Turbine Interaction Effects

K2 Management's Validated Approach

For better energy projects

K2 Management

Content

K2 Management Analysis Services

The K2 Management Analysis Services team offers financial-grade analysis and engineering services for wind farm projects of all sizes, at all life cycle stages. Clients worldwide rely on K2 Management to provide accurate and timely information to inform and de-risk their investment, development and operational decisions. The Analysis Services team is made up of over 30 individuals, with over 300 combined years of renewables analysis experience. Many of our staff have previously worked at a number of leading wind energy consultancies, wind farm developers and operators, and WTG manufacturers. This wide-ranging experience allows us to provide practical and focussed analysis advice throughout the development cycle. We optimise energy yield whilst minimising the associated uncertainty, so maximising project value for our clients.

Introduction

With the growing scale of wind farms, both onshore and offshore, there has been increased focus on wake, or turbine interaction, effects in recent years. Additionally, the blockage effect has been a hot topic in the industry over the past year. K2 Management has been a leading participant in this conversation since publishing a validation of our offshore energy yield assessment methods in January 2017. We have also been presenting our research into the performance of WTGs in varying flow conditions, including the high turbulence associated with turbine interaction effects, at a number of conferences and to the Power Curve Working Group since December 2014.

Due to the size and typically multi-array nature of offshore wind farms, turbine interaction effects are typically one of the dominant impacts on the net energy yield of these projects. Also, significant energy yield variables, such as wind resource across a site and WTG performance, typically vary less offshore than onshore, allowing turbine interaction effects to be isolated and studied more accurately. These factors, combined with the high value of offshore projects, have resulted in the majority of research and development efforts into turbine interaction effects across the industry being concentrated on offshore projects. The validation K2 Management presents here is no exception, however many of the valuable findings can also be applied to onshore projects.

This document describes K2 Management's wake modelling and turbine interaction effects calculation method alongside the validation and theoretical considerations which it is based upon.

What are wake effects and how are they calculated?

To produce power, operational wind turbine generators (WTGs) extract kinetic energy from the wind and consequently wind speed is reduced downstream from a WTG. The impact of this wind speed reduction on WTGs further downstream is modelled and assessed as wake losses.

The magnitude of wake losses depends on various factors, including but not limited to parameters such as wind farm size, layout configuration and density, WTG dimensions, power and thrust curve characteristics, wind resource and wind flow conditions such as turbulence intensity and atmospheric stability.

A number of wake models, such as Eddy Viscosity and PARK, are implemented by commercially available software. These wake models generally implement a relatively simplified physical approach to the calculation of the wind speed deficit, however numerous validations of their performance against operational data have been performed and their use in the wind industry is widespread and reasonably well understood.

As the understanding of wake effects has increased over time, empirical adjustments to these downwind wake model results, such as the DNV-GL WindFarmer Large Wind Farm Correction and UL Openwind Deep Array Wake Model, have been introduced to address the under-prediction of wake losses observed in validations.

Despite these corrections, significant limitations to the majority of current industry standard wake models remain. These models do not contain the physics to enable implicit consideration of factors such as the superposition of wakes, the impact of very large WTG rotors and low rotor swings or the upwind effects of WTGs on the wind flow, often termed the wind farm blockage effect.

What is the blockage effect?

Blockage effect has become prominent topic in the wind industry since October 2019 when Ørsted announced a reduction to the long-term energy yield predictions of their portfolio of wind farms which had a significant impact on the financial value of the company.[1]

The blockage effect phenomenon is observed upwind of wind farms. The WTGs act as an obstacle to the wind flow and cause a deceleration of the wind speeds entering the wind farm, reducing the available kinetic energy.

The phenomenon is well understood on an individual turbine scale and has been considered as part of turbine power curve measurement test procedures for several years, however modelling the effect across a whole wind farm remains a complex process. As mentioned above, the majority of commercially available wake models do not account for upwind effects. Similarly, wake models have typically been validated by comparing the performance of WTGs within a wind farm against the front row of WTGs, assuming that these WTGs experience freestream conditions and thereby not accounting for the upwind effects.

