

A Comparison of the UK Offshore Wind Resource from the Marine Data Exchange

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Abstract

Conducting offshore meteorological measurement campaigns is an expensive requirement of the offshore wind farm development process. This paper analyses the offshore wind measurements made publicly available by the Crown Estate to build understanding of the UK offshore atmosphere. The work makes use of data from 14 locations spanning 16 years from both masts and lidar. Some variation in mean wind speed profiles and prevailing wind directions are found, however the associated turbulence intensity shows less variability between sites. The UK average hub height wind speed is calculated to vary by 4ms^{-1} throughout the calendar year and average 8ms^{-1} , though these values depend on which datasets are considered. The south-west is shown to be the prevailing wind direction with small variation around the UK whilst the modal turbulence intensity is 6% and is shown to vary little throughout turbine operating wind speeds.

Introduction

In recent years there has been an increase in the number of wind farms being built offshore, particularly around the UK [1] despite building offshore being more expensive than onshore. The greater expense is in part due to greater uncertainties in the available resource and the higher associated costs of measurement campaigns. There are a number of projects aimed at trying to reduce this uncertainty, either by simulated wind atlases [2] or by the development of cheaper measurement techniques [3]. With no geographical obstacles such as hills combined with slow changes to surface forcing due to high water thermal capacity, the available wind resource at locations sufficiently far from shore is primarily dependent on synoptic scale weather features whose climatic frequency and strength have already been measured by previous developments. The process of sharing of costly data between industrial competitors however can be slow; therefore as part of their lease contracts, the Crown Estate requires that wind measurements made in UK waters to be made available for public distribution after a 2 year moratorium for commercial sensitivity. There are now a significant number of projects around the UK which have supplied data to the Crown Estate ready for release to other organisations. Therefore this work investigates how their measurements compare with each other and builds an overview of the UK's marine atmosphere and its wind resource from in-situ measurements.

Data Availability

Of primary importance to the approach used in this work is that the UK landmass and its surrounding territorial waters are smaller than the pressure systems associated with mid-latitude weather. Although the passage of said systems typically takes 2-3 days to transverse the region, this is of little significance when compiling aggregated long-term statistics. Therefore, wind measurements from offshore measurement sites around the UK have been obtained from The Crown Estate via its Marine Data Exchange program [4] and the wind measurement heights are shown in Table 1. Note that although data from two masts were available from both the Greater Gabbard and Shell Flats location, for consistency with other locations, only one mast's data was used at each site. Unlike datasets from other locations, the downloadable dataset from the Navitus Bay lidar did not include any measurements of the 10minute variance or standard deviation of the wind speed, leaving it to be excluded from some analysis carried out in this work. The locations and duration of each measurement site of depicted in Figure 1 and show a wide coverage, in both time and space. Data relating to additional parameters such as air temperature were also available for some locations, though lack of consistency between

Table 1 Description of measurement heights, dates and methods downloaded from the Marine Data Exchange [1]

Measurement Location	Measurement Method	Wind Speed Hights (m)	Wind Direction Heights (m)	Measurement Dates
Blyth	Lidar	31, 65, 100, 135, 170	31, 65, 100, 135, 170	Oct 2010 – May 2013
Celtic Array	Lidar	40, 50, 62, 80, 100, 120, 140, 160, 180, 200, 250	40, 50, 62, 80, 100, 120, 140, 160, 180, 200, 250	Oct 2013 – May 2014
Docking Shoal	Met Mast	30, 60, 70, 80, 90	88	Jun 2006 – Apr 2013
Greater Gabbard	Met Mast	40, 50, 70, 84	60	Sep 2005 – Dec 2012
Gunfleet Sands	Met Mast	35, 47, 60	47, 60	Jan 2002 – Nov 2006
Gwynt y Môr	Met Mast	25, 45, 64, 85	24, 64, 82	Sep 2005 – Apr 2008
Humber Gateway	Met Mast	34, 52, 70, 88, 90	68, 86	Jun 2012 – Oct 2012
Inner Dowsing	Met Mast	16, 29, 43	41	Aug 1999 – Feb 2008
Kentish Flats	Met Mast	13, 20, 35, 50, 65, 80	35, 50, 65, 80	Oct 2002 – Jan 2005
London Array	Met Mast	20, 32, 57, 82	29, 79	Dec 2004 – Dec 2011
Navitus Bay	Lidar	4, 20, 40, 60, 80, 100, 105, 110, 130, 150, 170, 190	4, 20, 40, 60, 80, 100, 105, 110, 130, 150, 170, 190	Apr 2015 – Sep 2015
Race Bank	Met Mast	30, 60, 70, 80, 90	88	Jun 2006 – Dec 2008
Rampion	Met Mast	37, 61, 84, 105, 107	82, 103	May 2012 – Jan 2014
Shell Flats	Met Mast	20, 30, 50, 70,	20, 30, 50, 70, 82	Jun 2002 – Jan 2013

