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SUPERGEN Wind Hub

Deliverables:

D1.3 Report detailing the impact of large offshore arrays on each other in terms of wind shadowing effects.

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This deliverables is in the form of an MSc report and case study (attached) – ‘An Evaluation of the Impact of External Wakes in Offshore Wind Farm Clusters’.

An Evaluation of the Impact of External Wakes in Offshore Wind Farm Clusters

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Abstract: Offshore wind farms are often located near one another in clusters. They can find themselves operating in an external wake from another wind farm and this may have an effect on their energy yield. It is therefore useful to be able to measure and quantify impacts from external wakes on offshore wind farm power production. This paper uses wind data and electricity generation data to determine whole wind farm power curves for conditions with and without external wakes present. From this, an assessment of the impact of external wakes on typical annual energy yield is made for two wind farms. In the case of a relatively small wind farm with a close, larger neighbour, a 3.6% reduction in annual energy yield is estimated. In the case of a very large wind farm with smaller, more distant neighbours, no reduction in energy yield is found. Quantifying the impacts of external wakes on offshore wind generation is valuable in reducing uncertainties in offshore wind development and power production.

Keywords: Offshore wind farms, wind farm wake, external wake, energy yield, power curve, cluster effects.

1. INTRODUCTION

The aim of this work is to evaluate the impact of external wakes on electricity generation from wind farms in an offshore cluster. Offshore wind farms are often built close to one another in clusters where sea bed conditions, grid access and other factors are favourable. Whole wind farm wakes may therefore impact on downwind wind farms in the same sea area. These intra-farm wakes are sometimes referred to as cluster effects and sometimes as external wakes, to differentiate them from the internal wakes due to each of the turbines operating within a wind farm. The impact of an external wake on another wind farm is expected to include a reduction in generated electricity output with a consequent impact on the profitability of the affected wind farm. Open questions remain as to how frequent and how large such impacts are and to investigate further this paper looks at whole wind farm power curves at four offshore wind farms in the UK for in and out of wake conditions. These power curves relate whole wind farm power output to wind speed.

The method that we have used is constrained by the data available to us.

- Data on the half-hourly power generation of most UK offshore wind farms is available to us in the Elexon P114 dataset[1]. The Elexon data cover the period from 27/12/2008 to 31/05/2016. Elexon is the company responsible for managing balancing and settlement between generators and suppliers in the UK electricity market.
- A selection of offshore mast data are available to us for various time periods, durations and locations. The latest available mast data finish in 2013. None of the mast data overlap the operating period of any offshore wind farms in their area, they always pre-date them.
- Global reanalysis data provide standardised meteorological and atmospheric data from forecast models run after the event. MERRA2 hourly reanalysis data are available to us for 1980 to the present, or ERA-Interim 3-hourly reanalysis data for 1979 to the present, with MERRA2 being selected for this study. The spatial resolution of MERRA2 is 0.5° latitude by 0.625° longitude and ERA-Interim is 0.75° latitude by 0.75°longitude.
- The offshore wind farm in question must be fully commissioned and the other wind farms in the cluster must be either fully commissioned or not generating any power at all yet as we don't have information about the status of partially constructed and operating wind farms.

Hence the time periods for which we compare in and out of wake power generation will be selected to accommodate the first generation and commissioning dates of wind farms in the cluster, and to fall before 31/05/2016 which is the end of the Elexon data. Wind speed and direction will be taken from reanalysis data. We will use the earlier mast data to adjust the reanalysis wind speed data with a Measure-Correlate-Predict method to better fit measured conditions at the wind farm sites.

The context for this research is a sizeable and expanding offshore wind industry in the UK. The UK has 5 GW of installed offshore wind generation capacity, which is over one third of the global installed offshore wind capacity[2]. The UK Climate Change Act 2008 established a legally binding target to reduce the UK's greenhouse gas emissions by at least 80% by 2050. A major and essential component of this is the planned decarbonisation of UK electricity generation such that by 2050 emissions from the power sector are close to zero[3]. Cost reduction of offshore wind, leading to large scale deployment, is expected to play a significant role in this[4].

It has been found that offshore, wind farm wakes can be very long under some atmospheric conditions. Satellite images from Synthetic Aperture Radar (SAR) instruments can encompass a wide view covering many offshore wind farms. The radar return over the ocean is related to wind speed at the surface and wakes behind wind farms have been observed that are several tens of kilometres long[5].

Modelling is widely used in the offshore wind industry to predict wake losses at proposed wind farm sites to optimise their layout and to assess their commercial viability. Models have long been developed to try and quantify energy losses in very large wind farms, such as those now seen offshore[6, 7]. More recently, wake modelling has sought to couple microscale models of the effects of turbine wakes to mesoscale models in order to model whole wind farm wakes and their impact on downwind wind farms[8-10]. The EERA-DTOC (European Energy Research Alliance – Design Tools for Offshore Wind Farm Cluster) project[11] benchmarked a number of wind farm scale wake models against available wind farm data[12] and these were validated for a two farm case with wind farm SCADA (Supervisory Control and Data Acquisition) system data[13]. The findings were that the spread of model results encompassed the SCADA results, but with a high degree of uncertainty. The extension of wake modelling into cluster effects is a reflection of the increasing need to understand and to anticipate these losses as more offshore wind farms are planned and developed. Improving the accuracy of these models is an active area of research, and is dependent on further research and measurements of the impacts at downwind wind farms than is generally currently available.

