

Offshore Energy Yield Predictions

A validation guide



For better energy projects



Management

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Executive Summary

Overview

Offshore wind continues to surprise the industry with lower costs, and turbines and projects at ever bigger scale. With these lower costs come lower margins, and an ever greater need to predict the output of projects with higher accuracy.

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

Through this approach, K2 Management has both measured and demonstrably improved state of the art offshore yield prediction. Refinements to best practice methods presented here provide unbiased, low uncertainty yield prediction across a wide variety of offshore projects.

Key findings

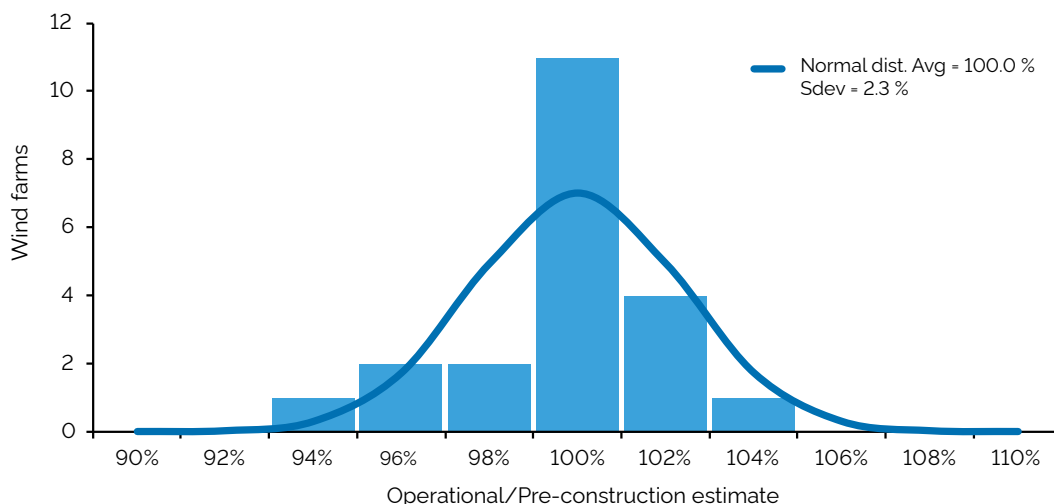
Of the UK fleet of 26 operational offshore wind farms, 21 were considered appropriate for inclusion in the study, spanning 1,338 turbines, or 91 % of the currently installed fleet.

Standard practice yield prediction methods work well, with all predictions within 8 % of operational observations. Some residual bias remains, however, largely related to projects with very high wake losses.

Multi-mast analysis methods can lower wind speed prediction uncertainties, particularly for projects with imperfect measurement campaigns, as is often the case offshore.

Projects with very high wake losses generally perform less well compared to predictions, even using best practice wake models. It is likely that these models either under-predict wake effects in these situations, or that there are additional losses that scale with wake effects.

An unbiased, lower uncertainty approach is possible with only minor adjustments to industry standard methods. These methods can increase investor confidence, supporting low risk offshore investment.



Introduction

This report

The study is presented in the following sections:

Pages 4 - 7 outline the context, geographic scope, data sources, and validation approach.

Pages 8 - 13 provide additional detail on best practice offshore analysis methods, and how uncertainty is minimised at each stage.

Pages 14 - 17 explore the causes of bias in the validation results and the potential to improve the accuracy of yield prediction methods.

Page 18 applies these methods, demonstrating the ability to predict offshore wind farm yield with high accuracy.

The need for accurate yield prediction

The acceleration in offshore wind installations in recent years has been extraordinary. Sometimes the scale can be hard to comprehend. At the time of writing this report, Europe has 11 GW operating and 20 GW consented, the US is targeting 86 GW by 2050, and China has constructed over a Gigawatt to date.

Meanwhile, as the European market matures, reverse auctions and lower tariffs are putting real pressure on costs and margins. Sometimes this has been gradual and sometimes seismic, as seen during the Borssele and Kriegers Flak auctions. The need to recycle capital by introducing debt and equity leaves no space for the inaccurate or over-predicted pre-construction yield assessments that have often dented confidence in the onshore market.

This study demonstrates the current accuracy of yield prediction across the entire UK offshore market, and outlines the steps required to reduce yield risk in offshore investment.

Study summary

We have estimated the long-term yield of 21 UK offshore wind farms using two methods, and then compared the results for each project, in order to better understand accuracy drivers for long-term yield prediction.

Method 1: Pre-construction

Method 1 uses pre-construction techniques: mast data, wind mapping, turbine power curves and wake models. This approach is close in scope and detail to that used for financial grade assessments.

