Analysis of Turbine Layouts and Spacing Between Wind Farms for Potential New York State Offshore Wind Development

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Analysis of Turbine Layouts and Spacing Between Wind Farms for Potential New York State Offshore Wind Development

Final Report

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Abstract

This study supplements a collection of studies prepared on behalf of the New York State Energy Research and Development Authority (NYSERDA) to provide information related to a variety of environmental, social, economic, regulatory, and infrastructure-related issues implicated in planning for future offshore wind energy development off the coast of New York State. The study provides information to support the sizing and orientation of Wind Energy Areas (WEAs) within the Area for Consideration identified by New York State in the New York State Area for Consideration for the Potential Locating of Offshore Wind Energy Areas report. NYSERDA's intent is to facilitate the principled planning of future offshore development, to provide a resource for the various stakeholders, and to support the achievement of the State's offshore wind energy goals.

Keywords

offshore wind, layout, spacing, orientation, shipping, navigation, vessel

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Acronyms and Abbreviations

AEP	Annual Energy Production
AWST	AWS Truepower
COD	Commercial Operation Date
COLREGS	International Regulations for Preventing Collisions at Sea
CPA	Closest Point of Approach
GIS	Geographical Information System
LCOE	Levelized Cost of Energy
MCA	Maritime and Coastguard Agency
MGN	Marine Guidance Note
MW	Megawatt
NCF	Net Capacity Factor
Nm	Nautical Mile
NYS	New York State
NYSERDA	NYS Energy Research and Development Authority
OWF	Offshore Wind Farm
RCG	The Renewables Consulting Group LLC
WEA	Wind Energy Area
WTG	Wind Turbine Generator

Executive Summary

This Turbine Layout Study provides information to support the sizing and orientation of the Area for Consideration identified by New York State and Indicative Wind Energy Areas (WEA) therein. The study consists of the following tasks:

- Review of power densities for a selection of European offshore wind farms (OWF).
- Review of inter-site distances for a sample of European OWFs.
- Development of wind turbine generator (WTG) layouts for Indicative WEAs within Area for Consideration East and West to inform the size and shape of the overall Area for Consideration.

The power densities and inter-site distances of 27 European offshore wind farms inform the design of example wind turbine layouts for the Indicative WEAs within the Area for Consideration.

From the European projects reviewed, there is a strong negative relation between power density and project size (in acres). This reflects a growing consensus that the efficiency of very large offshore wind farms can be reduced significantly by the effects of high wakes if sufficient space is not allowed between the WTGs. This has led to an increase in WTG spacing and a reduction in power density as the sizes of OWFs have increased over time. There is no trend in inter-site spacing for the projects reviewed, which may be attributed to the different planning strategies and navigation requirements in different countries. It may also be due to variations in each country’s policy on how much distance is required between projects for safe passage of vessels.

Based on the results of the power density analysis, WTG layouts were designed for the Indicative WEAs within the Area for Consideration West (two scenarios) and East (one scenario) using a recommended base-case power density of 0.01 MW/acre. Wake loss modeling was performed to confirm that the Indicative WEAs would provide adequate space for project sponsors to design efficient offshore wind farms for a range of potential WTG sizes. A sensitivity analysis was also performed to identify the likely increase in wake losses associated with using higher power densities and smaller inter-site distances. This analysis showed that inter-site spacing of 4 nautical miles (nm) effectively mitigates most potential wake effects. An indicative annual energy production (AEP) calculation is included to demonstrate the impact on net capacity factor of some scenarios modelled and provide support for the WTG layouts created for the Indicative Wind WEAs.

1 Introduction

This study supplements a collection of studies prepared on behalf of the New York State Energy Research and Development Authority (NYSERDA) to provide information related to a variety of environmental, social, economic, regulatory, and infrastructure-related issues implicated in planning for future offshore wind energy development off the coast of New York State, within a study area comprising a 16,740-square-mile area of the ocean, from the south shore of Long Island and New York City to the continental shelf break (the offshore study area [OSA]). The U.S. Bureau of Ocean Energy Management (BOEM) has jurisdiction over identifying offshore wind development sites within the OSA, and for issuing leases for those sites.

The study provides information to support the sizing and orientation of the Area for Consideration and Indicative Wind Energy Areas (WEAs) identified by the New York State in the New York State Area for Consideration for the Potential Locating of Offshore Wind Energy Areas report, which was submitted as an unsolicited lease request submitted to the Bureau of Ocean Energy Management in October 2017, and performs the following tasks:

- Review of power densities for a selection of European OWFs
- Review of inter-site distances for a sample of European OWFs
- Development of WTG layouts for Indicative WEAs within Area for Consideration East and West to inform the size and shape of the overall Area for Consideration.

NYSERDA recognizes that BOEM has primary jurisdiction over siting and development in the OSA and that any future development will be subject to future review processes and decision-making by BOEM and other state and federal stakeholders. Neither this study, nor New York State’s Master Plan or its collection of studies, commit NYSERDA or any other agency or entity to any specific course of action with respect to the development of offshore wind projects within the OSA. Rather, NYSERDA's intent is to facilitate the principled planning of future offshore development, to provide a resource for the various stakeholders, and to support the achievement of the State’s offshore wind energy goals. As such, this report is considered supplemental to the Master Plan and has been provided to aid decision-making by state and federal agencies and project sponsors themselves.

2 Power Density Review

2.1 Power Density and Turbine Layout Design

The power density of an OWF is a measure of how much electrical power can be harvested from a defined geographic area and is expressed as the total installed capacity (in MW) divided by the total area covered by the WTGs (in acres). Power density is determined by dividing the installed capacity of a wind farm by the area it covers. For a given project area, the power density (in MW/acre) can be increased by either installing more WTGs or increasing the rated power of the WTGs (the rated power is the maximum power that a WTG can produce). Both have the effect of increasing the installed capacity of the wind farm, but as power density increases so do the negative impacts of turbines on one another's energy production. These impacts are termed wake effects and they result in a lower efficiency for the wind farm, where the efficiency is expressed as the net capacity factor (NCF).

Wake effects are the key driver when optimizing layout design for offshore projects. Offshore there is limited scope to increase energy yield by moving WTGs to areas of higher resource because, the wind resource varies far less, compared to, for example, a mountainous region where wind speed increases markedly with elevation. Therefore, when designing the WTG layout for an OWF, a balance must be struck between maximizing the installed capacity and avoiding the effects of excessively high wakes.

2.2 Methodology

Prior to selecting which OWFs to include in the analysis, a high-level review was carried out of 300 European offshore wind farms, including those in the development, construction, and operational phases, to identify suitable candidates. The aim was to select OWFs of a range of different designs and sizes from the North Sea and UK waters which together comprise the most established area of OWF development in the world.