There is currently no industry standard model or agreed approach for the accurate calculation of the blockage effect. Various consultancies have developed empirical adjustments based on a variety of wind and wake modelling results, measurements and validation. These adjustments, either generic or site-specific, are typically applied as a separate loss to the site-specific wake modelling results in energy yield assessments.

As stated above, the blockage effect adjustments applied by all consultants are currently empirical, sensitive to the inputs used and assumptions made, and are therefore subject to high uncertainty. Methods based on a robust validation against operational wind farm data are considered to provide greater confidence in the predictions.

A number of companies have investigated wake modelling utilising high-resolution Computational Fluid Dynamics (CFD). CFD offers an opportunity to more accurately analyse both upwind and downwind effects of a WTG on wind flow, however accurately modelling these effects across a whole wind farm requires consideration of numerous wind speed and direction combinations. Thus, at the present time, the application of site-specific CFD wake modelling is very computationally intensive and not commercially cost-effective approach.

1 https://orsted.com/en/company-announcement-list/2019/10/1937002/

Turbine interaction effects

K2 Management considers it important to note that the way in which WTGs interact with each other is not limited to the downwind and upwind wind speed deficits that are calculated using wake models and blockage effect adjustments respectively. In addition to the reduced wind speed, the wake of WTGs causes increased turbulence and a disturbed boundary layer. These conditions detrimentally affect the aerodynamic performance of WTGs and increase WTG loading, which can result in increased component failure rates and associated lower WTG availability levels, further affecting energy yield.

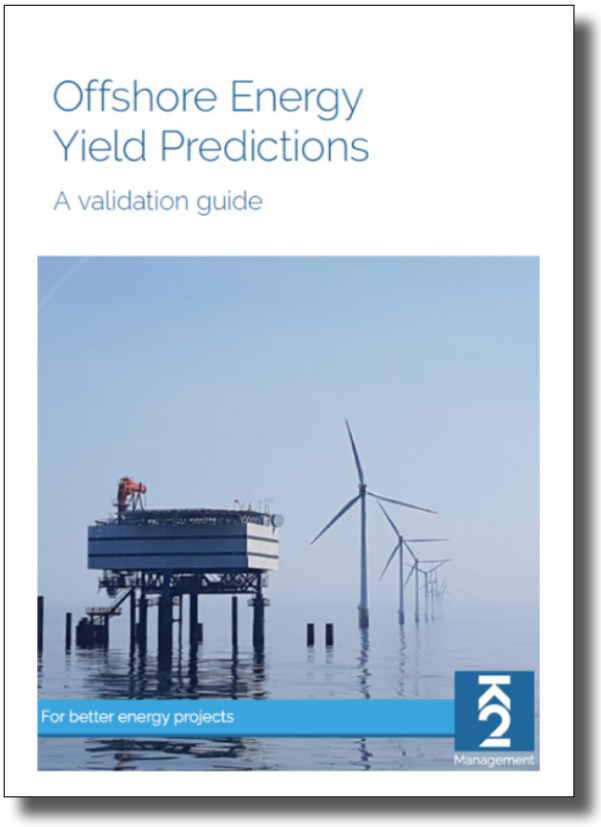
For the reasons above, and because our method is based on end-to-end validation (see Section 3), K2 Management uses the term "Turbine interaction effects" to represent both downwind and upwind effects, including those associated with wind speed deficit, WTG performance and availability issues.

K2 Management's validation of offshore energy yield predictions

K2 Management Analysis Services' approach to energy yield assessment is to ensure the minimum possible uncertainty in all aspects of analysis. We constantly review and refine our tools and methods based on our own project experience and the findings of research, development and validation carried out both internally within K2 Management and by others in the industry.

In January 2017, Prevailing Ltd (acquired by K2 Management in September 2017) published an industry-leading end-to-end validation of offshore energy yield predictions.[1] This study currently represents the largest published validation of offshore wind farms in terms of number of projects and total rated capacity undertaken by a wind analysis consultancy. The study demonstrated the robustness of our offshore energy yield assessment methods, but also highlighted a discrepancy that was related to the magnitude of the predicted wake effect. This observation led to a more specific focus on optimising the calculation of turbine interaction effects in order to reduce uncertainty yet further.