Method 2: Operational

Method 2 uses high level, operational analysis techniques using public data only: Monthly wind farm production, the ROC register, and major down-time events from industry news sources such as 4coffshore.com and others.

Geographic scope

There are 26 operational offshore wind farms in the UK Exclusive Economic Zone. Of these, we were able to include 21 in the validation study based on their proximity to wind data and the availability of sufficient operational production data. The study spans 1,338 turbines and nearly 5 GW of installed capacity.

The remaining 5 wind farms were not used in the analysis primarily because there was either a very short period of operational data available, or they were located too far away from a publicly available source of meteorological mast data to provide a robust prediction. Demonstrator projects were also excluded due to uncertainties over their performance consistency.



Data availability

We would like to express our gratitude to the organisations that have made this study possible through the public sharing of extensive data sets. Without these, this report would not have been possible. They include:

1. 47 mast-years of wind measurements and metadata from 11 masts on The Crown Estate's Marine Data Exchange;
2. the most recent 5 years of wind farm ROC production statistics published by OFGEM;
3. The Crown Estate, UK Offshore Wind Resource Map (UKOWRD);
4. wind farm layouts from the Kingfisher awareness charts.

We hope that this report highlights the immense value of these data sharing exercises and their potential impact in reducing the cost of energy.

1. <http://www.marinedataexchange.co.uk/>
2. <https://www.renewablesandchp.ofgem.gov.uk/>
3. <https://www.thecrownestate.co.uk/media/476245/ei-uk-offshore-wind-resource-dataset-2015.pdf>
4. <http://www.kis-orca.eu/>

Validation Overview



Validation result = Operational / pre-construction estimate



To review the performance of the UK offshore wind farm fleet, K2 Management has performed two separate analyses on each wind farm - one using wind mast data to form a 'pre-construction' yield prediction and a second using actual production data to form an 'Operational' yield prediction. An outline of each method can be found on the opposite page, with more detail provided in the following sections.

The two methods have been designed to provide an estimate of 100% available, long-term average energy yield. The validation process is that of comparing the pre-construction estimates with their operational counterparts, in order to improve prediction methods.

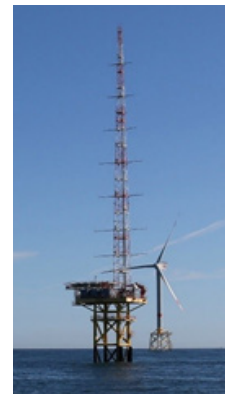
Pre-construction Analysis Methods

For the technically-minded, this chapter provides some additional detail on the assumptions involved in the study, and methods that allow us to produce the highest accuracy offshore yield assessments in the industry, with demonstrably lower uncertainty.

Mast data processing

Approximately 47 years of wind data from 11 anemometer masts were processed using industry standard techniques and included the following stages:

Calibration: A variety of anemometers are in use, each with wind tunnel calibration factors, some of which were applied by the on-mast data loggers and others that required adjustment. In some cases, due to whole scale deviations highlighted by wind tunnel owners, a correction factor was also necessary. Once corrected, the resultant wind speed is of a lower uncertainty than using generic factors alone.



Cleaning: the marine environment is a harsh one leading to increased wear and degradation of the anemometers, and wind vanes, recording the wind speed and direction. While some mast owners implement rolling replacement programs, failures and degradation do occur and data from these instruments were removed.

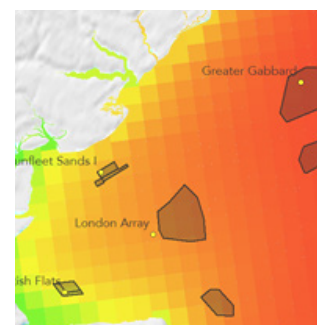
Wind vane alignment: Often the wind vanes on a mast are not aligned to north or the alignment of their north is not recorded at installation. It was therefore necessary to reference the wind data recorded by these instruments to grid north, to allow for accurate weighting of the directional wake effects.

Mast effects: While onshore anemometry masts are typically guyed for stiffness, this is not possible offshore and so thicker, free standing lattice structures are required. This not only causes wake effects when the anemometers are behind the mast but can also cause speedup effects around the mast and blockage effects in front of the mast. These effects also vary with height as the mast tapers. K2 Management has used careful selection of anemometers, and averaging of parallel instruments, to minimise these effects on wind speed.

Spatial variation

The UK Offshore Wind Resource Database (UKOWRD), commissioned by The Crown Estate, and produced by the Met Office, was used to establish expected spatial variation in wind resource, between masts and turbine locations.