There are limited studies to date that have been able to measure the impacts of offshore wind farms on each other. Two papers by Nygaard [14, 15] use SCADA data from wind farms to measure intra farm impacts. Nygaard looks at Walney Phase 1 before and after the operation of the immediately adjacent Walney Phase 2 and at Danish wind farms Nysted (commissioned 2003) and Rødsand 2 (commissioned 2010). Nysted and Rødsand 2 are 3.3km apart. The papers establish a loss of energy production in wind farms when they are downwind. In the second study, which focuses in detail on Rødsand 2 and Nysted, it is shown that the external wake losses in the downstream wind farm are seen in the first rows of the array of turbines, but then recover, such that losses in generation seen deeper into the array are no greater than those seen from internal wake losses only, before the upstream wind farm and any external wake was in place. This leads to the observation that the relative impact of external wakes on a wind farm will diminish as the physical extent of the wind farm increases. It should be noted that at some turbines in the downwind wind farm, a wind speed increase and energy gain was seen.

The MERRA2[16] data set is produced by NASA and is an update from their MERRA data set which has been widely used for long-term wind resource prediction in wind energy. The use of MERRA in long-term correction methods to obtain a long-term average 100m wind speed was found to agree very well with measured data and a range of other correction methods when assessed by EERA-DTOC[17]. And it has been shown that MERRA2 results agree well with MERRA and with sample mast data when comparing averages and range and hence that MERRA2 is a reasonable replacement for MERRA in established uses[18]. However, it is not a direct measurement of wind conditions and may contain biases. For example, MERRA2 was found to under-predict wind speed in comparison to two UK offshore masts by one study[19], but was shown by another to over-predict wind resource at country level in the UK, in Ireland and in North West Europe in general[20]. There is some evidence that reanalysis data, including MERRA2, show smaller bias in wind speed for offshore locations due to the lack of topography[20].

We will use a Measure-Correlate-Predict method to correct MERRA2 for our wind farm sites. The MCP technique takes a short-term wind data series at a site of interest and correlates it with a long-term data series. This correlation is then used to provide long-term wind speed and hence energy resource predictions at the site of interest. There are a number of refinements to the method, with 12 separate correlations for 12 30° direction sectors being common[21]. Woods and Watson[22] describe a method for assessing whether wind direction is biased between long and short term data series sites. We will make use of this, as the accuracy of the wind direction is significant to this study.

2. METHODOLOGY

The aim of this work is to see if there is a measurable effect on the electricity generation from an offshore wind farm when it is in the wake of another wind farm compared to when it is not. In order to make the comparison whole wind farm power curves are constructed for the in-wake and out-of-wake cases. Information about the operational status, known as the availability, of the wind farms is not available to us and so the power curves will include data from operations with varying levels of availability. By comparing the power curve of all power responses across the range of wind speeds for all in wake cases and comparing it to that for all out of wake cases, it can be seen if any wake effect is discernible above the underlying operational variability of the wind farm. By looking too at the power curve of the median wind farm power found in each wind speed bin, we will be able to reduce the impact of availability on our results.

In outline the method followed in this study is as follows:

- A 12 sector Measure-Correlate-Predict (MCP) method is used to correlate reanalysis data with short-term mast data and the results are used to improve the accuracy of the reanalysis wind speeds at wind farms of interest.
- Reanalysis wind direction data is used to classify each hour in a period of interest as in or out of wake or too close to call.
- Two power curves are derived for the wind farm: one from the whole wind farm power output and the adjusted wind speed for every hour classified as in wake, and another for every hour classified as out of wake. The power curves for the median power seen in each wind speed bin are also derived, in order to remove some of the uncertainty arising from a lack of information about the wind farm availability.
- For two wind farms historic mast data is used to calculate the long-term probability of the wind speed and this is used with the in and out of wake power curves to calculate the probable annual energy yield with and without any wake effects. The difference gives us the likely impact of external wakes on the annual energy yield.

An initial assessment was made in order to select which reanalysis data to use. A short period of mast wind speed data from a mast to the west of the UK (Gwynt-y-Môr) and from a mast east of the UK (Greater Gabbard) were correlated with 1 hourly MERRA2 winds speeds at 10m and at 50m height and with 3 hourly ERA-Interim wind speeds at 10m height. The 50m MERRA2 data was found to give the best correlation at both sites and so is used for the remainder of this study.

In order to classify generation periods as in or out of wake, MERRA2 wind direction data are used in conjunction with knowledge of the relative positions of offshore wind farms. Offshore wind farm location and position data comes from web resource 4C Offshore[23] and from satellite radar images from the Sentinel-1 mission[24] where offshore wind farms are clearly visible as arrays of bright dots. Consideration was given to classifying wind farms as in or out of wake by using Synthetic Aperture Radar (SAR) data. The advantage of SAR would be a definite identification of clear in and out of wake cases for wind farms. Derivation of wind speeds over the sea from SAR images is well established[25] and has been used in wind farm wake studies before[5, 26]. However the availability of Sentinel-1 SAR images (one every few days since November 2015) and coincident generation data (only available until May 2016) did not provide sufficient clear cases at any one wind farm to construct two power curves, so this method was rejected.