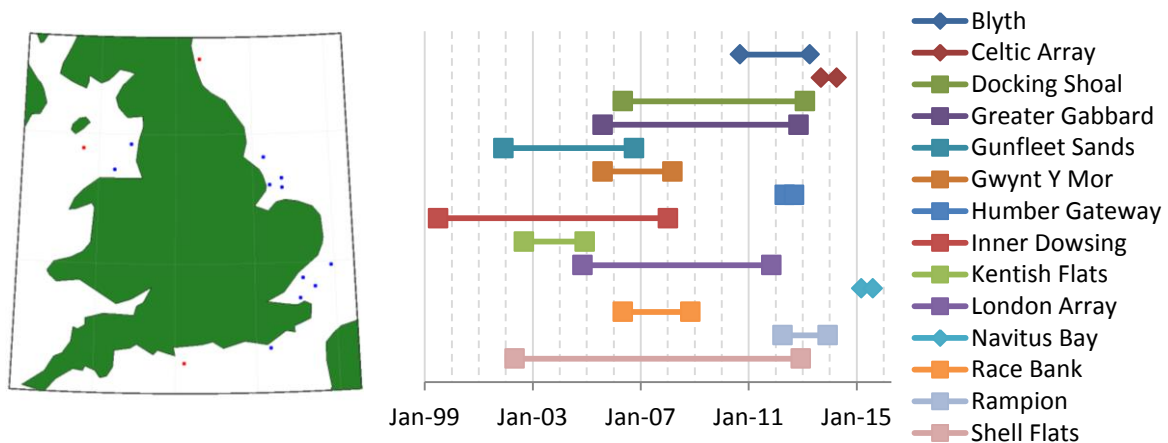


Figure 1 (left) Location of mast (blue) and lidar (red) measurement campaigns around the UK. (right) Dates of available data, note mast measurements are represented by squares and lidar measurements by rhombus.

Analysis

Whilst Figure 1 shows the 14 available data sets cover a range of years, there are usually at least three locations contributing to the over-all analysis for any point in time. The main exception being the most recent dataset (Navitus Bay) consisting only of part of 2015 when no other location contributed to the Marine Data Exchange. It is therefore reassuring that Figure 2 shows the average wind speed profile measured at Navitus Bay to be representative of the other measurement sites. Figure 2 does however reveal three other locations to seemingly report anomalous wind speeds: the Blyth and Celtic Array lidars and the Inner Dowsing met mast. These anomalies are caused by

location, campaign period and age respectively. Although the Blyth lidar recorded offshore wind speeds it was itself located onshore, this explains the higher levels of wind shear at lower levels as the shore's proximity to measurement location implies there will not be a long enough fetch to develop a marine boundary layer and thus the lidar reports a wind profile more associated with onshore locations. The anomalously high wind speeds reported by the Celtic Array lidar are linked to the measurement campaign being conducted for less than a year and during the windiest season. The only other dataset to be even partially collected data at the same time is from the Rampion met mast which reports average wind speeds faster than most but spans more than one year, including 2 summers and does not include the second half of the Celtic Array's collection dates. It is the authors' belief that the age and thus design of the Inner Dowsing mast has resulted in significant mast shadowing effects, although this is hard to prove with the available data and may alternatively been operational during years with lower wind speeds.