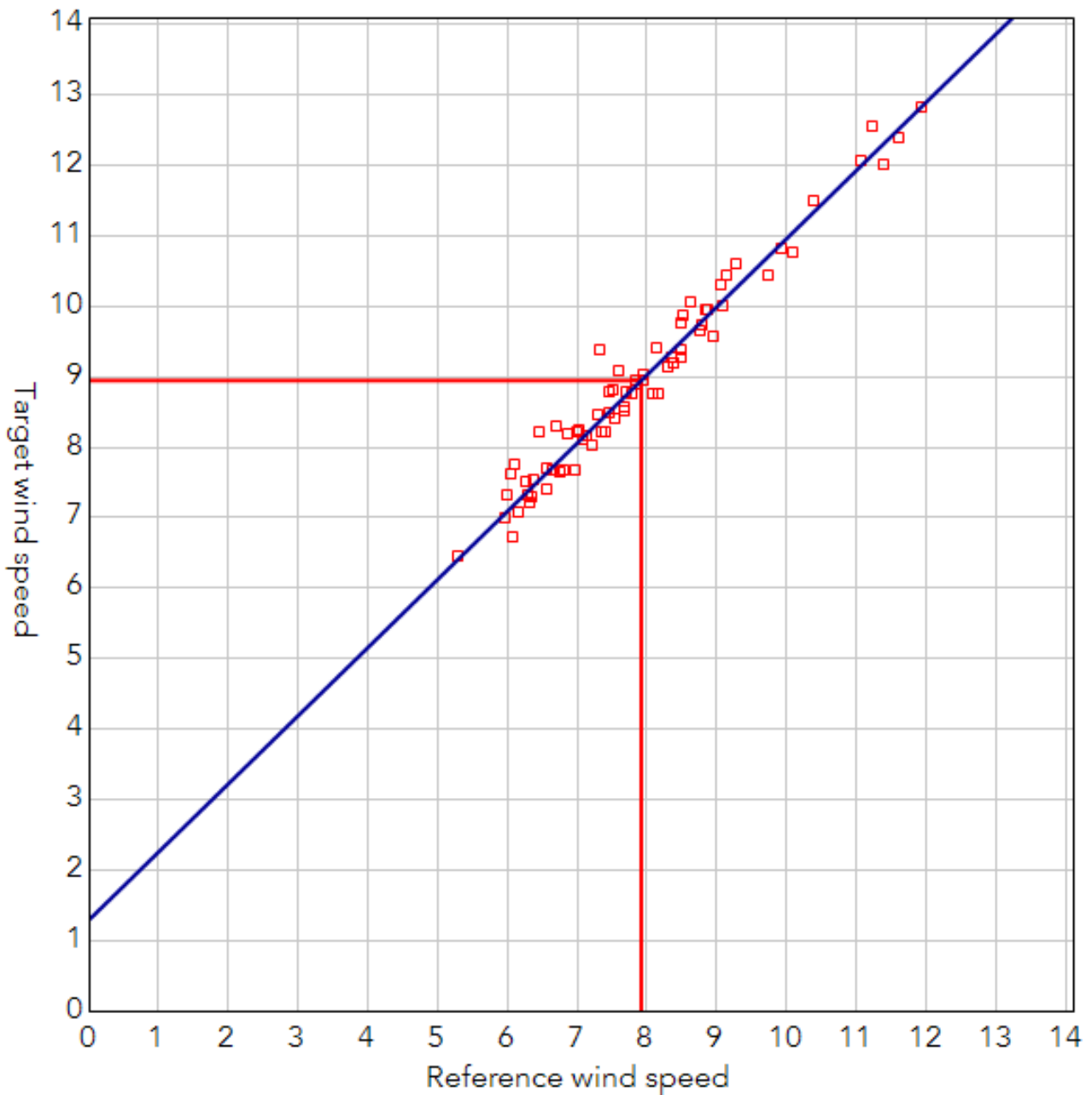
Other approaches, such as bi-cubic interpolation were applied in order to extract maximum accuracy from the model data.



Long-term adjustment

For financial grade analysis, K2 Management would typically undertake a detailed study of nearby meteorological stations and reanalysis datasets to define a robust, consistent and representative long-term dataset. This generally takes the form of an index of several datasets to reduce uncertainty in the long-term wind speed.

For the purposes of the validation, however, we simply required a dataset that was consistent over the mast and wind farm operational periods in order to eliminate long-term adjustment differences from the study. MERRA-2 reanalysis data is well validated in the UK and hence was used to tie the two analysis routes together.