The power density for each OWF was then calculated by dividing the installed capacity of each OWF by the total of sea area covered by the WTGs. The area of each wind farm selected was calculated based on the as-built or planned WTG coordinates.

2.2.1 Determination of Example Projects

The European offshore wind market has multiple operational OWFs representing a broad range of sizes, layout designs, and permitting strategies. There are approximately 300 European OWFs at various stages, from development to operation, providing the best benchmarks for this study. A sample of 27 European offshore wind farms was selected to provide a diverse range of project capacities, commercial operation dates (CODs), and layout designs to ensure a representative view was taken for typical power density of a European offshore wind farm.

Eleven OWFs were selected from the UK, all of which are currently operational apart from one (Galloper Offshore Wind Farm, which is currently under construction). Sixteen were selected from Germany, Belgium, and Denmark, all of which are currently operational except for Nordsee 1 and Merkur Offshore that are under construction, as well as the pre-construction Horns Rev 3 with a WTG layout design unlikely to change significantly. The oldest project reached COD in 2005, and the most recent is due to start operating in 2019.

2.2.2 Data

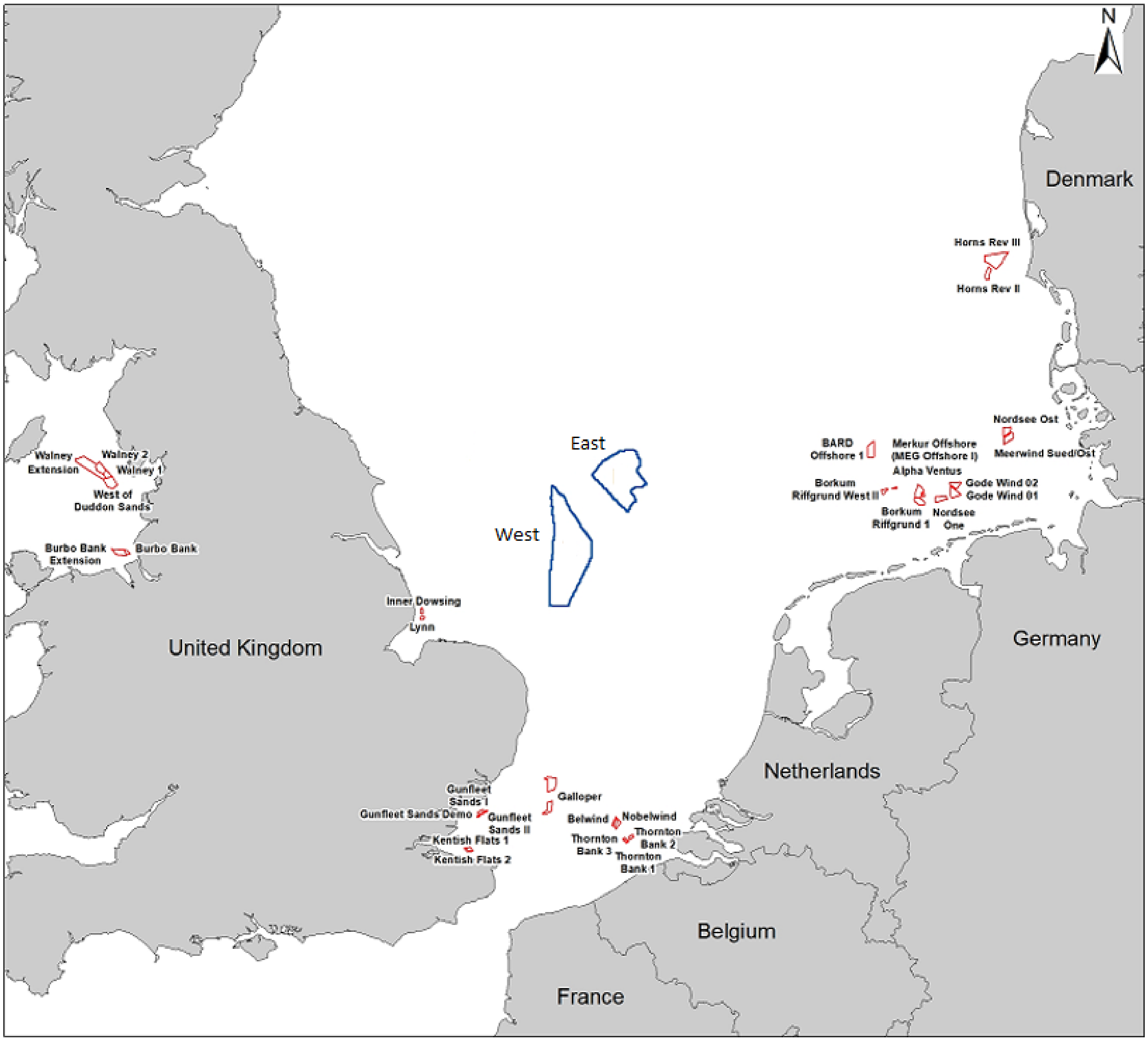
For the operational OWFs, maps of cable routes for the UK OWFs were obtained from publicly available records and used to derive WTG coordinates. WTG coordinates for the Belgian, German, and Danish OWFs were obtained from Admiralty charts. For projects not yet built, the current site boundaries were sourced from publicly available records. The power density of a project may change frequently during the development phase as the choice of layout and WTG model evolves; therefore, development-stage projects were excluded from the review.

The outer WTG coordinates in each wind farm were traced around, to create an accurate site boundary. The area covered by the WTGs was then calculated based on this boundary. The installed capacity of each OWF was sourced from the database and divided by the area to derive the power density in MW/acre.

An overview of the projects is provided in Figure 1 with the current boundaries of Area for Consideration East and West included for scale comparison.

Figure 1. Map of European Offshore Wind Farms

European offshore wind farms are in red and included in the power density review with Area for Consideration East and West overlaid in blue for comparison.



2.2.3 Power Density Trend Analysis

Once calculated, the power densities of the sample European wind farms were plotted against several variables to identify any trends. A regression line is provided for all charts, along with the R^2 value returned. The regression line provides the best fit to the data, and the R^2 value is a statistical measure of how close data are to the regression line. The R^2 value represents the proportion of the variance in the power density that is predictable from the independent variable (WTG rated capacity, for example)—and the higher the R^2 value, the stronger the relation between the two plotted variables.