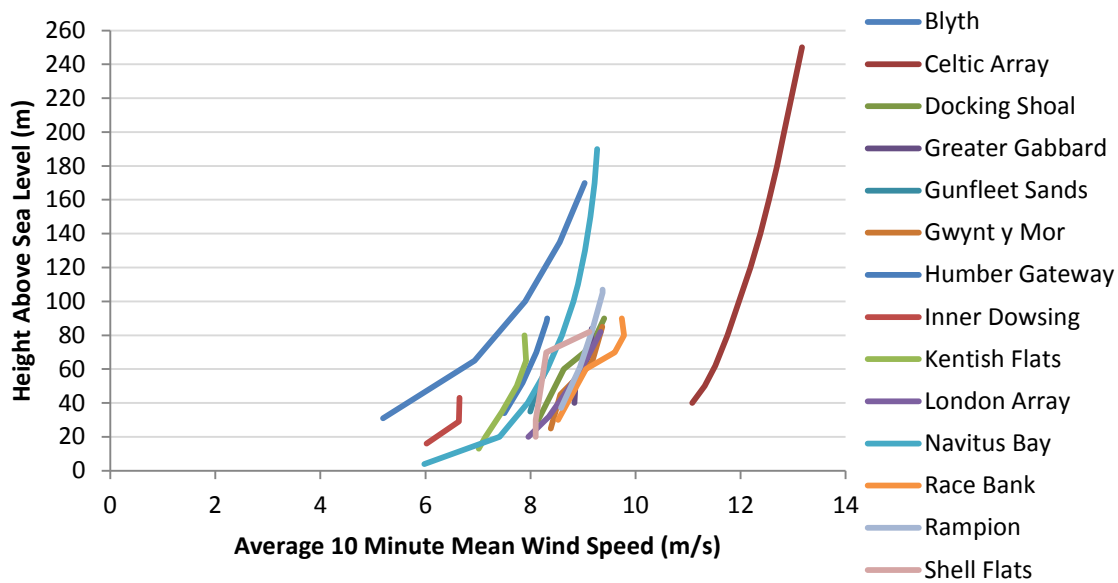


Figure 2 Mean 10 minute wind speed profiles from the 14 measurement locations

Each location's wind rose is shown below in Figure 3. The directions were binned by 10° for clarity and where a choice of measurement heights existed, the closest available height to 70m above sea level was used, considered a reasonable compromise considering the lack of a consistent height amongst the available heights. Most significantly, all the measurement locations record a prevailing south-westerly wind with small but significant differences in which 10° bin is the prevailing direction. It is also of note that the prevailing direction in the Blyth dataset is both more frequent and more northerly; the more frequent occurrence of specific directions is symptomatic of onshore terrain features whilst the clockwise rotation in direction can be linked to the Coriolis force's effect on the slower wind speeds. Interestingly the three most significant south-easterly spikes in the rose collection come from locations in the Irish Sea, Celtic Array, Gwynt y Mor and Shell Flats, suggesting the measurement locations may not be completely independent of coastal terrain.

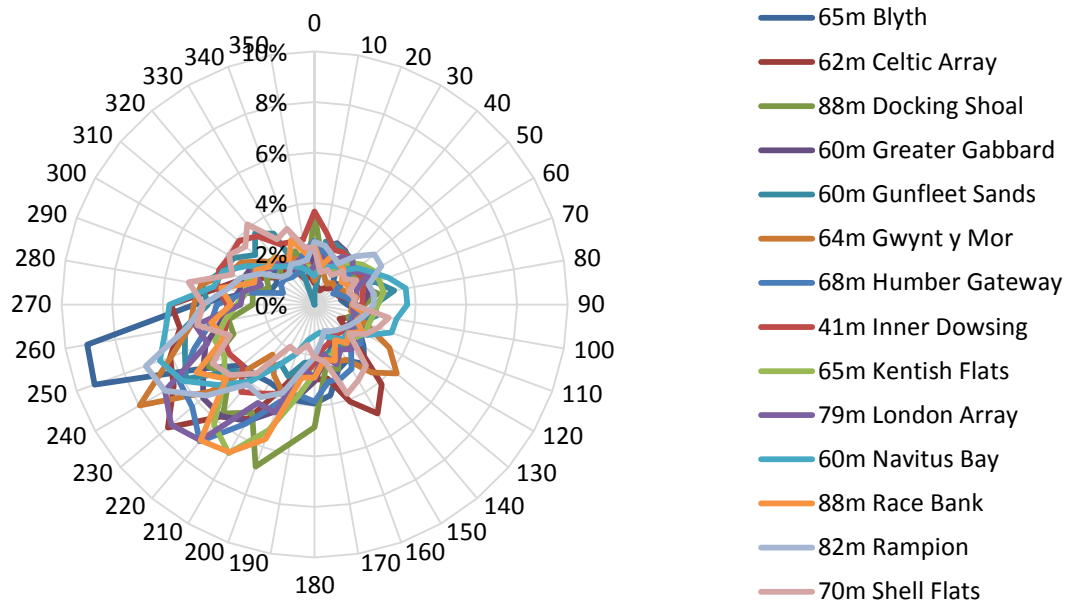


Figure 3 Wind Roses from each of the 14 measurement locations. The measurement height is shown in the legend.

Having seen in the previous two figures that the Blyth dataset is significantly different from those of locations further from shore, it is interesting to observe its mean wind speed to be roughly uniform with direction with a small increase rather than decrease for the prevailing direction shown in Figure 3. The Celtic Array data by comparison shows that where its directional frequency deviates most from the other sites (specifically at 150°) the difference in wind speed is also greatest. This could help explain why the Celtic Array profile in Figure 2 is so different to the others; it is possible that in early 2014 when data is not available from other sites, there may have been a period of strong wind from the south-east. This possible solution highlights the importance of both long-term measurement campaigns – to counter the significance of apparently freak events – and also to ensure that any significant events that do occur can be verified by measurements at multiple locations. It should be noted however that the Celtic Array also returns high average wind speeds for all westerly sectors. It is observable across all 14 locations that mean wind speeds from the south-west are stronger than from other sectors and since this also corresponds with the prevailing wind directions shown in Figure 3, it is advisable for new wind farm developments without localised flow obstacles to be optimised for south-westerly winds.