Pre-construction Analysis Methods

Multi-mast analysis

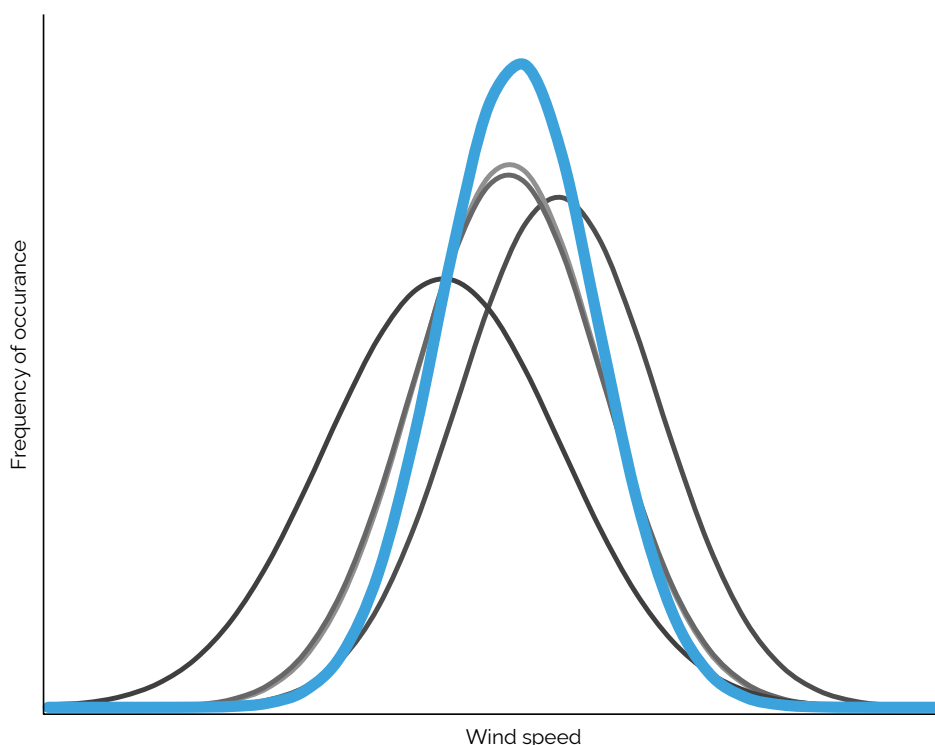
Onshore, wind flow structures are complicated. They require substantial, high-resolution modelling effort and can be a significant source of uncertainty, even across relatively small sites.

Offshore, the spatial variations in wind speeds are more gradual and predictable. It is possible to predict wind speed at distances such as 40 km away from a mast with a level of confidence unachievable onshore. This widescale prediction allows the use of multiple regional masts to inform wind speed predictions for a single offshore project.

K2 Management has used The Crown Estate UKOWRD wind speed map to extrapolate the long term mean wind speed prediction from each mast to each wind farm in the region. This provides up to four independent wind speed predictions at each wind farm, with varying uncertainty associated with each.

Rather than pick the closest mast prediction and discard the other measurements, we have employed Gauss-Markov minimum uncertainty theorem to derive a weighted average of these predictions. This method uses the uncertainty in each wind speed prediction to define the overall mean wind speed at each site. The approach results in a lower uncertainty than the use of any single mast, and substantially improves accuracy for sites without an available mast dataset.

This approach is of particular value when short, or non-standard data sets are considered, such as those available early in a project's life, or where devices such as floating LiDARs have been deployed.



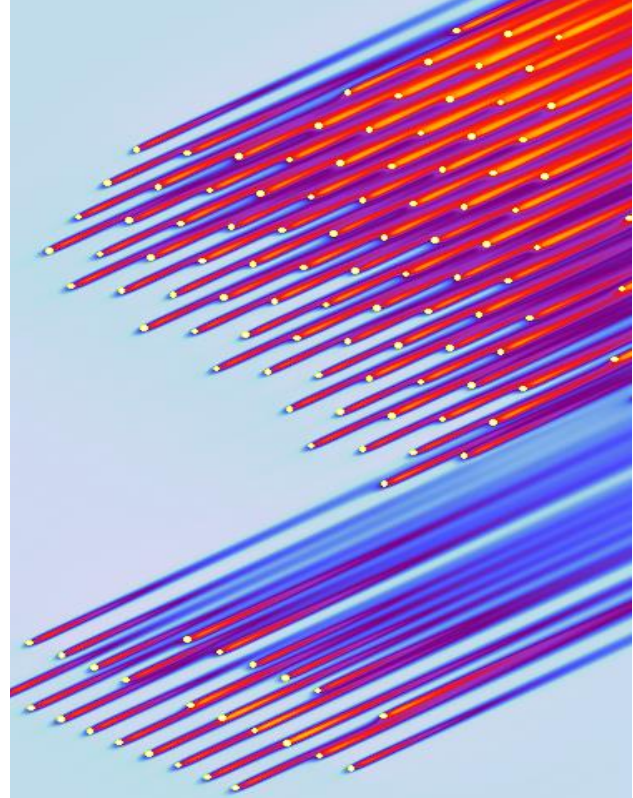
Ensemble wake modelling

The interaction of the 1,338 wind turbines constructed in the three areas covered by this study have a significant impact on energy yield. The modelling of these interactions have been conducted using three separate industry standard wake models:

- Risø FUGA2 , 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-weighted ensemble of these results is used to provide a robust prediction of wake loss.