This study considers two UK wind farm clusters, one in the Irish Sea, off the north-west coast of England, and one in the Thames Estuary off south-east England. Details of the clusters' wind farms are given below in Table 1. Time periods for this study were selected to avoid unknown levels of generation from partly operational wind farms under construction. The Irish Sea cluster was considered for 1st January to 31st December 2013 and the Thames Estuary cluster for 1st October 2013 to 31st July 2015.

The mast data used came from the Shell Flats and the London Array masts, both 80m high, and used the top anemometer and wind vane available to minimise mast shading effects. The Shell Flats mast is the nearest available mast to the wind farm cluster of Barrow, Ormonde, Walney and West of Duddon Sands. It is about 27km south-south-west of Ormonde. MERRA2 wind direction data was compared to mast wind direction data at both masts for evidence of any systematic veer and none was found, so MERRA2 wind direction was used unadjusted in the remainder of the study.

The layouts of the clusters are shown in the Figures 1 and 2 below and the separation distances of the wind farms (taken centre to centre) and masts are included in Table 1. Given the uncertainties in the wind direction data, sectors of 10° on the borders of the in wake sectors are disregarded in constructing in or out of wake power curves.

In the Irish Sea cluster it can be seen that Ormonde is expected to be in the wake of Walney 1 and 2 for wind directions from a significantly sized sector. These wind farms also have the smallest separation of about 3 km at the closest point. It is hypothesised that the in wake power curve may well show lower power outputs than the out of wake power curve at Ormonde. In the Thames Estuary cluster it can be seen that London Array potentially sees wakes from surrounding wind farms in several directions. However they are all at least 20 km away. They are also all smaller in capacity than London Array which is currently the largest offshore wind farm in the world. The next largest wind farm in the cluster is Greater Gabbard which is also the furthest away at 42 km. It is hypothesised that there may be no discernible difference between in and out of wake power curves at London Array.

Table 1

Cluster	Wind farm or mast	Farm capacity (MW) [23, 27]	Distance from Ormonde (Irish Sea) or London Array (Thames Estuary) (km)	Date of first generation [23]	Date of farm commissioning [23]
Irish Sea	Ormonde	150.0	0	Aug-2011	Feb-2012
	Walney 2	183.6	7	Nov-2011	Jun-2012
	Walney 1	183.6	11	Jan-2011	Jul-2011
	West of Duddon Sands	388.8	11	Jan-2014	Oct-2014
	Barrow	90.0	14	Mar-2006	Sep-2006
	Shell Flats Mast	-	27	-	-
Thames Estuary	London Array	630.0	0	Oct-2012	Apr-2013
	Gunfleet Sands	108.0	22	Aug-2009	Jun-2010
	Gunfleet Sands 3	64.8	22	Jan-2013	Sep-2013
	Thanet	300.0	24	May-2010	Sep-2010
	Kentish Flats	90.0	33	Jun-2005	Dec-2005
	Kentish Flats Extension	49.5	33	Aug-2015	Dec-2015
	Greater Gabbard	504.0	42	Dec-2010	Sep-2013
	London Array Mast	-	0	-	-

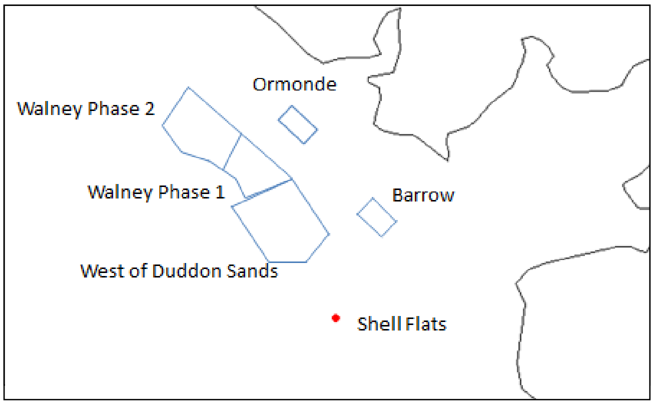


Figure 1

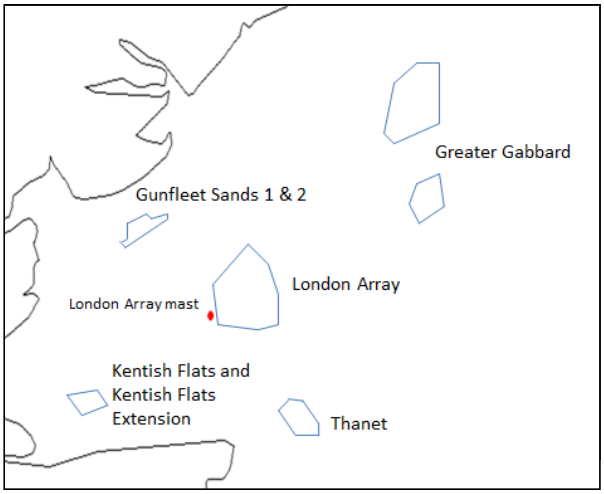


Figure 2

To produce the power curves we take the hourly wind speed data and wind direction data and the average power generated at the wind farm in the corresponding two half-hourly generation periods. The wind direction allows us to identify each data point as in wake, out of wake or unknown. The unknown classification is used for a 10° margin between the in and out of wake directions. Filtering the data by wake classification we discard the data classified as unknown, and derive two power curves. The median power for each wind speed bin was also calculated for all the in wake data and for all the out of wake data. By taking the median power in each wind speed bin we reduce the uncertainties associated with the unknown state of operation of the wind farm at any one time. The maximum power in each wind speed bin is not used as the wind speed data is not exact at any one time and so we cannot be sure that single data points are classified in the right wind speed bin.