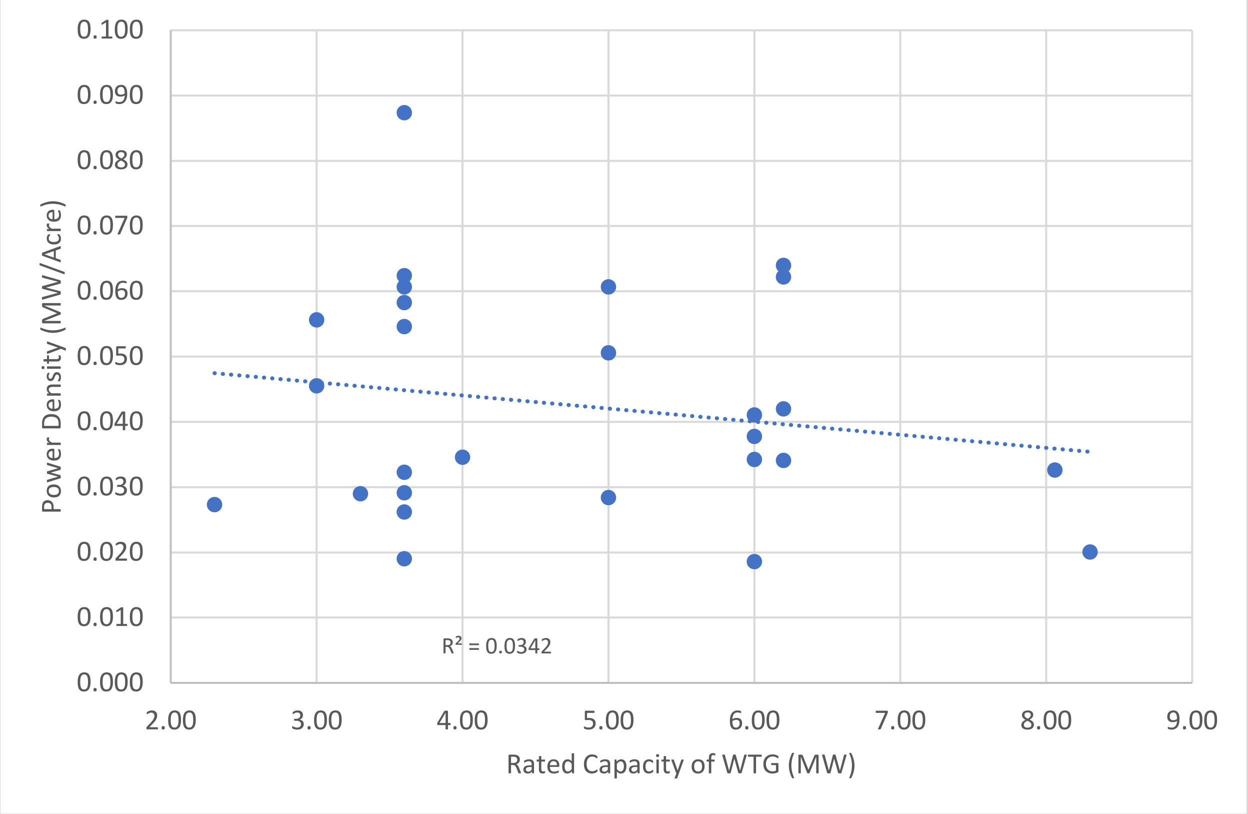
2.3 Results

The average power density for the 27 OWFs is 0.043 MW/acre and varies significantly across the OWFs. The following section includes plots of the density against several other characteristics of the OWFs, some of which have a stronger relation to power density than others. The full-data sets are provided in appendices B and C.

2.3.1 Power Density Variance with Wind Turbine Rated Capacity

Power densities for the projects were plotted against their turbines' rated capacities. Given the very low R^2 value in Table 1 (0.0342), there does not appear to be a relation between the variables.