We continue to add projects to our validation database and will publish an updated validation in the near future.



1 https://www.k2management.com/hubfs/Guides_PDF/PDF%20-%20Guide%20-%20Offshore%20Energy%20Yield%20Prediction%20-%20a%20validation%20guide.pdf

Validation approach

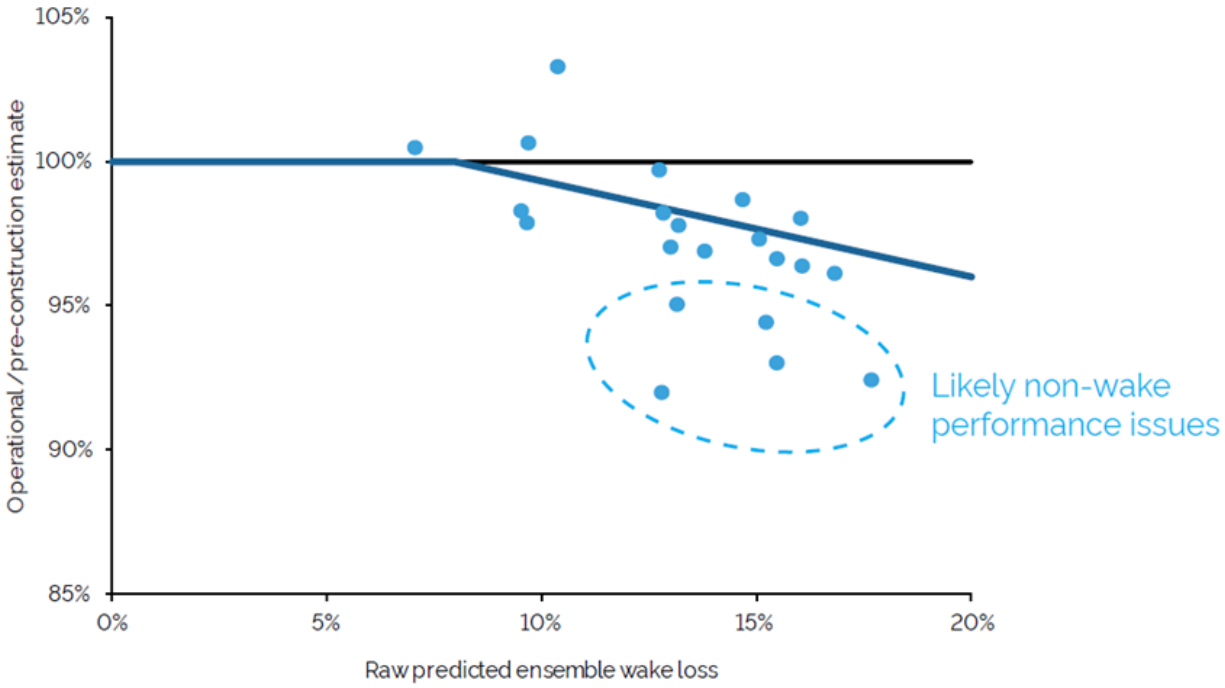
The UK offshore wind sector benefits from globally unique, publicly available data sources, including those provided by The Crown Estate Marine Data Exchange. K2 Management leveraged these data sets to calculate long-term energy yield using both pre-construction and operational methods, across 5 GW of operational offshore wind farms. At the time of publication this represented 91% of the total UK installed capacity of offshore wind.

Using wind data from 11 offshore measurement masts available via the Crown Estate Marine Data Exchange, best practice approaches were applied to determine the pre-construction energy yield predictions. This included consideration of multiple wind measurements in the prediction of long-term wind resource for each site and use of an ensemble of industry standard wake models to calculate wake losses. By this method, low uncertainty predictions of long-term energy yield were obtained for each of the 21 offshore wind farms considered in the study.