At Ormonde and London Array we use a number of years of historic mast data to give the probability distribution of wind speeds seen in each of 12 x 30° direction sectors and apply the median power by wind speed bin power curve to predict a typical annual energy yield. The direction sectors are chosen so that waked sectors fall within, not across them. This works particularly well for Ormonde where the large angle that sees the wake from Walney spans 2 sectors. The Barrow wake is disregarded as it is only 1° wide. At London Array the sectors can be arranged such that waked directions fall within them, but the sectors designated as waked are in fact only partially waked. Firstly, the annual energy yield is predicted using in all 12 sectors the power curve found for out of wake conditions. This predicts an annual yield for the wind farm as if it saw no external wakes. Then the exercise is repeated, but with the power curve found for in wake conditions applied in only the sectors identified as wake sectors, and the out of wake power curve used in all remaining sectors, with any reduction assumed to result from energy loss due to external wakes.

3. RESULTS AND DISCUSSION

3.1 Comparison of Mast and Reanalysis Wind Data

3.1.1 Results

Wind roses showing the frequency of wind speed measurements in each direction sector are compared for the same time period for Shell Flats 80m mast (Fig 3) and for the 50m wind speed at the nearest MERRA2 grid point (Fig 4). Similarly wind roses for coincident London Array 80m mast data (Fig 5) and the nearest MERRA2 grid point to London Array (Fig 6) are compared. In the Irish Sea, MERRA2 shows an underestimation of the frequency with which winds are seen from the south-south-west direction sector compared to the Shell Flats mast data. Otherwise the wind roses show reasonable similarity. In the Thames Estuary, the MERRA2 and London Array wind roses show reasonable similarity in all sectors and only small differences can be observed.

In order to check for any systematic veer or turning in wind direction between the wind seen at the selected masts and that produced by the MERRA2 reanalysis data, the difference between the mast measured wind direction and the MERRA2 wind direction (the veer) was calculated and binned against 10° bins of MERRA2 wind direction. Fig. 7 shows the results of this at Shell Flats / Irish Sea and Fig. 8 shows the results of this at London Array / Thames Estuary. The plots show the veer measurements binned by direction in black, with the average veer in each direction bin overlayed in red. The blue lines mark the ±10° veer line. It can be seen from this exercise that at both sites the average veer is small for all directions. There is no evidence of any systematic veer or turning between the mast and the reanalysis data in either case.

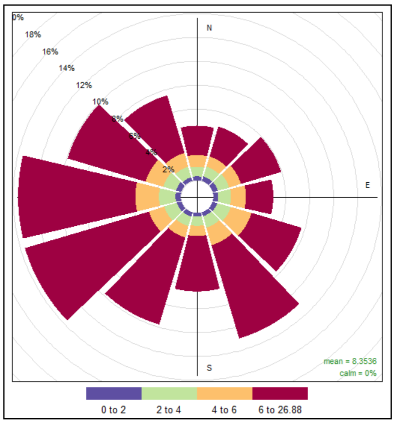
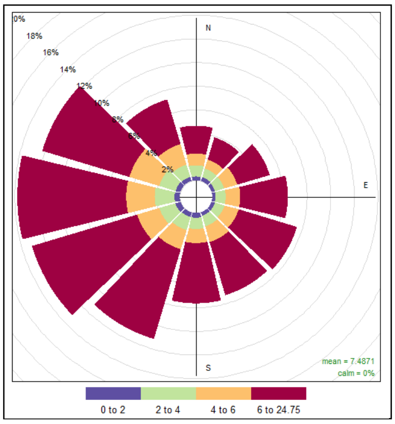


Figure 3



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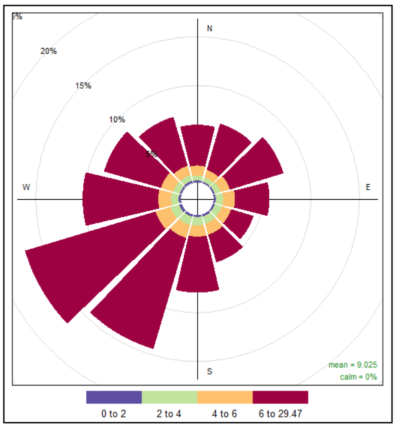