Table 1. Power Density as a Function of WTG Rated Capacity



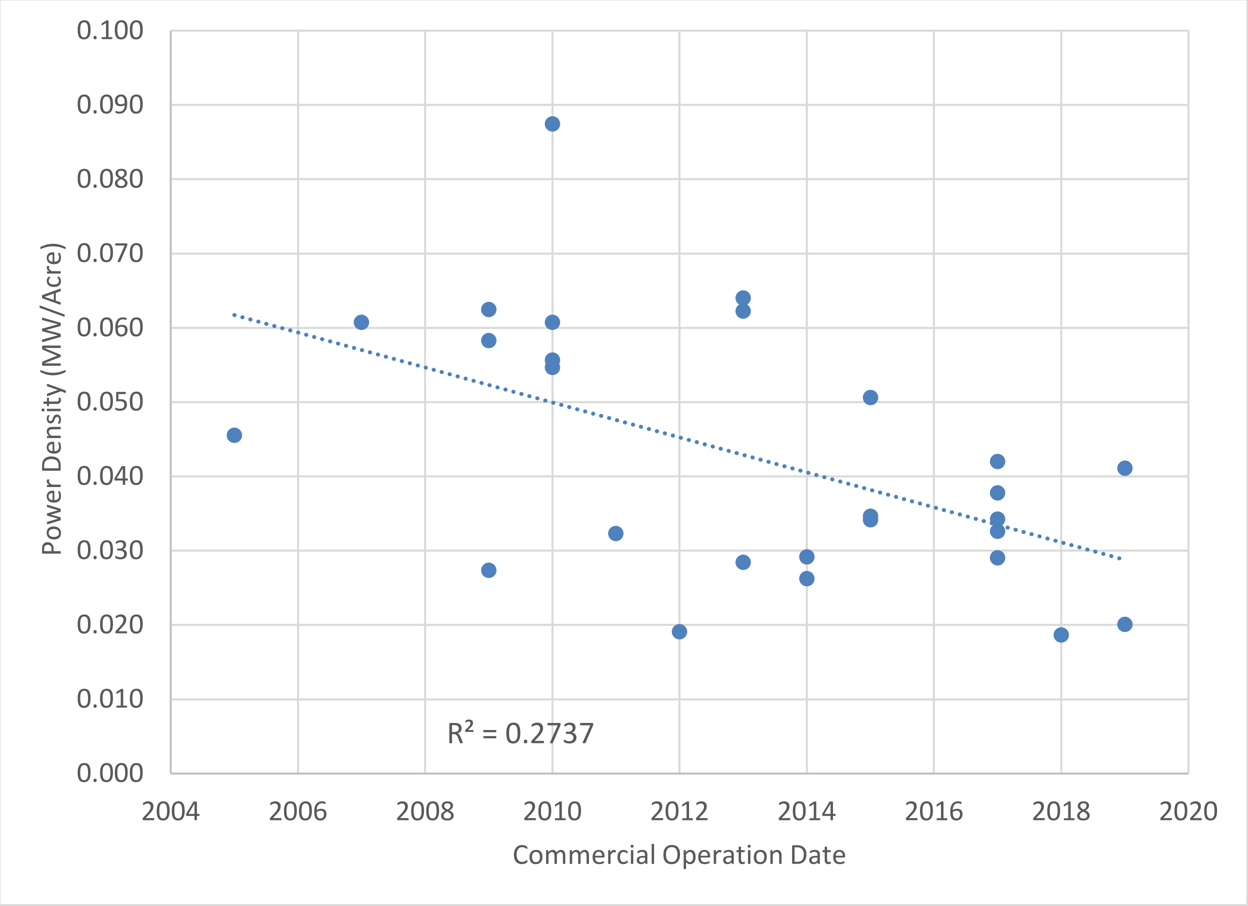
2.3.2 Power Density Variance with COD

Prior to the mid-2000s, wake losses for OWFs were usually predicted using semi-empirical wake models, which were developed for use on onshore wind farms. No adjustments were made to the wake models to account for the different wind conditions prevalent on offshore wind farms compared to large onshore wind farms. Initial validation studies carried out by consultants and project sponsors using production data from projects such as Denmark's Horns Rev 1 suggested that these tools tended to under-predict so-called "deep array" wake losses for large OWFs, particularly when power density was relatively high and inter-WTG distances relatively small. Deep array wake losses occur at offshore wind farms with more than 6 rows of WTGs aligned perpendicular to the prevailing wind condition and are exacerbated by the low turbulence of the wind offshore, which causes wakes from the WTGs to extend further downwind than they would onshore.

From 2010 onwards, more advanced wake models, such as those using computational fluid dynamics approaches, became more common, and validation studies performed by Walker (*et al.*,2014) and others have demonstrated the improved accuracy of them, compared to the first-generation models. The advanced wake-modeling tools predict higher wake losses than the first-generation models, for a given layout; therefore, it could be expected that large OWFs designed after 2010 would have lower power densities as project sponsors seek to maintain good net capacity factors (NCFs).

Power density data therefore were plotted as a function of COD. Table 2 shows a weak negative relation between power density and COD, suggesting there has been no consistent move towards lower power density layouts in Europe. This may be due to the variance in wind conditions, installed capacities, site boundary shapes, or some combination thereof at each OWF. Alternatively, it may reflect the lack of consensus among project sponsors on how to design efficient WTG layouts.

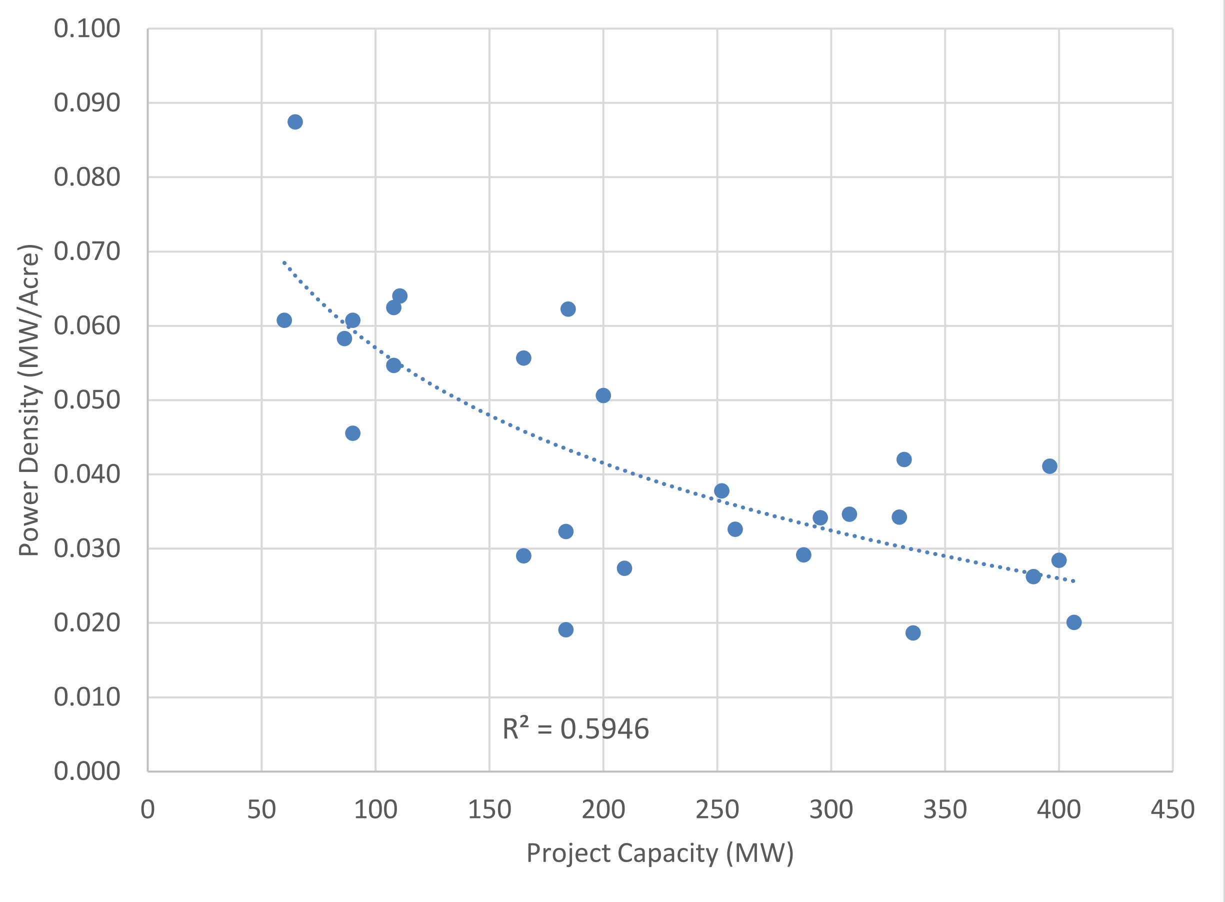
Table 2. Power Density as a Function of COD



2.3.3 Power Density Variance with Project Capacity

Power density data were then plotted as a function of the project capacity of each OWF—and a clearer trend emerged. This is shown in Table 3.

Table 3. Power Density as a Function of Project Capacity



The relation to installed capacity is stronger than the previous comparison, and it implies that as project capacity has generally increased over time, project sponsors have sought to reduce the higher wake losses associated with larger project capacities by reducing power density.

However, even the OWFs with project capacities greater than 350 MW show a large variance in power density, from 0.02 MW/acre to 0.04 MW/acre. This is reflected in the relatively low R^2 value (0.5946).

2.3.4 Power Density Variance with Project Area

Plotting the power density as a function of the total area covered by WTGs in each OWF provided the highest R^2 value of any variable plotted, demonstrating a strongly negative relation between project area and power density. This is shown in Table 4.

