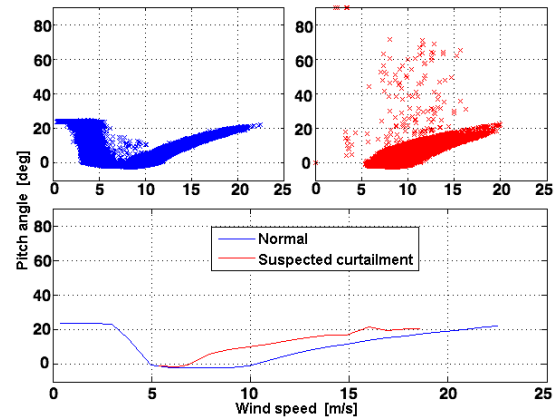

Figure 3: Pitch curve analysis to identify curtailment periods.

3.3 Wake losses

The observed wind farm output is divided by the no-loss power production time series to get the wind farm efficiency as a function of wind speed and direction. This efficiency is used along with the Weibull distribution for each sector and the power curve to estimate total production per sector. The resulting power productions for all sectors are then combined through the observed wind rose to get a single energy production figure. This process is analogous to calculating a wind farm or wind turbine AEP, but introducing the intermediate step of the efficiency curve. It has to be done in this way rather than taking raw losses since the efficiency function is derived from filtered data and the raw losses have components from other factors. Finally,

the result obtained with this method is divided by the result obtained by the same process but using a unitary wind farm efficiency, to represent the no loss case. The ratio of these two numbers is the actual wind farm efficiency, and the wake losses are taken as what it lacks from 1.

By using this method, it does not matter if the initial data set had a homogeneous coverage of hour in the day or month in the year for the calculation to be accurate. As long as all the (sector, speed) bins are well populated, weighting their information with the sectorwise Weibull distribution and then with the wind rose ensures that the information contained in the speed and power pairs is combined in a way that represents the site climatology. This is subject to some assumptions, like whether the range of observed speeds is representative. On the other hand, factors that could lead to different efficiencies at the same speed and sector, such as different turbulence levels, are not distinguished and so the different cases are just averaged out. This could introduce errors in the calculation, but since no met data was available to assess the effect of those factors in a more thorough way, this is the highest level of detail that can be attained.

4. Results and discussion

The overall wake losses, expressed as percentage of the annual energy production, were found to be 3.5% higher than estimated with the N.O. Jensen model [1]. Turbines with overestimated losses are in general located in the west side of the wind farm, while turbines with underestimated losses are located in the east and northeast sides (see Figure 4). Since the prevailing wind direction is west, this suggests the disagreement comes from a problem to model wake development after a number of turbines. Another factor possibly affecting this calculation is a violation of the model assumptions regarding atmospheric stability. It is known that the N.O. Jensen model works fine for neutral atmospheric stratification or for cases when the deviations from neutral

even out. If this was not the case, however, a certain bias is to be expected.

Two test cases are studied: the effect of atmospheric stability on wake losses along a turbine transect and the effect of a nearby forest on the wake losses for turbines at different downstream distances from it. Both test cases are illustrated in Figure 4.
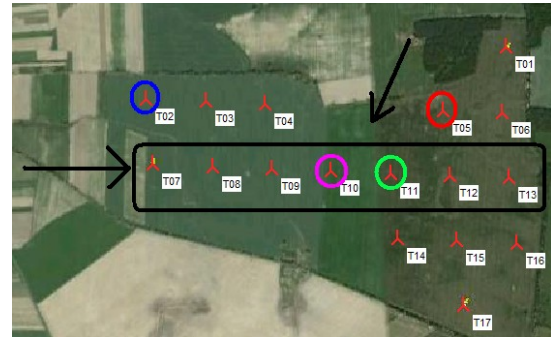

Figure 4: Layout and indication of the two test cases.

4.1 Effect of atmospheric stability

Due to their turbulence levels and vertical mixing, different atmospheric stability conditions lead to different wake recovery and wake loss profiles along a transect. An unstably stratified atmosphere enhances vertical mixing and is more turbulent. More turbulence hinders power performance; but it also enhances recovery towards free stream wind speed in a wake. Stable stratification, on the other hand, implies less mixing and so speed in wakes takes longer to recover. With these basic concepts as base, situations with different atmospheric stability conditions can be studied to try and assess whether this phenomenon is likely to have an effect. It is of interest to assess the impact of atmospheric stability on onshore wake losses to improve knowledge on how to choose or tune the wake model.