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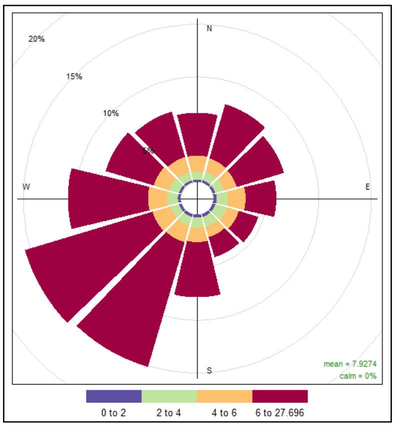


Figure 6

3.1.2 Analysis

Both the wind rose and the veer analyses demonstrate that MERRA2 reanalysis data cannot provide a perfect description of the wind at sites of interest, as we

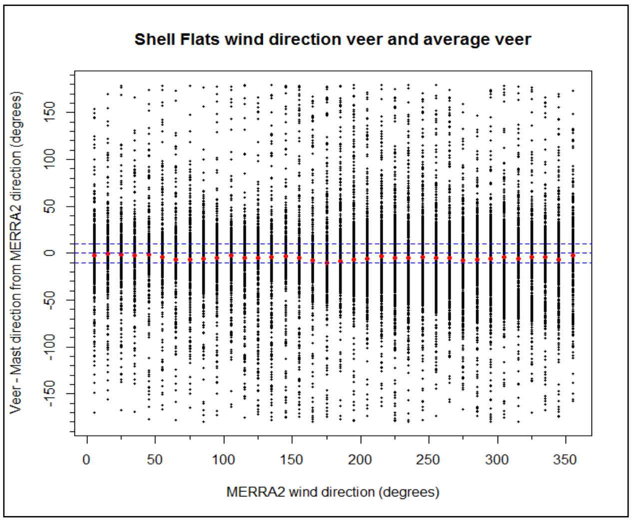


Figure 7

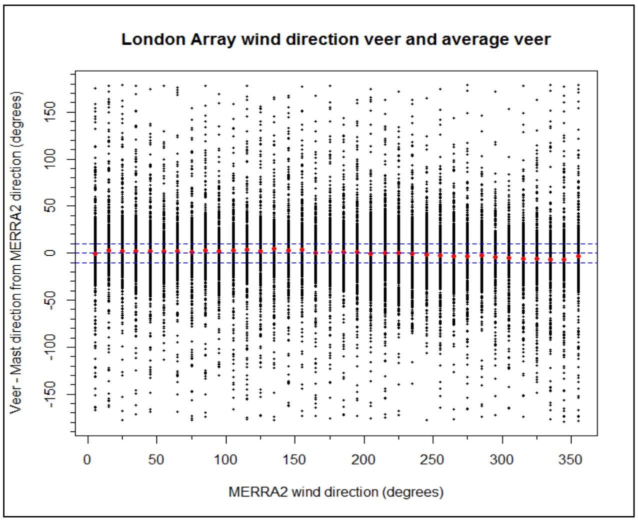


Figure 8

would expect of any reanalysis or other modelled data. However, they also show that MERRA2 reproduces on average similar wind conditions at our sites of interest. For the purpose of producing wind farm power curves the wind speed data is important to us, and it can be seen in the wind roses that over a period of time MERRA2 reproduces general wind conditions reasonably well. We further apply corrections derived by a Measure-Correlate-Predict method carried out on the data used to produce the wind roses, and so adjust the MERRA2 wind speeds in each sector in line with the measured mast data. In order to classify the wind farm as in or out of wake in any one hour, the likely accuracy of the MERRA2 wind direction data is significant. The veer analysis gives confidence that on average the MERRA2 direction data is very close, within 10°, of the mast direction data at both sites. The MERRA2 data, with an MCP adjustment applied, is likely to produce reasonable whole wind farm power curves, so long as the power curves are constructed from many data points, as the average reproduction of wind conditions is reasonable and doesn't show large, systematic bias in direction or speed.

3.2 Power Curves

3.2.1 Results

The power generation data for Barrow, Ormonde and Walney in the Irish Sea cluster, and for London Array in the Thames Estuary cluster have been combined with adjusted MERRA2 wind speed data for the area to produce whole wind farm power curves. In Figures 9-12, power curves resulting from all data points classified in or out of wake are shown, with data classified as out of wake plotted in black and data classified as in wake over-plotted in red. Walney phases 1 and 2 are treated as one wind farm in this study as they are immediately adjacent to one another and so cannot be separated for wake classification in the absence of very accurate wind direction information.