Table 4. Power Density as a Function of Project Area

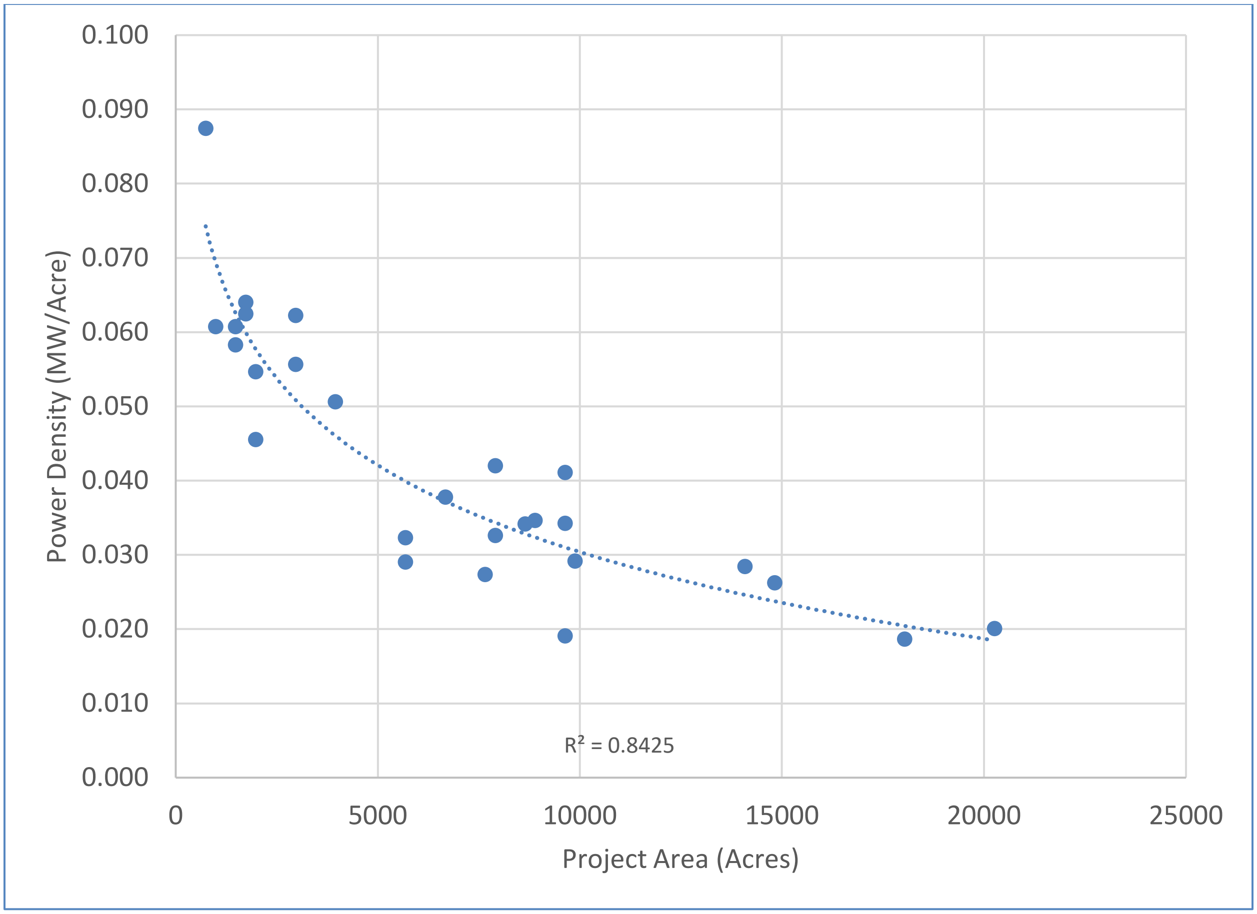


Table 4 also shows a step change in the power density of projects smaller and larger than 5,000 acres. Furthermore, when projects below this size are excluded from the analysis, the average power density falls to 0.03 MW/acre. The largest OWF in the sample set (Horns Rev 3) with an installed capacity of 406 MW and total area of 20,263 acres has a power density of just 0.02 MW/acre and was developed by Vattenfall. Along with the Walney 2 project in the UK Irish Sea (which has a 0.019 MW/acre power density and was designed by DONG), Horns Rev 3 is deemed to represent a well-designed WTG layout informed by a good understanding of the wake effects that could be expected on such a large array. Both DONG and Vattenfall have designed and built a number of large OWFs and have taken an active role in the development of advanced wake models. Extending the trend line out to larger wind farm sizes implies a reduction to even 0.015 MW/acre may be expected for very large projects in the future, although there are insufficient data to make a robust prediction in this regard.

2.3.5 Specific Site Examples

Appendix D contains additional tables with further detail on those OWFs with similar power densities but that vary in other characteristics such as age and installed capacity.

2.4 Recommendations

Since a clear trend emerged from the data regarding lower power densities with project size, from a peak of nearly 0.09 MW/acre for a 64.8 MW project to less than 0.02 MW/acre for the largest OWFs currently being planned (400 MWs and greater), a power density of between 0.02 and 0.03 MW/acre is deemed reasonable for the Indicative WEAs. The minimum value is based on the power density of the largest and latest project in the dataset (Horns Rev 3), and the maximum on the average power density of the OWFs with areas greater than 5,000 acres.

However, European experience has shown that the power density of a sites usually increases as the design phase progresses. This may be caused by detailed site assessments highlighting areas of the seabed unsuitable for WTG siting, therefore reducing the available area, or by project sponsors choosing significantly larger WTGs than was initially envisioned, thereby increasing the installed capacity. Both result in a higher power density so an additional “packing factor” must be added (see section 5.2.3) to allow for this. A power density of 0.01 MW/acre is therefore recommended to take into account the packing factor and ensure the Areas for Consideration are prepared for future contingencies.

3 Inter-site Distance Review

3.1 Inter-site Distance and Turbine Layout Design

Wake losses generated by one OWF that affect one or more downwind OWFs are called “cumulative” wake losses. Sufficient distance must be maintained between OWFs to allow wake effects from the upwind sites to dissipate and wind flow to recover before reaching the subsequent farms.

Despite significant growth over the past 20 years, the European offshore wind industry has not adopted a universally agreed-upon limit on the distance between neighboring OWFs to safeguard the downwind resource, and consequently, the distances between sites vary considerably. The distances are governed by the leasing and permitting process in each country.

In Germany and the Netherlands, many lease areas for OWF development have been located adjacent to each other with relatively consistent spaces between them, giving project sponsors little scope to move projects further apart. By contrast, in the UK, project sponsors have been allowed more choice over where to locate projects, subject to an agreed minimum distance they must maintain between existing developments. This situation, coupled with other reasons for requiring space between projects, such as for navigation, has resulted in a large variance in inter-site distances in Europe.

3.2 Methodology

Prior to selecting which OWFs to include in the analysis, a high-level review of those analyzed for Task 1 was carried out. The objective was to determine whether neighboring projects could be considered separate OWFs, and therefore, eligible for the review, or merely extensions of existing projects, and therefore ineligible.