Likewise, publicly available monthly operational data for the projects available via OFGEM was used in conjunction with best practice operational assessment approaches, in order to determine the long-term energy yield based on actual wind farm production data.

Findings of the validation

The plot below, taken from the 2017 validation paper, shows the relationship between project performance and modelled wake loss for the 21 projects considered in the study. Some projects were known or suspected to have experienced significant performance issues unrelated to wake effects such as grid curtailment, so were excluded. This showed a clear trend of pre-construction over prediction or operational under-performance, particularly at sites predicted to have very high wake losses.



The technique of end-to-end validation compares the final results of the pre-construction offshore energy yield assessment methodology with the project energy yield derived from publicly available operational data. So by definition, this validation method includes all factors that impact the energy yield of the considered wind farms. This is a particularly powerful technique as it directly assesses the ultimate aim of an energy yield assessment; predicting the operational net energy yield of a wind farm.

While a clear relationship between under-performance and increased wake loss was observed, the root cause cannot be isolated. We consider that there are several potential drivers of this effect:

- Wake model inaccuracy: While industry standard wake models had been used, as discussed in the previous section, the development and validation of these models is generally limited to downwind effects only, so they do not consider a number of other turbine interaction effects, such as the blockage effect.

- WTG aerodynamics: Even if the wind speed deficit effect of WTG wakes is correctly predicted, the boundary layer behind WTGs is heavily disturbed, particularly for the multiple array configurations often used at offshore wind farms. This highly turbulent flow affects the later rows of the wind farms and has the potential to reduce the aerodynamic performance of heavily wake-affected WTGs.

- Wake-correlated down-time: The highly turbulent flow experienced by wake affected WTGs has the potential to cause increased failure rates. There have been a number of high-profile replacements at offshore wind farms for issues such as gearbox degradation and blade flex damage. It is likely that these issues are in part linked to vibration levels caused by wake-induced, highly turbulent wind.

Conclusions

A comparison of industry best practice pre-construction and operational energy yield assessments was undertaken by K2 Management for the majority of the UK's operational offshore wind farm fleet in January 2017. From this study, the following conclusions were drawn:

- The end-to-end validation technique is a powerful technique in the assessment of pre-construction and operational energy yield assessment, since it directly assesses the aim of energy yield assessment to evaluate net energy yield of a wind farm.

- A clear trend was observed between high wake effects and lower project performance.

- Whilst the precise causes of this trend cannot be defined for each project in the validation, this is considered to be due to a combination of wake model inaccuracy, WTG aerodynamics and wake-correlated downtime.

- K2 Management considers it appropriate to apply an additional adjustment to the modelled wake loss results from an ensemble of industry standard wake models in order to account for these effects. In combination with the use of the offshore wake model ensemble, by this method, it is possible to reduce the uncertainty associated with the final energy yield prediction for a wind farm.

K2 Management turbine interaction effects calculation method

Based on the results of the validation and other studies into WTG performance, K2 Management refined the pre-construction energy yield assessment methods in order to account for the full range of turbine interaction effects, thereby reducing the uncertainty in the resultant energy yield predictions for both offshore and onshore wind farm projects.

Offshore wind farms

For offshore wind farms, K2 Management generally applies an ensemble of industry standard wake models:

- Risø FUGA-2, run with both neutral and stable atmospheric configurations;
- Eddy Viscosity (WindFarmer implementation with Large Wind Farm Correction);
- PARK (WindFarmer implementation with Large Wind Farm Correction).

A confidence-based weighting of the individual wake model results is applied to determine an overall modelled wake loss for the project. The applied weighting is based on the findings of the validation, where a review of the theory, modelling approach and level of external validation of the individual models was undertaken.

As mentioned in the previous section, the findings of the end-to-end validation indicated that this ensemble wake modelling approach provides a low uncertainty wake loss prediction and that this uncertainty could be further reduced by applying a site-specific adjustment to the modelled wake results. This adjustment is necessary to account for the turbine interaction effects not captured by the constituent wake models in the ensemble.