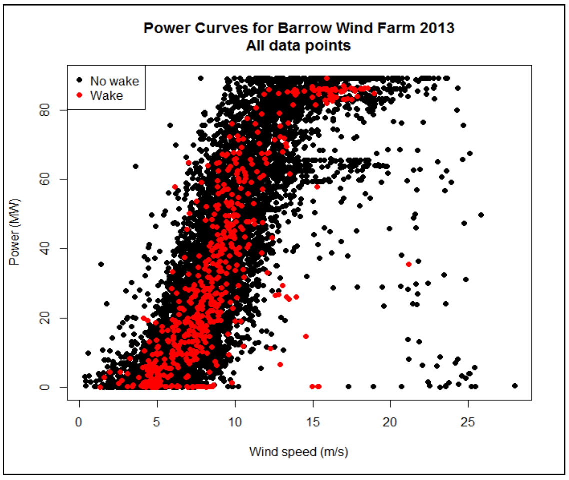


Figure 9

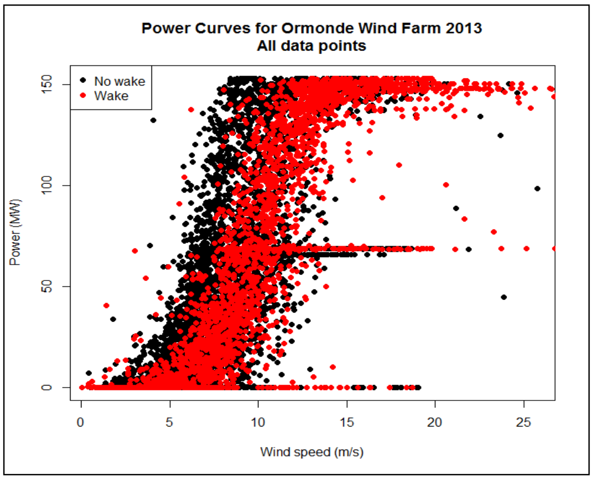


Figure 10

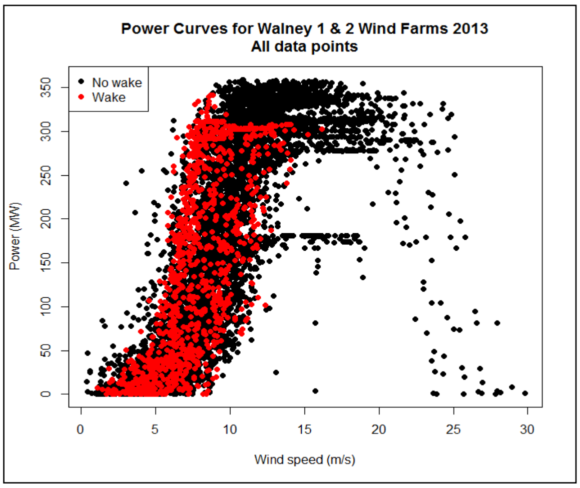


Figure 11

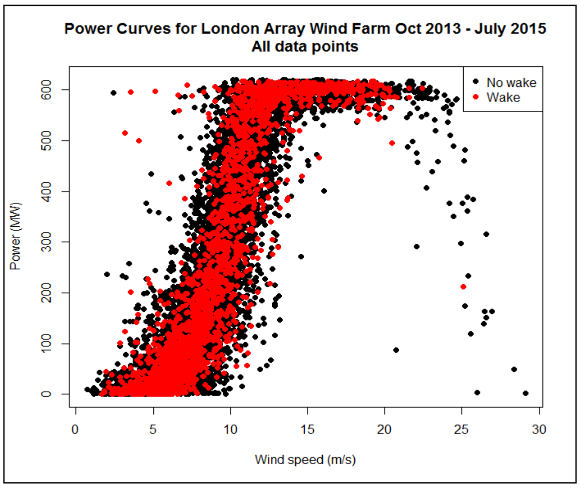


Figure 12

The power curves in Figures 9-12 take the recognisable general shape of turbine power curves: lower power is produced at lower wind speed, rising to a maximum power above a certain wind speed. They are very much noisier than a single turbine power curve, reflecting the fact that they are constructed with no information on the availability of the wind farm and its constituent turbines and sub-arrays. With this in mind power curves are also plotted showing the median wind farm power seen in every 0.5ms^{-1} wind speed bin, again for the in and out of wake cases (Figs 13-16).

3.2.2 Analysis

It is interesting to note that in the power curves from all data points at Barrow, Ormonde and Walney there are clear signs of partial wind farm operation at certain power capacities. These partial capacities can be seen where there is a levelling off of power across wind speeds. For example, at Ormonde (Fig. 10) the power curve levels off at just about 150 MW, which is consistent with the full wind farm capacity as given in Table 1. There is also a distinct levelling off of power at around 70 MW and at 0 MW indicating that during this period there are also a significant number of occasions on which a 70 MW subset of the wind farm is available and a significant number of occasions when the whole wind farm is unavailable. There are similar, but less frequent effects seen at Barrow (Fig. 9) and Walney (Fig. 11). One of Walney's subset maximum power levels is seen at about 180 MW, which is consistent with either Phase 1 or Phase 2, but not both, operating fully. In contrast, the power curve of all data points at London Array (Fig. 12) shows no evidence that only a subset of the array is available for periods of time. There is some evidence in the all-data power curves of reduced power for in wake conditions at Barrow and Ormonde. However at Walney (Fig. 11) the power production in wake seems to be higher than that out of wake. At London Array, there is little difference to be seen between the curves.

The power curves showing median power in each wind speed bin remove most of this availability noise. A single, whole wind farm power curve is clearly discernible for each wind farm and for in and out of wake conditions. Viewed like this, it appears that any power reduction in wake at Barrow (Fig. 13) and at London Array (Fig. 16) is minimal and confined to lower wind speeds. Walney (Fig. 15) again shows a gain in power production. Ormonde (Fig. 14) again shows a lower power curve at wind speeds up to rated wind speed for in wake conditions.