A stable atmosphere is expected to relate to periods with low convection, such as cold nights when the ground is not heated. An unstable atmosphere could be expected during the morning-afternoon transition of a sunny day after a cool night, when the sun heats up the surface enhancing convection and vertical mixing. For this simple qualitative
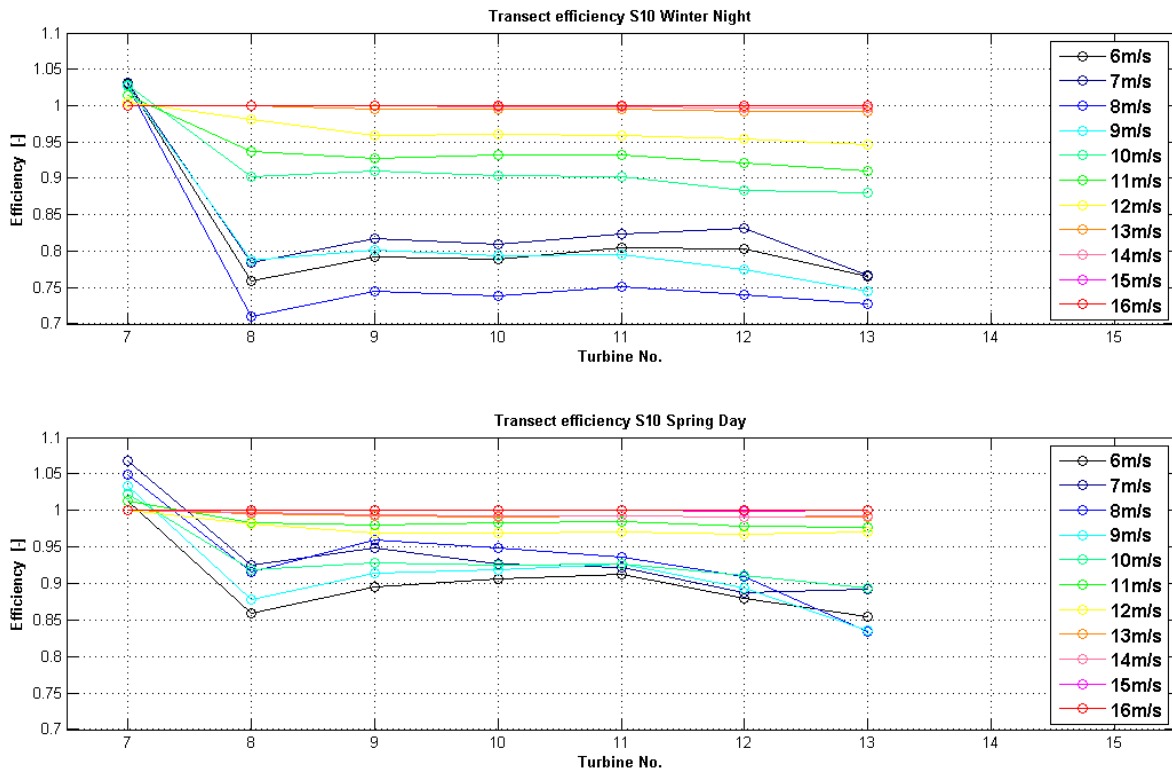
Figure 5: Efficiency profiles for different wind speeds along the W-E transect.

classification of stability conditions, stable stratification is associated to winter nights, while unstable conditions are associated to spring days. The efficiency of turbines in the west-east transect is compared for westerly winds, the prevailing direction.

Figure 5 shows the efficiency profiles for turbines in the W-E transect at different wind speeds and for both stability data sets. Efficiencies are seen to reach much lower values for winter nights (stable conditions, upper plot) than for spring days (unstable conditions, lower plot), with the difference being up to 10%. Turbines reach efficiency close to 1 at lower speeds during spring. These results agree with the conceptual picture of stability affecting wake development and with previous work on the Horns Rev offshore wind farm [2], which found the same qualitative trend of higher wake losses at stable conditions.

4.2 Effect of forestry

The presence of forestry modifies terrain roughness and flow displacement height. It is a complicated factor to assess and subject of ongoing research. For an area with several forest patches of variable size, it is interesting to assess how their presence affects the nearby turbines. This could be useful for improving forest modelling methods in future estimates. This can be done by taking the efficiency and power curves of a turbine in a sector where forest blockage is the only possible source of losses and comparing them with those of a free stream turbine. The basic argument is that the turbines would be in the free stream had it not been because of the forest, and so any difference in performance can be attributed to it.