The inter-site distance between pairs of wind farms was then calculated by taking the as-built or planned WTG coordinates and measuring the distance in nautical miles (nm) between the closest WTGs.

3.2.1 Determination of Example Projects

An initial review of the same 300 European OWFs considered in the Power Density review was carried out to identify pairs of OWFs located upwind/downwind of one another in the prevailing wind direction.[1]

Pairs of sites with no clear buffer between them were rejected. Specifically, if the space between neighboring sites was less than or equal to the turbine spacing within the upwind project, then the pair was excluded from the analysis. Using this criterion, 18 OWFs were selected: six from the UK, eight from Germany, two from Belgium, and two from Denmark. These are listed in Table 5.

Table 5. List of European Offshore Wind Farms Included in the Inter-site Distance Review

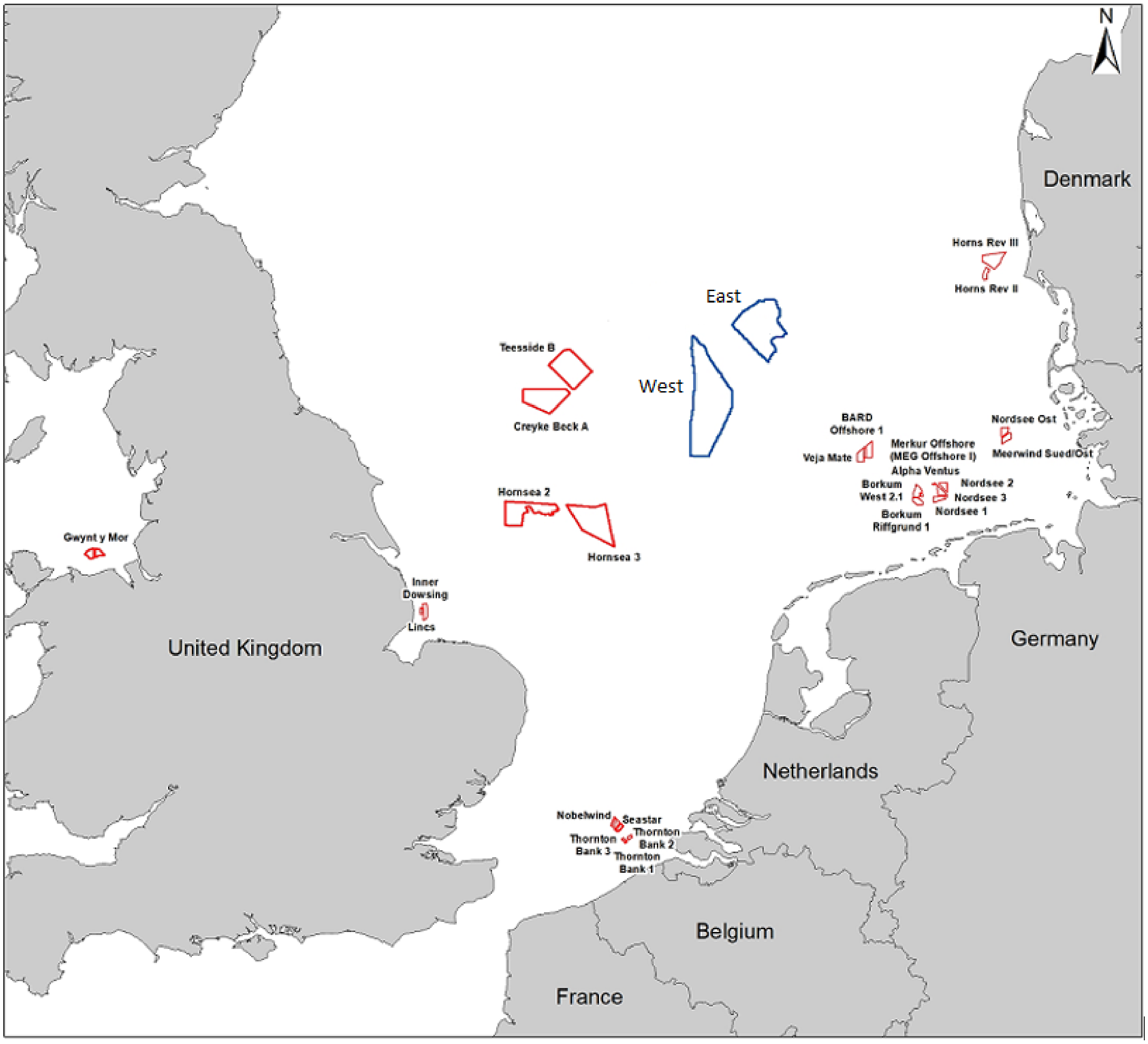
Offshore wind farm	COD year	Country	Project capacity (MW)	Nearest upwind OWF(s)
Alpha Ventus 1	2010	Germany	30	Merkur Offshore
BARD Offshore 1	2013	Germany	400	VEJA MATE
Borkum Riffgrund 1	2015	Germany	308	Borkum West 2.1
Burbo Bank	2007	UK	90	Burbo Bank Ext
Dogger bank Teeside B*	2032 (planned)	UK	1200	Creyke Beck A
Gwynt y Mor East	2015	UK	288	Gwynt y Mor West
Horns Rev 3*	2019 (planned)	Denmark	407	Horns Rev 2
Hornsea 3*	2029 (planned)	UK	2,400	Hornsea 2
Inner Dowsing	2009	UK	108	Lynn
Lincs	2013	UK	270	Inner Dowsing
Merkur Offshore*	2019 (planned)	Germany	396	Bokrum West 2.1
Nobelwind (Belwind 2)	2017	Belgium	165	SeaStar
Nordsee 1	2017	Germany	332	Nordsee 3
Nordsee 2*	2033 (planned)	Germany	295	Nordsee 3
Nordsee 3*	2033 (planned)	Germany	369	Nordsee 1
Nordsee Ost	2015	Germany	295	Meerwind
Rodsand 1	2004	Denmark	166	Rodsand 2
Thornton Bank 2	2013	Belgium	185	Thornton Bank 3

* As-built WTG coordinates not available

Figure 2 shows a subset of the OWFs included in the review with Area for Consideration East and West included for comparison.

Figure 2. Map of European Offshore Wind Farms Included in the Inter-site Distance Review

European OWF are in red. Area for Consideration East and West overlaid in blue.



3.2.2 Data

Twelve of the OWFs are operational. Where possible, inter-site distance was measured between the closest WTGs on each site using the as-built WTG coordinates. If the as-built WTG coordinates were unavailable, the distance was measured based on the site boundaries contained in publicly available documents. The data collected for the power density (Task 1) review were also used to define the site boundaries.