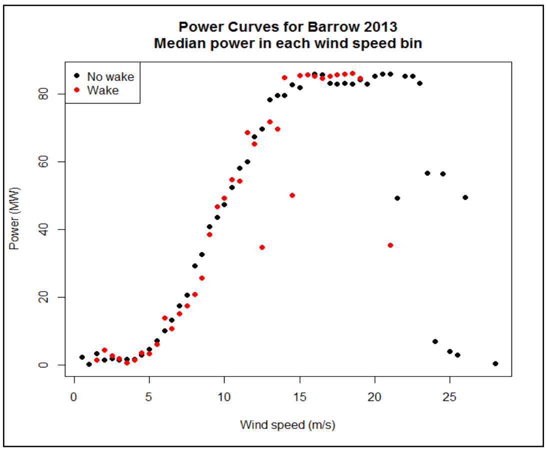


Figure 13

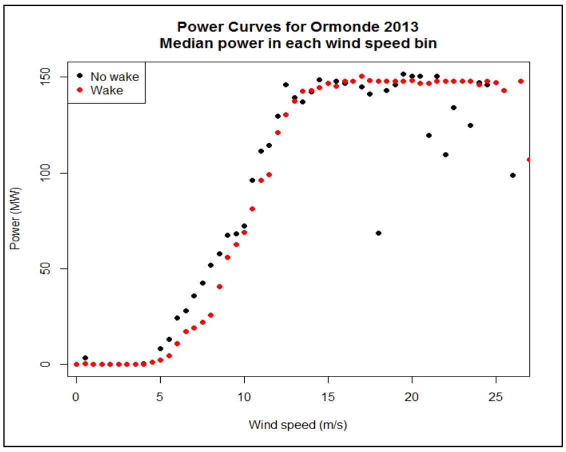
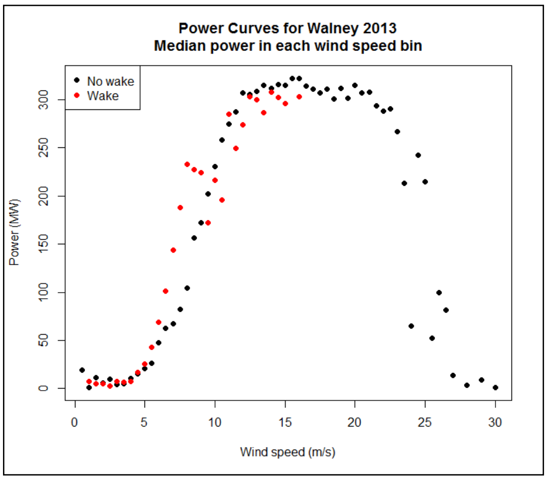


Figure 14



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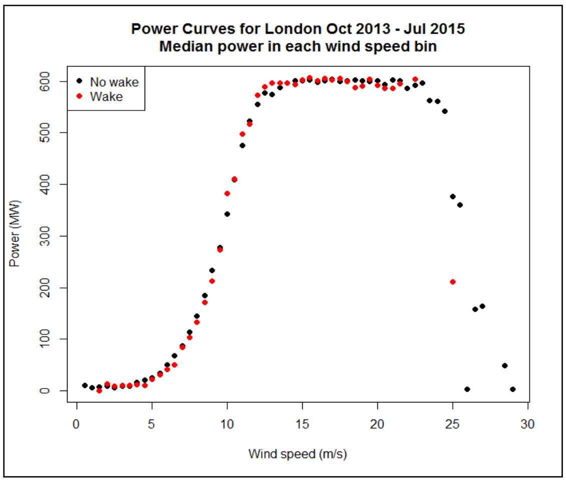

Figure 16

The layout of the Irish Sea cluster (Fig. 1) makes these results unsurprising. Ormonde is close to Walney, and can be expected to be in its wake over a wide range of wind direction bearings. For most of those in wake directions it can be expected to be fully in the wake of Walney. Walney is much larger than Ormonde in extent and in capacity. The wake from Barrow, which will only be incident on Ormonde for a very narrow range of wind directions, is probably a negligible part of this effect. Barrow is, like Ormonde, much smaller in extent and capacity than Walney, but it is further away and will see it over a smaller range of wind directions. At the time of this study, West of Duddon Sands is not yet operating at all. Walney is of large enough extent that any wake from Ormonde or Barrow can only impinge on part of the array, and as shown by Nygaard[14], is likely to only reduce energy from the first rows of affected turbines. It may even be benefitting from wind speed up as the wind flows around Ormonde or Barrow which could explain the higher power seen at some wind speeds for in wake conditions at Walney.

In the Thames Estuary cluster (Fig.2) the distances between wind farms are greater. London Array is a very large wind farm in extent and capacity. As such it is to be expected that in wake conditions would have little or no impact on the power generation of the wind farm. A small reduction in power output at lower wind speeds may be evident, but is not clear.

3.3 Impact on Annual Energy Yield

3.3.1 Results

At Ormonde, there is an anomalously low median power in the 18 ms^{-1} bin in the power curve for out of wake conditions. This appears to reflect real availability issues falling in this relatively low count bin. As the purpose of this exercise is to estimate typical annual energy yield, we use the average of the median power at 17ms^{-1} and 19 ms^{-1} to prevent this distorting the outcome. The resulting impacts on energy yield at Ormonde and London Array are shown in Table 2.