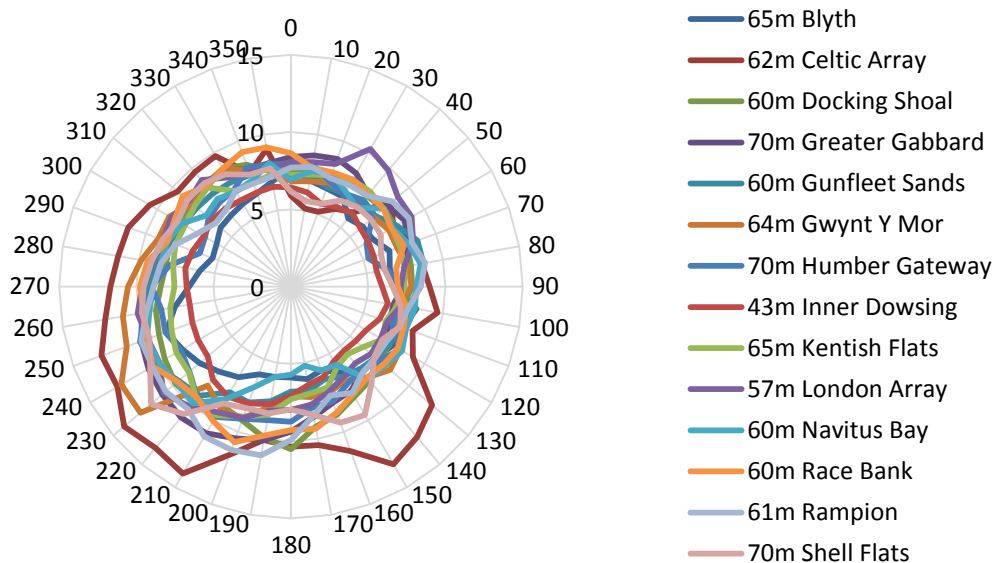


Figure 4 Mean wind speed by 10° binned direction from the 14 locations

To complement the directional distributions shown above, the frequency of each wind speed is shown in Figure 5 where the 10 minute mean values are binned by 1ms^{-1} . Whilst most sites report a greatest frequency between 7ms^{-1} and 10ms^{-1} between 8% and 10% of the time with steady decrease in frequency away from the mode, four sites indicate significant variation from this regime. The most significant outlier is the Celtic Array data which reports a mode speed of 12ms^{-1} occurring roughly 8% of the time with gentle slopes on either side of the peak. The shift in the mode speed by more than 2ms^{-1} combined with the lack of sharp increases in frequency at high wind speeds further suggest that the measured values are a true representation of the conditions in early 2014. Both the Blyth and Inner Dowsing datasets report a 6ms^{-1} mode wind speed with significantly lower frequencies of faster wind speeds. This is reflective of the results shown in Figure 2 and symptomatic of onshore locations which is understandable for the Blyth data. However, the lower speeds recorded offshore at Inner Dowsing roughly 5km from shore are more likely to be linked to the lower measurement height, roughly 20m below the height used at the other locations. The fourth anomalous dataset is from the Humber Gateway mast and although the mode speed is 8ms^{-1} the frequency is higher than most at 13%, and is countered by less frequent wind speeds above 12ms^{-1} . Whilst this leads to a more predictable wind resource Figure 2 shows it also leads to a lower overall average wind speed.