We will look later at the wake models, both on an individual basis and alongside other wake models used in the industry.



Other losses

Standard loss assumptions have been applied and include:

- site specific turbine performance assumptions;
- internal electrical system losses between the turbines and OFTO connection point;
- environmental factors such as blade degradation.

Availability assumptions have not been applied since the comparison baseline with the operational analysis path does not include this loss.

Operational Analysis Method

Standard operational analysis methods have been applied and include: data quality filtering; long-term adjustment; and removal of project commissioning and ramp up periods. Due to the use of public data only in this study, a different approach to availability was required.

Availability assumptions

Operational wind farm yield analysis typically includes analysis of availability data, either at monthly resolution provided by the project operator, or derived from SCADA data directly.

Since wind farm availability data is not made public, for the purposes of this validation, another approach was required.

For this purpose, two imperfect, pragmatic methods were employed:

- 1 Any months with extensive unscheduled down time affecting the whole wind farm, for example subsea export cable failure, were identified using public industry news sources of down-time and their causes.
- 2 Scheduled maintenance is generally carried out through rolling programmes across a project, and is therefore difficult to identify. In order to estimate 100 % available production, it was necessary to assume a turbine availability value. For the purposes of the validation, 95 % has been assumed to represent residual availability over months not identified in the first stage.



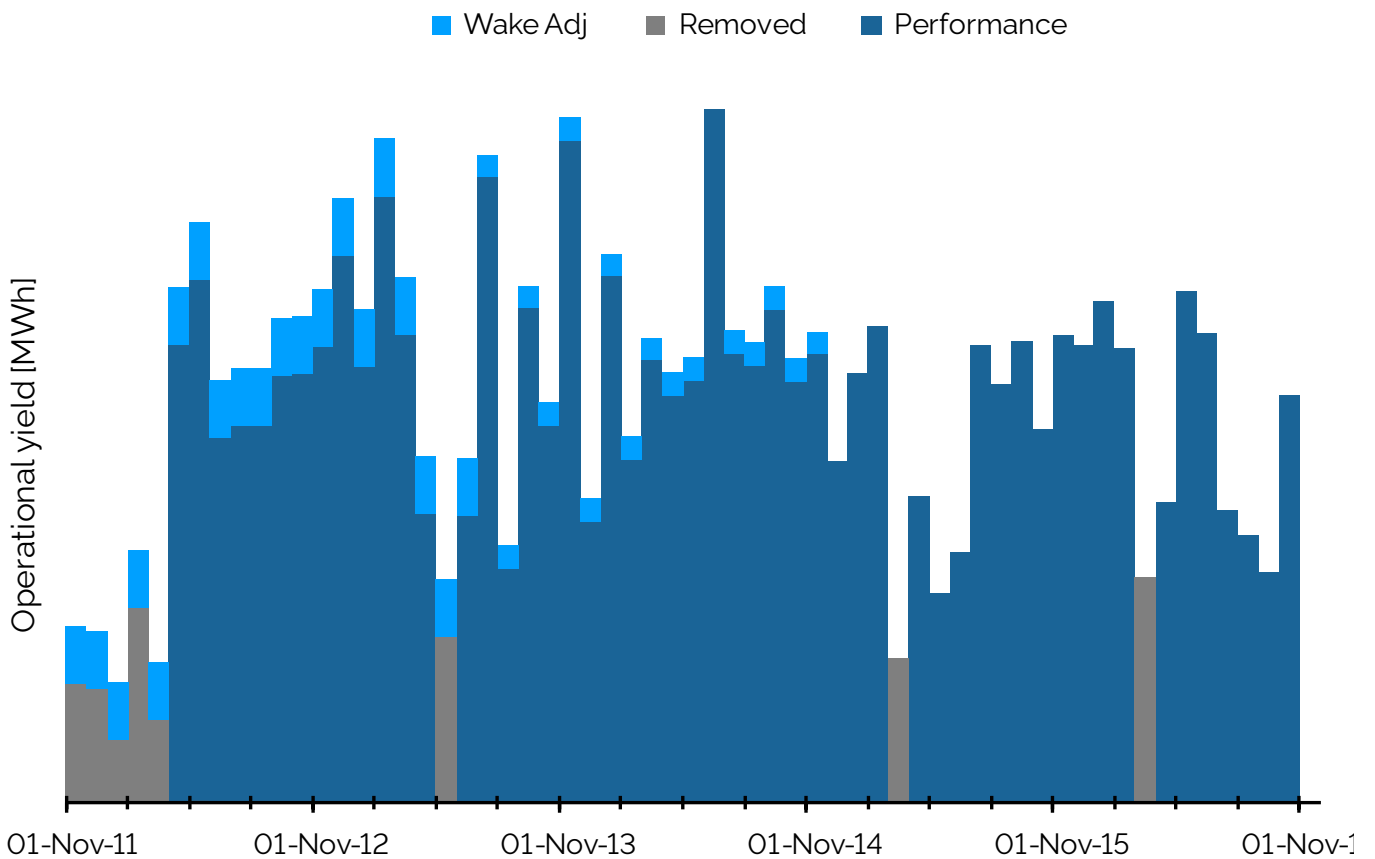
In order to correlate fully available monthly production, we have removed months with major down-time and increased the remaining data by 5%. This is crude compared with use of known monthly system availability values and has degraded correlation quality to some extent. However, the validation process allows us to consider the residual availability assumption in more detail, and assess the impact of known causes removed from the data set.