Table 2

	Ormonde	**London Array**
Annual energy yield (MWh) - no wakes	486,796	2,185,736
Annual energy yield (MWh) – with wakes	469,805	2,183,755
Loss due to external wakes (MWh)	16991	1,981
Loss due to external wakes (%)	3.6	0.09

3.3.2 Analysis

Typical annual yield is calculated without consideration of hub height compared to mast height. At Ormonde the hub height is 10m higher than the Shell Flats mast instruments and at London Array the hub height is 7m higher than the London Array mast instruments. It is likely that wind speeds at hub height will therefore be slightly higher, but no attempt is made to adjust for hub height in this study. That said, the energy yields calculated are close to approximate annual energy yield figures given on the Ormonde website[28] (485 GWh, no specific year given) and approximate energy yield for 2014 given on the London Array website[29] (2.2 TWh). This suggests that the wind data and the power curves that we have used to calculate yield provide reasonable representations of these wind farms.

The results show a significant impact on energy yield at Ormonde wind farm of 3.6% loss per year due to external wakes. The power curves for Ormonde in 2013 show some availability issues. As we have only considered 2013 data it is not possible to say whether this is typical or not and therefore whether the power curves we have derived are typical in the longer term. 2013 is the first, full calendar year of operations for Ormonde. However, the power curves still demonstrate a clear difference for in and out of wake operations and that difference is likely to persist regardless of availability levels. In contrast, any reduction in energy yield at London Array is negligible. Given that the coarse, 12 sector, approach used here will have overstated the reduction in energy yield due to external wakes rather than not, the conclusion is that external wakes are not impacting the energy yield at London Array. This is very much to be expected. London Array is a very large offshore wind farm (for now the largest in the world). It has been shown with SCADA data[14] that the impact of an external wake is only seen in the first few rows and that therefore the bigger the array, the smaller the impact on overall power production. It is separated from its neighbouring wind farms by at least 20 km and none are large enough or positioned so as to be able to cast it entirely into their wind shadow.

3.4 Discussion and Implications

The results presented here show for the first time the impact of external wakes on the electricity delivered to the UK grid. This result is as expected and confirms earlier results seen in wind farm SCADA data. The uncertainties inherent in the use of reanalysis data for wind conditions are overcome by using many data points to derive power curves and so demonstrate the average behaviour of the wind farms in conditions with and without the impact of external wakes. As expected power reduction and resultant energy yields are seen very clearly at Ormonde wind farm which is behind larger wind farms for a wide range of wind directions. Also as expected, impacts are not detected at London Array, a very large wind farm with greater separation to its smaller neighbours.

Reduced generation at some wind directions has clear commercial impacts in reducing product that can be sold by the wind farm. It is also important to the wind farm and to the grid to be able to predict how much electricity will be exported to the grid in a half hour generating period. Some uncertainties in wind direction will provoke larger uncertainties in generation prediction where they are around the boundaries between in and out of external wake conditions.

It is already clear in designing a wind farm scheme that existing or already planned wind farms and their energy take and wakes need to be considered in planning wind resource and income expectations, though this may be difficult to quantify. Net wind resource over the long-term is critical to predicting income, minimising risk and hence reducing the cost of capital for initial wind farm development. More difficult is planning for wind farms that arrive after initial plans and commissioning. Barrow wind farm for example was operational six years before neighbouring Ormonde and Walney, and 8 years before West of Duddon Sands. A very large wind farm, Walney Extension (659 MW capacity), is under construction now, extending Walney to the north and west. It would be interesting to extend this study into later periods to see the impact of West of Duddon Sands on Barrow and on Ormonde, and in the future to also consider Walney Extension. The evidence of loss of energy yield presented here has policy implications that should be considered by wind farm developers and consenting bodies in the future when considering wind farm separation.

We have not followed up the apparent increase in power generation seen at Walney in wake conditions, which could be related to wind speed up along the edges of Ormonde. It would be interesting in future work to apply an energy yield prediction to Walney to see if this translates into any gain to the wind farm.

Although data measurements of actual impacts on electricity generation are hard to come by, it is useful to carry out studies that attempt to quantify these impacts in order to constrain and benchmark modelling work. Effective models can reduce the uncertainties faced in developing wind farms, and in managing existing ones with new neighbours. This can reduce the risk and the cost of capital and aid selection of the best sites.

4. CONCLUSIONS

We are able to use reanalysis wind data and generation data from UK offshore wind farms to show differences in the power performance of wind farms when they are subject to external wakes and when they are not. This is the first time that such an effect has been shown in the electricity delivered to the grid. At Ormonde wind farm which sees external wakes over a large angle from a closely neighbouring, much larger wind farm, we see a distinct reduction in the power performance when subject to an external wake. We are able to generalise the impact of this on the wind farm's annual energy yield by assuming that the wind farm is subject to a distribution of wind conditions measured for that sea area. The impact on energy yield is found to be significant, leading to a 3.6% reduction in annual energy yield. In contrast we show that no such impact can be seen at London Array, a very large offshore wind farm with more distant neighbours. This suggests that the impact of wind farm separation on existing wind farms is a matter for attention in future offshore wind farm consenting and development.

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