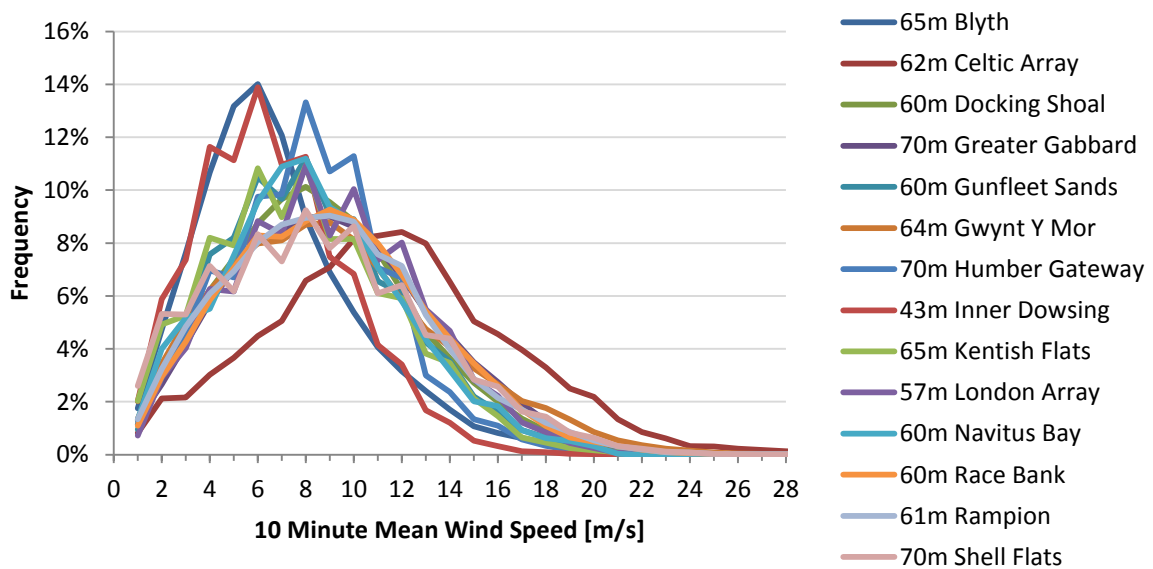


Figure 5 Wind speed frequency distribution measured at each of the 14 locations

Having considered the 10 minute mean flow characteristics associated with power production at individual turbines, it is becoming increasingly important to also consider the short term variation in wind speed described as the turbulence intensity (TI) as it is associated with both turbine fatigue and the significance of turbine wake losses **reference**, thus the measured offshore TI profiles are shown in Figure 6. Three important features to mention is the lack of TI data from the Navitus Bay lidar, significantly higher TI values at the Blyth measurement site and the small variation in TI between the other 12 locations – despite Figure 2 showing clear variation in the mean wind speeds. The larger TI values at Blyth are consistent with the sites coastal proximity and provide evidence of the contrasting meteorological climates on and off shore whilst the consistency of TI between the other sites imply it is more predictable away from obstacles and high surface roughness values. It is not surprising that the Celtic Array data aligns with the other offshore locations despite its clear differences in Figure 2, this is because TI is calculated as the wind speed standard deviation divided by the mean value, ensuring the TI values in Figure 6 are all relative to those in Figure 2.

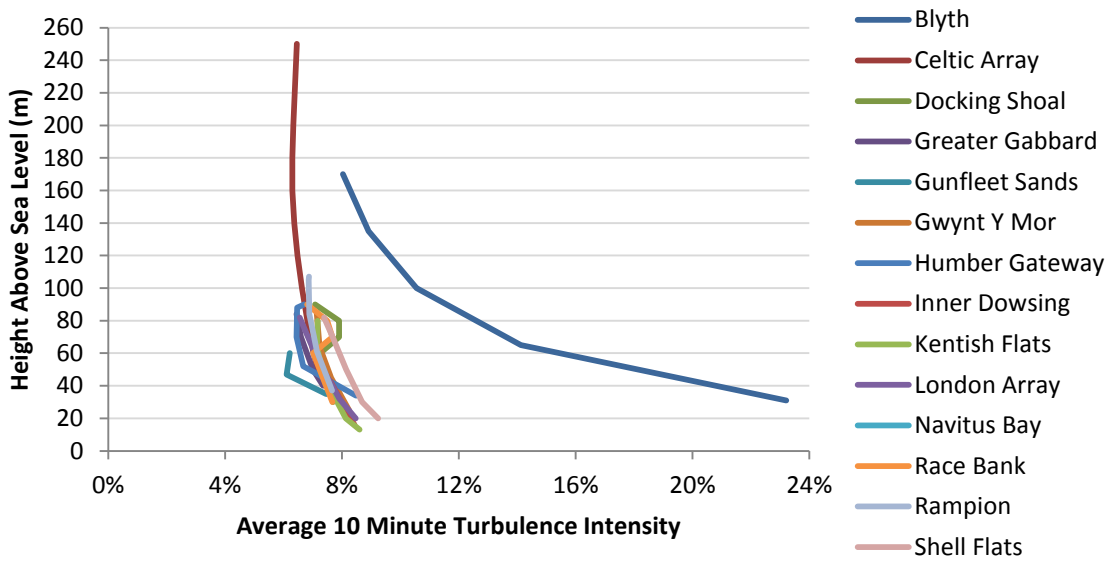


Figure 6 Mean 10 minute turbulence intensity profiles from 13 of the 14 locations (No data from Navitus Bay)

Figure 7 below shows how the TI measured at each location varies by direction with the measurement height chosen to be as consistent as possible. Most locations report a roughly uniform distribution with TI not varying significantly between individual 10° bins, but a slight bias does exist towards higher turbulence from more northerly directions. Consistent with previous figures, the Blyth data reports the most significant deviation from this, with both the highest levels of turbulence and a bias towards the south-west. The significant increase in TI towards the north-east of Blyth could either be caused by a local obstruction or a feature of the lidar’s alignment. The information available from the Marine Data Exchange was not sufficient to determine if its cause was artificial or a feature of the local micro-climate. The increase in TI recorded at Shell Flats from Easterly winds is likely to be similarly related to its shorter fetch for this direction.