Operational data period selection and adjustment

Two steps were included to improve the accuracy of operational analysis results:

Firstly, as a precaution, initial commissioning periods were removed, in order that the results would represent long-term performance levels.

Secondly, where changes in external wake effects from construction of neighbouring projects were minor, production values were adjusted to simulate current exposure. Periods prior to major changes due to neighbouring project construction were removed to avoid biasing the results.



Observations

Initial results using typical industry methods

The final stage of the analysis was to compare the two sets of energy yield predictions.

Despite some major assumptions in the operational analyses, such as a fixed 95 % turbine availability value, there is a high level of agreement between operational and pre-construction estimates.

All wind farms were seen to operate within 8 % of their pre-construction prediction. This is higher than the average P90 value assigned to offshore wind farms and indicates the high level of confidence that can be gained from correctly performed pre-construction offshore yield predictions.

The error distribution has an average bias of -2.8 %, however this is driven by some older projects, often with very high wake effects, unrepresentative of expected round 3 layout designs.

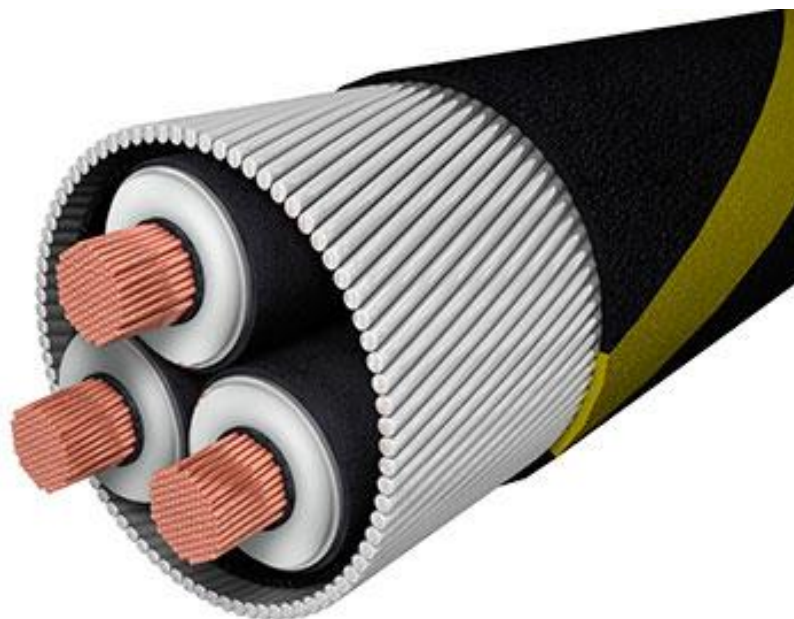
The broad range of the validation has allowed us to examine, in detail, the underlying causes of this bias in order to refine the prediction methods and seek a zero-bias approach.

Balance of plant availability

In calculating the operational energy yield prediction, we removed any months in which major or newsworthy downtime events occurred. These included items such as sub-station failures or issues with the cable connection to shore. The majority of these whole wind farm affecting issues are typically assigned to Balance of Plant availability.

In a pre-construction energy yield assessment, Balance of Plant availability is typically assessed using details of the equipment involved, and O&M infrastructure and schedules. In the absence of this information, a value between 0.5% and 2% is typically assumed.