Six of the OWFs are in the planning stage. For these projects, the inter-site distance was based on the site boundary provided in publicly available documents. These boundaries may include a buffer zone of unused seabed or reflect an out-of-date layout that has since been abandoned. Therefore, the distances measured for these OWFs may be less accurate than the distances for the operational wind farms.

3.3 Results

The average inter-site distance of the sample set is 1.1 nm. This figure drops to 0.8 nm if the largest three OWFs are removed:

1. Hornsea 3 (2,400 MW) at 4.9 nm to nearest OWF
2. Forewind Teeside B (1,200 MW) at 2.2 nm
3. BARD (400 MW) at 1 nm

The average inter-site distance for these three OWFs is 2.7 nm.

Table 6 provides a summary in terms of both nautical miles (nm) and WTG rotor diameters.

Table 6. Summary of Inter-site Distances

Subset	Average installed capacity (MW)	Average distance to nearest WF	
		Nautical Miles	Rotor Diameters*
All OWFs in sample (18)	409	1.1	14
3 largest OWFs (MW)*	1134	2.7	27
All excluding 3 largest	254	0.8	12

* Rotor diameter of *upwind* OWF.

3.3.1 Variance with OWF Characteristics

The inter-site distances between the OWF pairs are shown in Table 7. Distances range from 0.4 to 4.9 nm. Table 8 shows the distance expressed in terms of the diameter of the WTGs in the upwind project. It is commonplace for project sponsors to work in terms of rotor diameters when designing WTG layouts, and it was anticipated that a rule of thumb expressed in such terms would have been used when determining inter-site distances.

The relations between inter-site distance and each project's (1) COD and (2) installed capacity are shown in Table 9 and 10 respectively. The full list of results is contained in appendix E.

Table 7. Inter-site Distances (Nautical Miles)

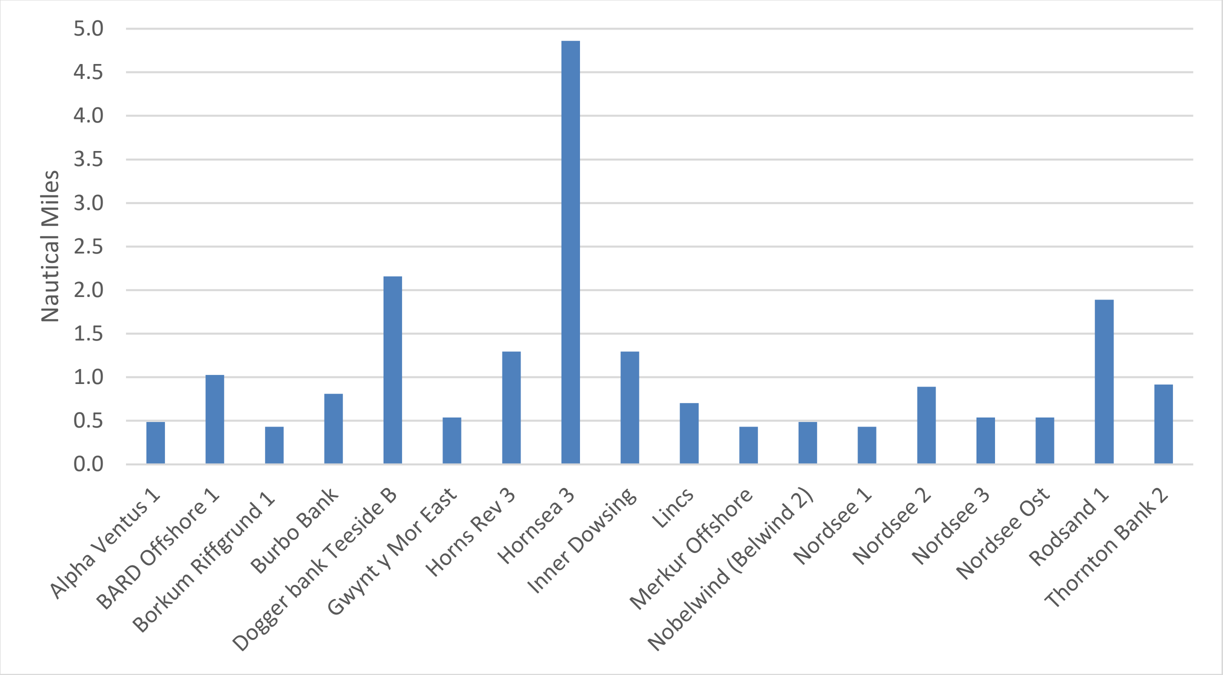


Table 8. Inter-site Distances (Rotor Diameters)