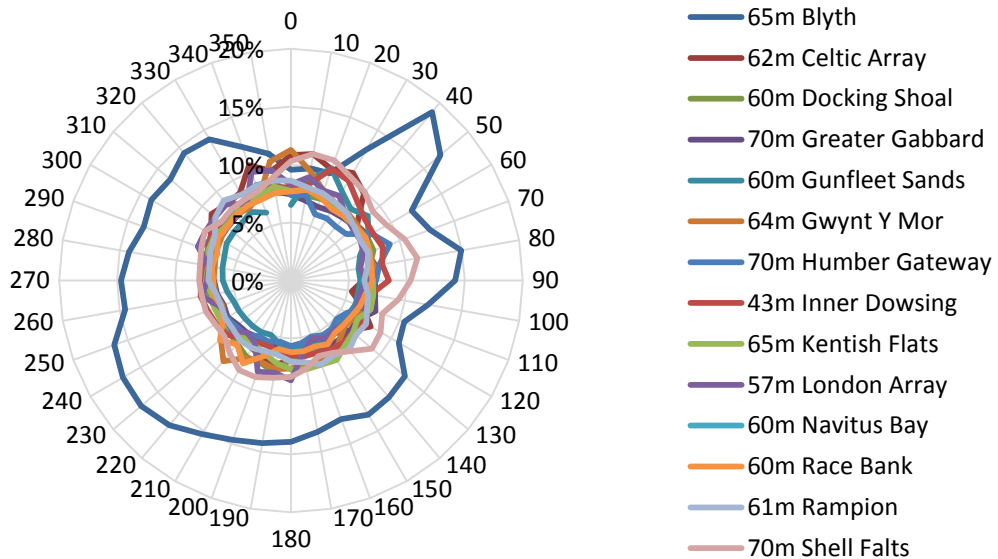


Figure 7 Mean TI by 10° binned direction from 13 of the 14 locations (No data from Navitus Bay)

Figure 8 displays the frequency distribution of TI at each location binned by 1%. Excluding the significantly different data from the Blyth lidar, there is little difference between the locations with Gunfleet Sands and Humber Gateway measuring small increases in the frequency of lower turbulence levels. Interestingly, the measurements from Inner Dowsing suggest the frequency

distribution of TI changes very little vertically across the 30m represented by various locations. This will however be subject to local atmospheric stability, which is not considered in this work.

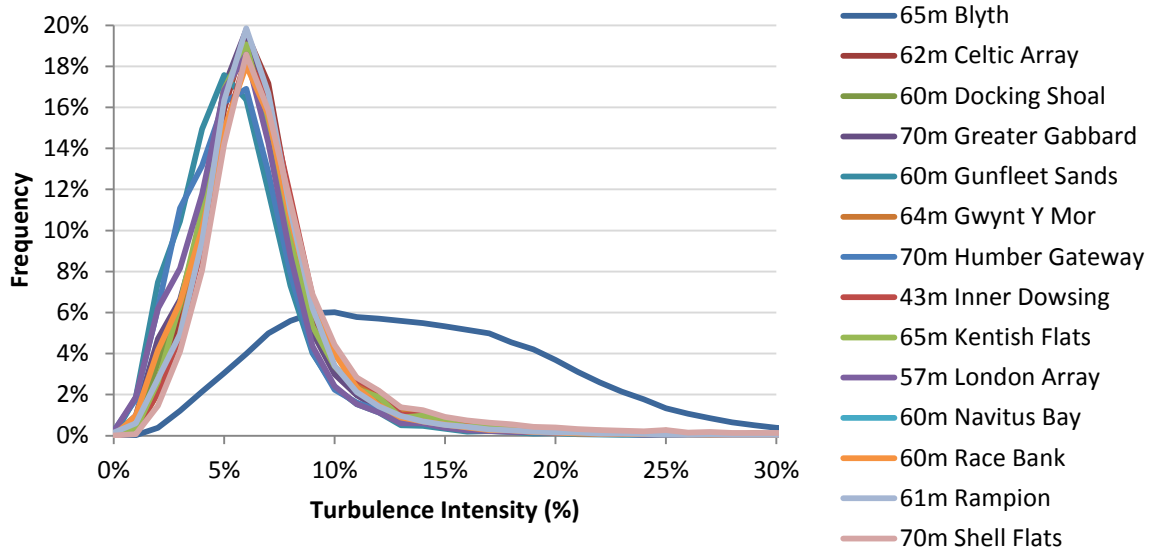


Figure 8 Turbulence intensity frequency distribution at 13 of the 14 locations (No data from Navitus Bay)

Despite the model TI for each location is roughly 6%, Figure 8 also shows that TI values in excess of 15% can be expected. Such rapid fluctuation in wind speed and the stress they exert on turbine blades can be a significant source of turbine fatigue. Therefore Figure 9 shows the distribution of mean TI by 10 minute mean wind speed, revealing that whilst there is a small increase in mean TI with mean wind speed within the usual turbine operational range, it remains significantly lower than would be expected for onshore locations. High levels of TI do occur at speeds less than 3ms^{-1} , but as this is below regular turbine cut-in speeds, these events are of less significance.