The net energy impact of these months on long-term yield is a reduction of 1.1% across the UK operational fleet. This can be seen to be an approximation of typical Balance of Plant downtime.



Selection of wake models

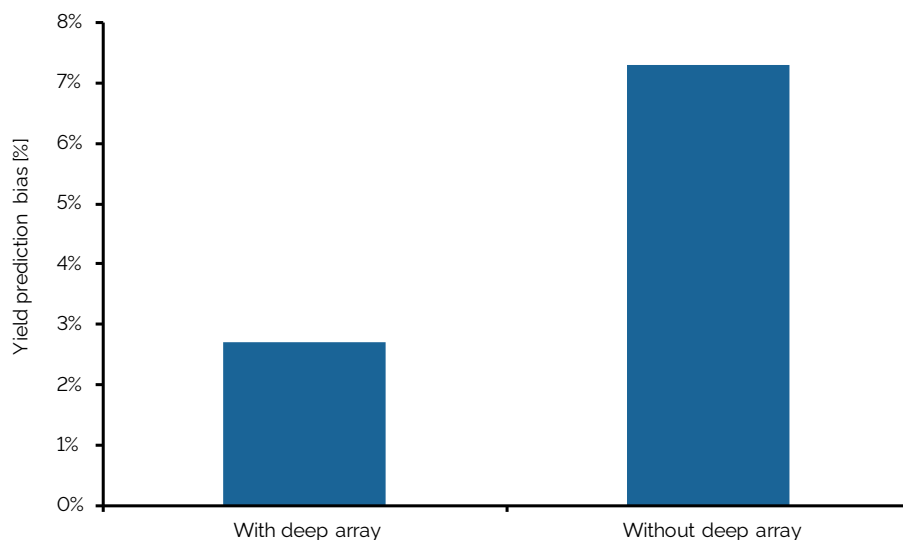
Wake losses are the single largest loss in energy for offshore wind farms and therefore one of the first places to look when refining the pre-construction assessments.

As part of our offshore energy yield assessments, three wake models were considered:

- 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).

As part of this study, we also looked at the following wake models which are in common industry use:

- Eddy Viscosity (WindFarmer implementation without Large Wind Farm Correction);
- PARK (WindFarmer implementation without Large Wind Farm Correction);
- PARK (WAsP implementation).



Using results from individual models, across all 21 wind farms, it is possible to show the bias caused by each. The associated results are shown in the graph above, grouped by models that either do, or do not, account for deep array effects.

Findings of this comparison are as follows:

- There is a significant risk associated with using any one model to predict wind farm energy yield, with individual wake models having higher scatter than an appropriately weighted ensemble.
- Older generations of wake models, that do not account for large wind farm effects, are significantly more likely to over-predict wind farm yield.

Observations

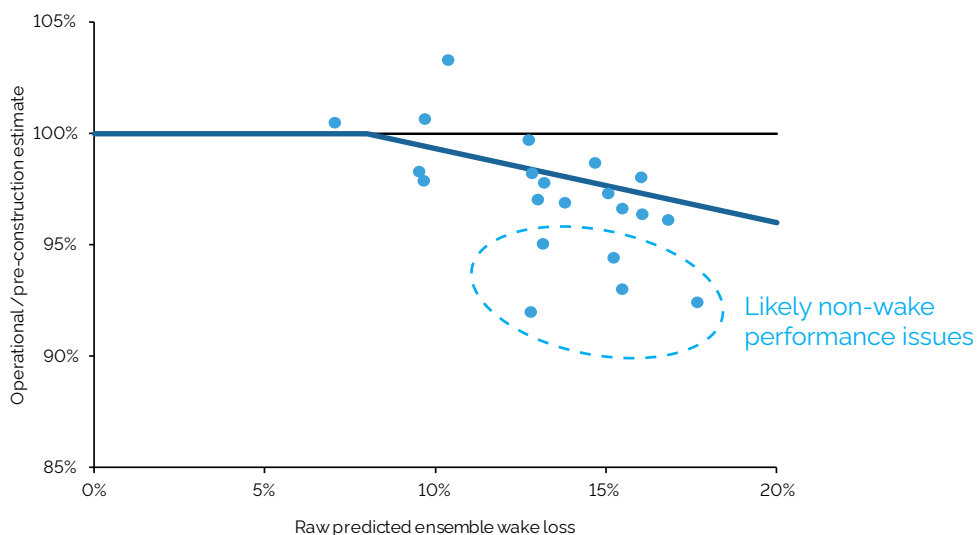
Refined wake modelling

The plot below shows the inter-relation between project performance and wake effect. Some projects are either known, or suspected to have, experienced significant performance issues unrelated to wake effects such as grid curtailment. Once these are excluded, a clear relationship indicating pre-construction over-prediction or operational under-performance is visible, particularly at sites predicted to have very high wake effects.