From consideration of the validation results, a post-modelling adjustment equal to 33% of the modelled wake losses above 8% wake loss is applied to offshore wind farms where the K2 Management offshore wake model ensemble is applied. The adjustment is supported by strong empirical evidence from the end-to-end validation and accounts for site-specific effects by virtue of the relationship to the modelled wake losses.

For offshore wind farms with low wake losses, our validation showed that the wake model ensemble performs well and no post-modelling adjustment is required.

In energy yield assessments, an uncertainty is applied to account for potential errors in the wake modelling results and the associated post-modelling adjustment. The application of uncertainty is based on a framework taking into account various parameters associated with the calculation of turbine interaction effects, including the size and capacity density of the project and surrounding wind farm cluster, the WTG dimensions and rated power, and the local wind climate. These parameters are compared with those of the projects included within the validation. Based on this framework a proportion of the overall turbine interaction effect is applied as an uncertainty; typically between 20% and 40% of the overall loss.

The results of the K2 Management offshore wind farm ensemble wake modelling approach and associated post-modelling adjustment have been compared with high-fidelity comprehensive CFD wake model simulations of two offshore wind farms in the North Sea, undertaken by two major wind farm developers, as part of Lenders Technical Advisor assignments by K2 Management. As discussed previously, CFD wake modelling offers an opportunity to more accurately analyse downwind wake effects and upwind blockage effects.

In both cases, the K2 Management method performed exceptionally well against the CFD results; for the project with relatively low turbine interaction effects, the K2 Management and CFD predictions were within 3% of each other; for the project with relatively high turbine interaction effects, the predictions were within 10% of each other. In both cases, the K2M turbine interaction effect predictions were slightly higher than those from CFD, however it is noted that the CFD predictions do not consider the WTG performance and wake-correlated downtime aspects also considered in the K2M post-modelling adjustment. Whilst it is acknowledged that this is a case of comparing modelled results against each other, the technical independence of the methods provides additional confidence in the K2 Management approach.

K2 Management may consider a different wake modelling approach for wind farms located in nearshore locations or within archipelagos of islands where more "onshore" conditions are experienced. This is considered on a site-specific basis.

Onshore wind farms

Naturally, the blockage effect and other turbine interaction effects also affect onshore wind farms. The significant number of factors which affect wind speed variation within an onshore wind farm make it difficult to isolate turbine interaction effects and particularly the blockage effect. Consequently, it has not been possible to draw conclusions of the kind presented in the offshore validation to date. Whilst it is acknowledged that the configuration of wind farms and flow conditions experienced by WTGs can vary materially between onshore and offshore projects, it is considered appropriate to apply some of the principles of the findings of the offshore validation to onshore sites. Due to this, K2 Management applies an additional post-modelling adjustment to our modelled wake results for onshore projects.

In addition to the findings of the offshore validation, for onshore windfarms we have also considered our research into WTG performance in varying flow conditions, presented regularly to the Power Curve Working Group and an internal validation study following a large portfolio of development and operational onshore wind farms in Europe. From these studies, it was observed that the relatively tight WTG spacing often associated with onshore wind farms had a material impact on WTG performance and thus energy yield.

For onshore wind farms, K2 Management typically utilises a single industry standard wake model, Eddy Viscosity (WindFarmer implementation with Large Wind Farm Correction). Based on the findings of the offshore validation for this specific wake model and the additional studies mentioned above, post-modelling adjustments equal to 5% of the modelled wake losses plus 25% of the modelled wake losses above 8% wake loss are applied to onshore wind farms.

Similarly to offshore wind farms, an uncertainty is applied to account for potential errors in the calculation of turbine interaction effects, based on a framework of parameters associated with the wind farm configuration and its location. A proportion of the overall turbine interaction effect is applied as an uncertainty; typically between 20% and 50% of the overall loss.

Similarly to offshore wind farms, K2 Management considers turbine interaction effects on a site-specific basis, and therefore in certain situations K2 Management may consider a different wake modelling approach, depending on the observed wind flow conditions at a project.

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