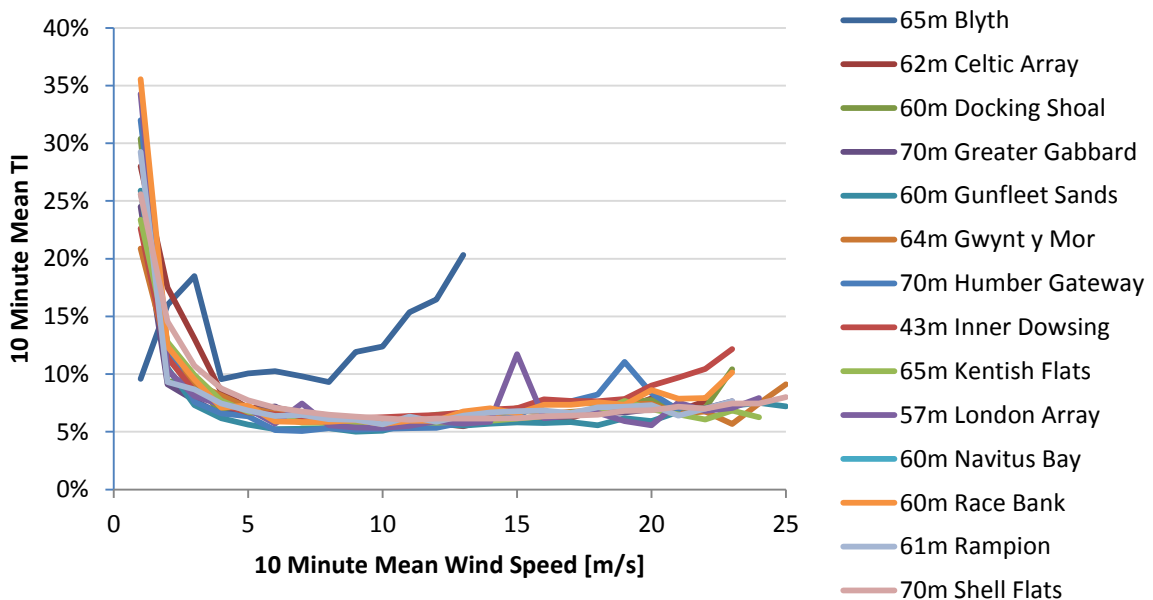


Figure 9 Mean 10 minute TI binned by 10 minute mean wind speed from 13 locations (No data from Navitus Bay)

Due to the similarity between sites for each of the previous figures, it is considered reasonable to produce statistics representing the average UK offshore conditions. In order to compare the wind speed measurements from each site, they must first be levelled to an equivalent height above sea

level, here we use 78m as it is the hub height of many turbines currently installed in UK waters. This will be done using the logarithmic relation in Equation 1 assuming neutral atmospheric conditions.

$$u_z = \frac{u_*}{K} \left[\ln \left(\frac{z}{z_0} \right) \right] \quad \text{Equation 1}$$

Care must also be taken to ensure the averaged results are not biased from the seasons in which measurements were made. For example, if there were twice as many wind measurements made in winter months than in summer months, the resulting average speed is likely to be higher than in reality. Therefore Figure 10 shows the how the average monthly 10minute mean wind speeds vary from site to site and the individual data points will be first aggregated by month before averaged throughout a year. As usual the three locations with data significantly different to the others are Blyth, Celtic Array and Inner Dowsing. It can be seen that the Celtic Array only has data for the 8 windiest months of the year and February, October and December were particularly exceptional. Both Blyth and Inner Dowsing report significantly slower than average wind speeds across all months, for reasons previously discussed. Since the Blyth dataset has consistently proven to be significantly different to those from other locations, it has not been included in calculating the UK average. The data from Celtic Array and Inner Dowsing shall be included however as they have shown themselves to be representative of the offshore atmosphere, albeit measured at different times and heights. The calculated monthly Average value for 78m above UK waters is shown in black Figure 10 whilst the annual average wind speed is 8.07ms^{-1} .