While there is a clear relationship between under-performance and increased wake loss, The root cause cannot be defined using publicly available data. There are several potential drivers of this effect:

- Wake model inaccuracy: While efforts have been made to use the cutting edge of validated wake models, these models are primarily validated on a small number of wind farms which contain fewer, smaller turbines than later projects included in this study. It is therefore possible that the accuracy of wake models is decreasing for more recent projects.
- Turbine aerodynamics: Even if the wind speed deficit effect of wind turbine wakes is correctly predicted, the boundary layer behind wind turbines is heavily disturbed. 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 turbines.
- Wake-correlated down-time: The highly turbulent flow experienced by wake affected turbines 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.

The cause of the linkage between wake effects and lower project performance cannot be conclusively proven from publicly available data. However the trend is sufficiently clear that it is appropriate to consider a sub-optimal performance adjustment. The green line on the graph shows the approximate trend likely to be related to very high wake effects.



Other losses

After the identified trend with wake loss has been applied, a 0.7% average deficit between operational and pre-construction predictions is observed.

It is expected that this residual bias may include a number of factors including:

- inaccuracy of the 95 % turbine availability assumption – no public availability data was available for any project considered;
- influence of grid curtailment (not modelled in this study);
- non-turbine down-time events not considered in the major event removal process;
- turbine performance below the levels assumed;
- assumed electrical losses of 2.0 % between the turbines and OFTO metering point. In reality this value will vary between projects.

In general these issues are related, to an extent, to the limitations imposed by use of publicly available data only. Such issues would typically be expected to be investigated in detail during the investment process, and quantified to a high level of certainty.

Conclusions

Most of the UK offshore capacity has been analysed in a major validation of offshore yield prediction methods. Through this process, K2 Management has identified improvements to best practice methods that reduce both uncertainty and bias in yield prediction offshore.

(i) Current best practice

Robust analysis methods are a vital component of accurate offshore yield prediction. Highlighted methods in this report include the following:

- Multi-mast analysis methods reduce wind prediction uncertainties, particularly when measurement campaigns are imperfect, as is often the case offshore.
- Ensemble wake modelling, combining multiple deep array models, reduces prediction uncertainty and bias. Excluding deep array effects causes significant over-prediction of wind farm yield.

(ii) A refined wake modelling approach

When standard methods are applied to the UK operational fleet, yield predictions over-predict compared to operational results by around 2.8 %. However, much of this bias is caused by older projects with high wake losses compared to next-generation designs.

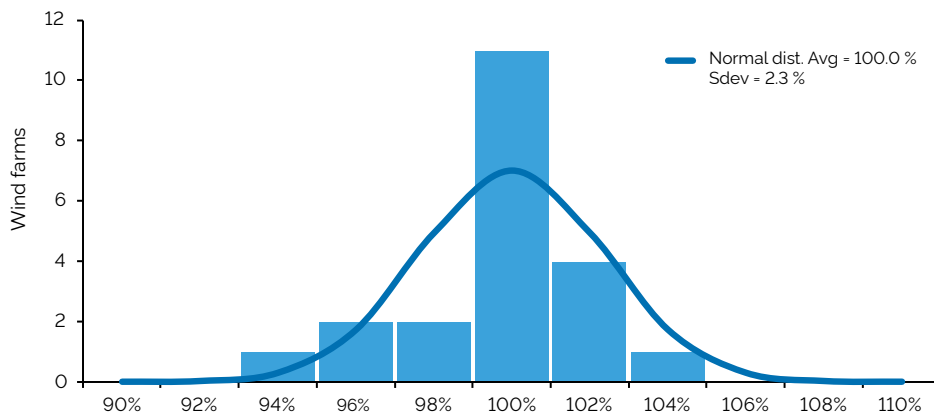
Projects with very high wake losses generally perform less well compared to predictions, even using a deep array ensemble approach. It is likely that this is due to under-prediction of wake effects, or that there are additional losses that scale with wake effects.

K2 Management has refined best practice methods for high wake loss projects to improve accuracy.

(iii) Low uncertainty, low bias

With K2 Management's refined wake modelling approach for high wake cases, a residual bias of just 0.7 % energy remains. Much of this bias relates to aspects that would normally be well understood in an investment scenario, such as availability expectations and grid curtailment.

The standard deviation of long-term predictions compared to actual yield is just 2.3 %, demonstrating high confidence yield prediction, vital for a low-subsidy or subsidy free offshore future.



More than half of the wind farms operate at the 100 % prediction level, with equal numbers either side, demonstrating low bias prediction.

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