Figure 6 compares the efficiency curves for a forest affected turbine and two free stream

turbines under westerly winds. The forest affected turbine is T01, in the NE corner of the wind farm, and the two other turbines are T01 and T02 in the W end. Efficiency values larger than 1 are attributed to the particular turbine simply having a higher wind speed than the other ones involved in the reference speed recalculation, and since the deviation from 1 is small, the fact is not considered relevant. It is seen that T01 has an extremely low efficiency for a turbine that should be in the free stream, with losses of up to 35% at low speeds and still over 20% at 10m/s.
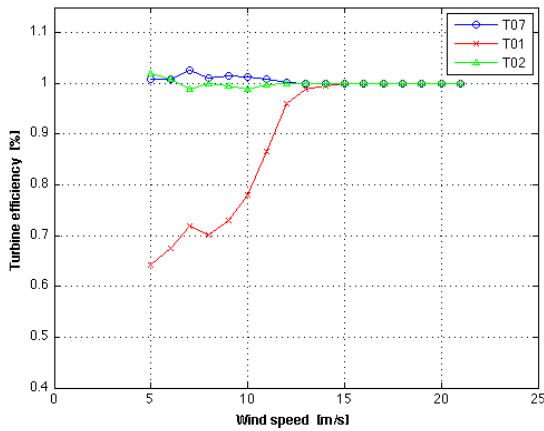

Figure 6: Efficiency curves for two free stream turbines and one forest affected turbine (T01).

A similar situation is observed in Figure 7, which Figure 7: Efficiency curves for different forest affected turbines.compares the efficiency curves for a free stream turbine with those of three different forest affected turbines for winds coming from the NNE. The turbines of interest here are marked by colored circles in Figure 4, with colors indicating which curve they represent in the plot. Efficiency values larger than 1 are again attributed to that turbine having a higher wind speed than the other ones involved in the reference speed recalculation and deemed irrelevant. The highest loss value in this case is lower than that in the previous case. This could be due to different factors, but the most obvious would be to think that it is related to the distance from the turbine to the forest, which is higher for T05 than for T01.

Another interesting feature of Figure 7 is to comparatively show the efficiency for turbines

T10 and T11, which are SW of T05 and should be exposed to relatively undisturbed flow in that sector. These turbines also show some losses at low speeds, and the efficiency profiles look like that of T05 but gradually smoothed. This suggests that a wake is created and propagates behind the forest, reaching quite long distances.

This wake development behind a forest is expected to depend in the type and height of trees, along with the distance from turbine to forest and forest fetch, among other factors. Table 1 summarizes the relevant forest dimensions and associated losses from figures 6 and 7.
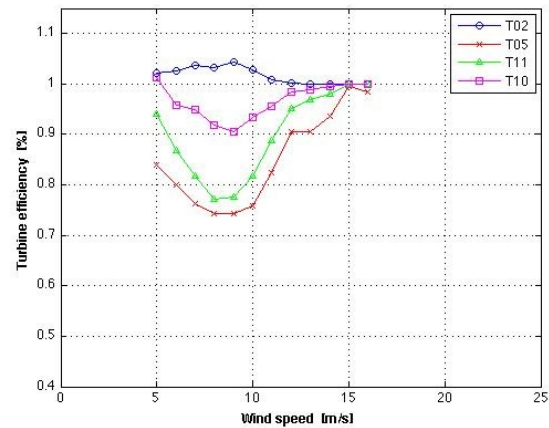

Figure 7: Efficiency curves for different forest affected turbines.

Turbine	Distance to forest [m]	Forest fetch [m]	Minimum efficiency [%]
T01	160	340	65
T05	220	420	75
T11	620	440	78
T10	900	250	90

Table 1: Summary of forest dimensions, distances and associated losses.

5. Conclusions

A framework for performance assessment of wind farms without quality on-site met data has been developed. The proposed method can be used to assess wind farm performance in the case where only SCADA data is available, identifying the loss

contribution from the year to year variability of the wind resource, availability, electrical losses, curtailment and wakes.

The method has proven to be valuable to assess wake losses, which were found to be underestimated by the standard N.O. Jensen model in WAsP, especially in conditions associated with stable atmospheric stratification. A simple classification of stability was used to assess the impact on wake losses, which was found to be significant.

The effect of nearby forests on wakes was assessed by comparing turbines with similar conditions except for their forest exposure. The effect was seen to be large and affecting turbines moderately far from the forest, in a kind of forest wake propagation.

8. Further work

Several improvement measures can be pointed for future implementation. An ice accretion detection algorithm based on 10-minute or, if available, higher frequency SCADA data could be used in order to quantify the related losses. The stability dependant wake loss analysis should be performed with a more precise stability classification, which can be done by having ground temperature measurements, for example. More detailed conclusions could be drawn about the forest effect on wakes if the cases are divided into stability classes and if the analysis is repeated for turbines near forests of different heights and extensions.

7. References

1. Jensen, N. O. A note on wind generator interaction. Risø-M-2411, Risø National Laboratory, Roskilde.

2. Jensen, L. Array efficiency at Horns Rev and the effect of atmospheric stability. In Proceedings of the 2007 European Wind Energy Conference.