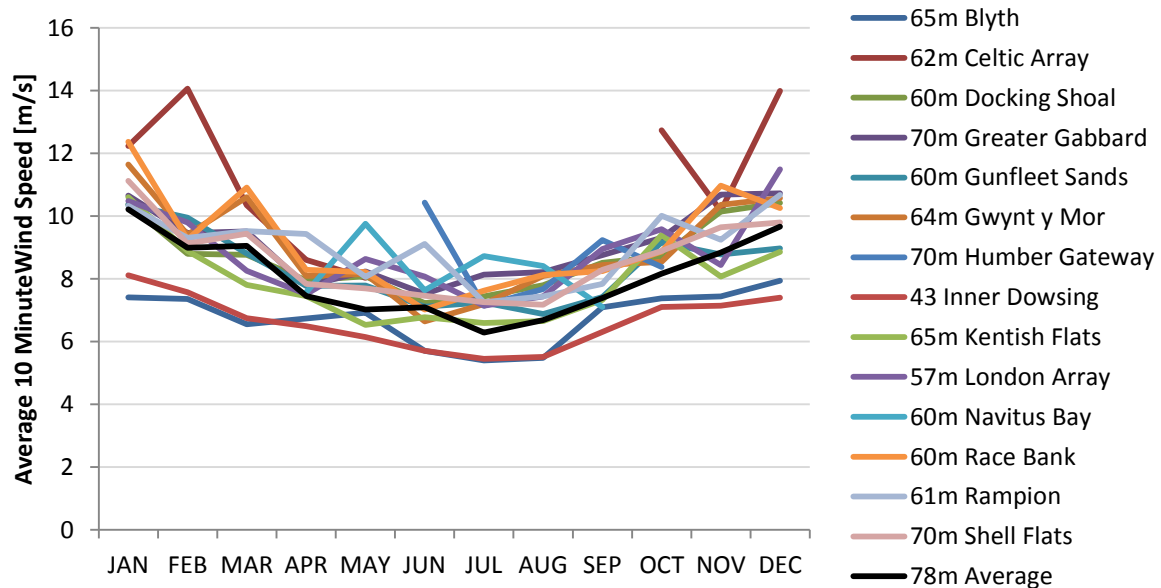


Figure 10 Average 10 minute mean wind speed by month with the logarithmically extrapolated average between sites

For completeness, a similar process was undertaken with the measurements of wind direction. Assuming neutral atmospheric stability, Equation 1 was used to convert the individual trigonometric components of the measured flow directions to 78m above sea level before averaging the results by calendar month across each location and then across a calendar year. The resulting UK offshore wind rose is shown in Figure 11, showing the south-west to be the prevailing wind sector followed by the north-west.

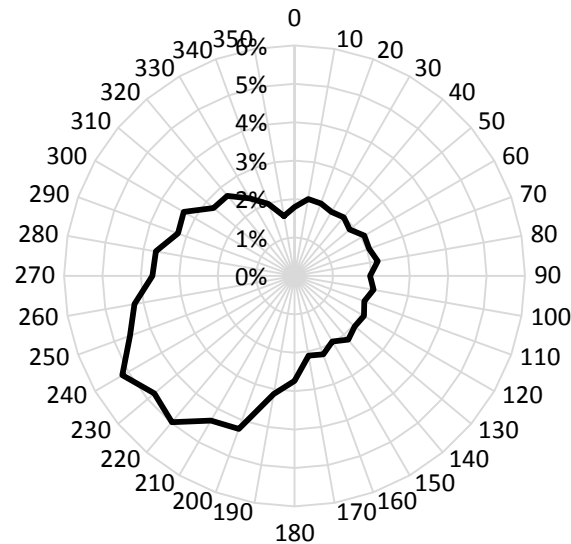


Figure 11 Average UK wind rose for offshore locations at 78m above sea level

Conclusion

This work has compared wind speed and directional measurements from 14 different offshore locations from around the UK across a range of time scales using data obtained from the Marine Data Exchange [1] and found them to be in general agreement with each other, suggesting that the offshore wind resource is consistent throughout the region. However there was some variation found when considering non-sufficient fetch, most significantly from the Blyth lidar data which displayed a local wind climate more synonymous with onshore conditions due to the lidar being physically mounted onshore with only its beam angled to collect measurements above the North Sea. Of the 13 locations with significant fetch, the Celtic Array lidar showed the most extreme wind speeds, though these were restricted to only 3 months out of the 8 month dataset and no significant differences were found in the site's measurements of TI. Excluding the Blyth location, the consistently slowest mean wind speeds were reported by the Inner Dowsing met mast, though as its records contain the oldest measurements it is unclear if this was due to mast design, measurement height or inter-annual variation. Whilst there were small variations in the wind speed frequency distributions between locations, the variation in TI was much smaller with only two offshore datasets deviating from the general group - excluding the Blyth dataset which represented a more onshore distribution. It was also shown that for a representative UK offshore hub height 10minute mean wind speeds in winter is around 3ms^{-1} faster than in summer, with the overall average being 8.07ms^{-1} . Similarly strong consistencies between wind direction measurements between locations lead to the prevailing south-westerly sector being expected more than twice as frequently as winds from the easterly compass half.

Although the findings in this work should not be used as a wind farm's resource assessment to the exclusion of local measurements, it could serve to add confidence that shorter measurement campaigns are in agreement with the long-term expected conditions, and thus reduce the time required and subsequent investment risks linked to variable resource availability for new developments, particularly when located far from shore.

Acknowledgements

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