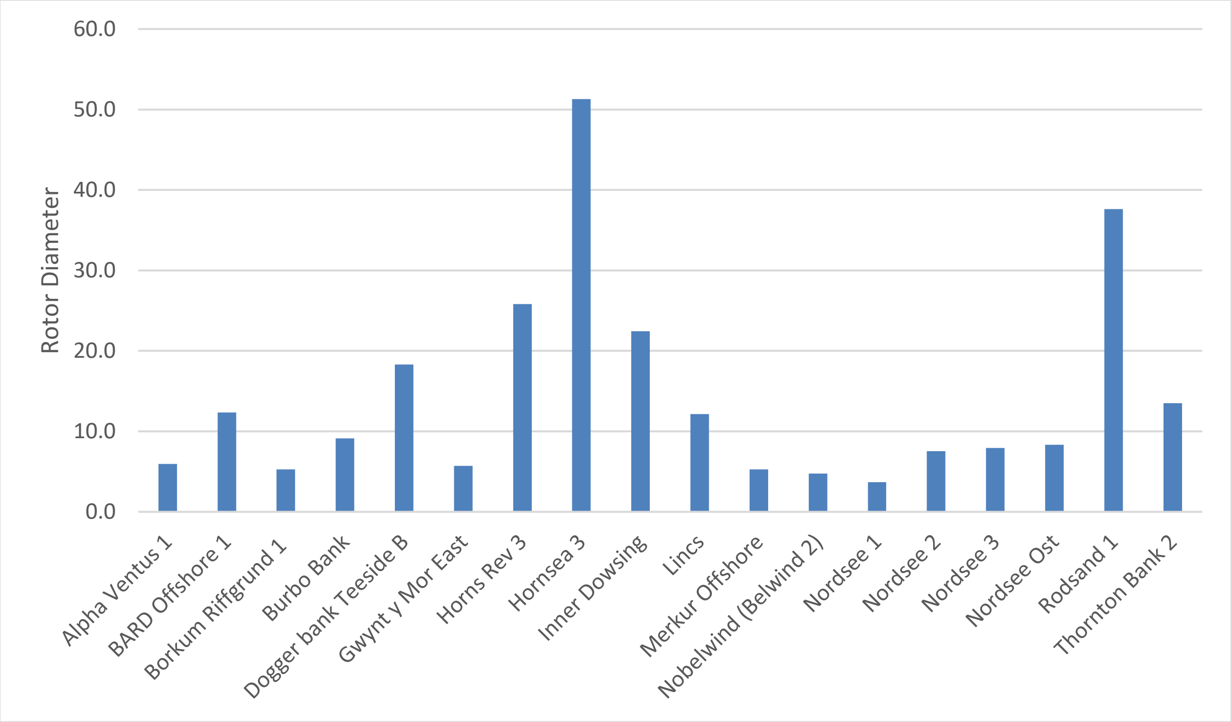


Table 9. Inter-site Distance by COD

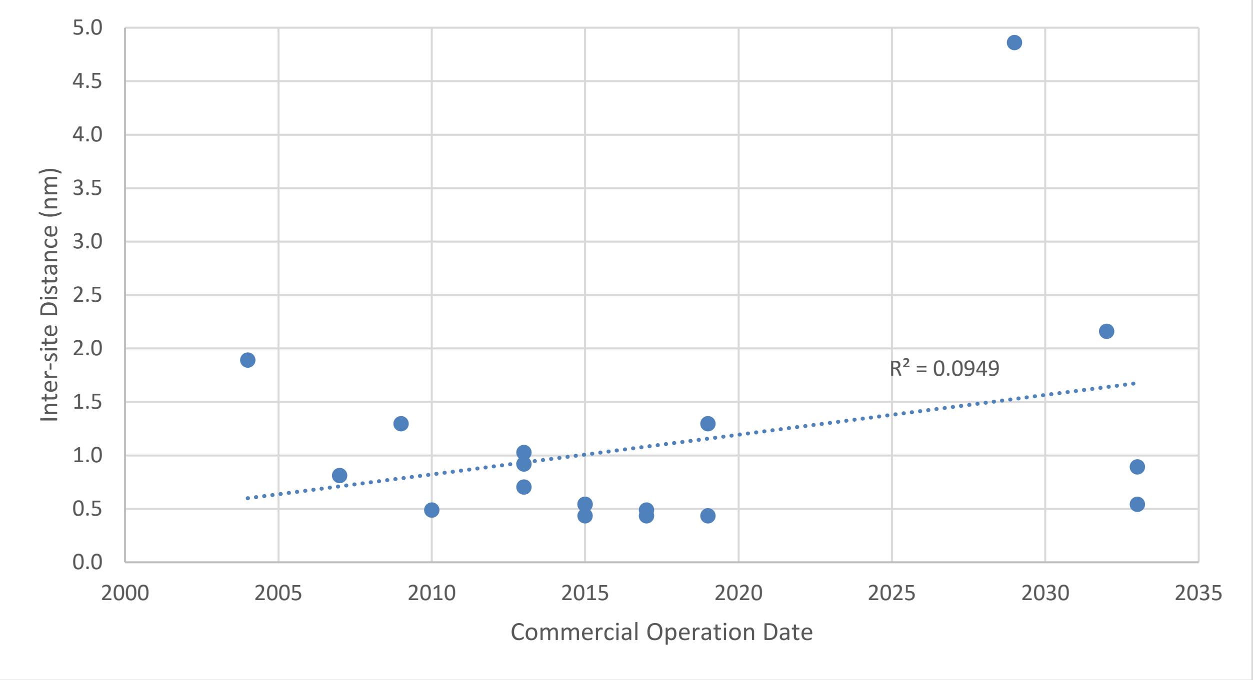
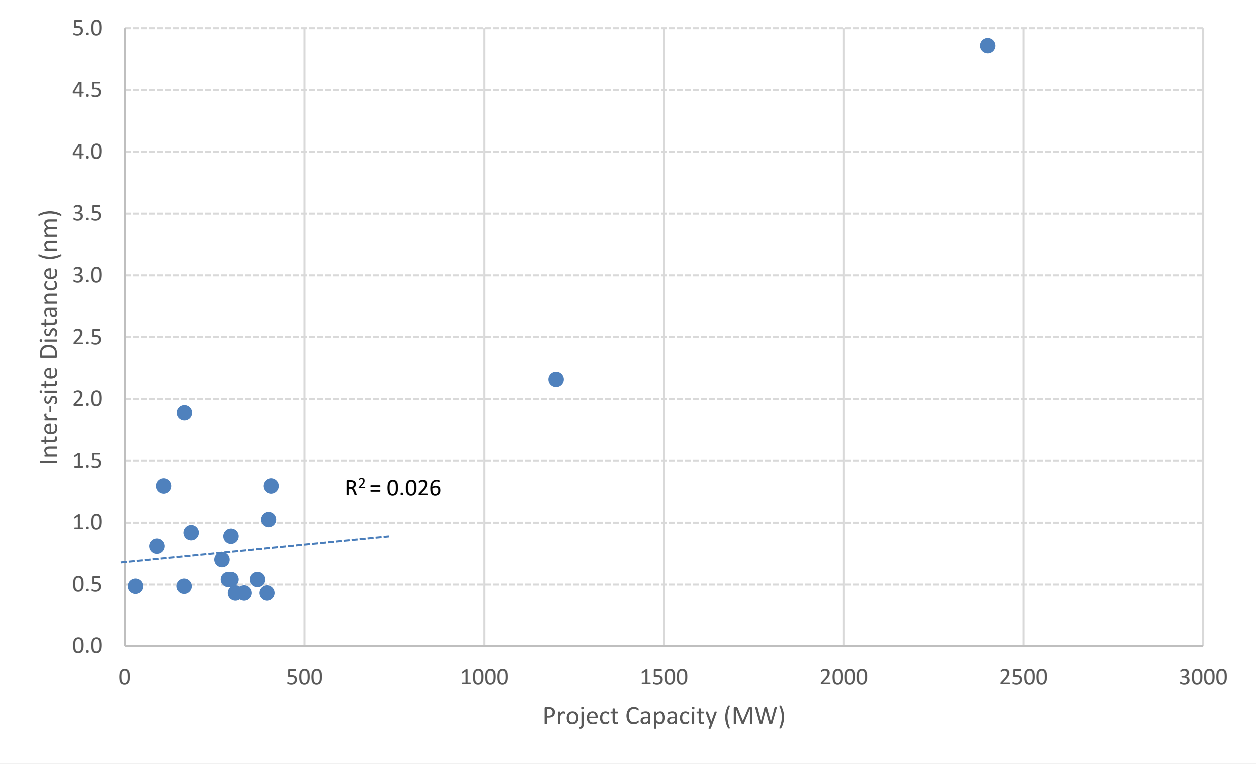


Table 10. Inter-site Distance by Project Capacity



3.4 Recommendations

Tables 7 and 8 show the wide variance in inter-site distance, albeit with the majority of OWFs having a distance of 1.5 nm or less. The low R^2 values in Tables 9 and 10 shows there is no statistical relation between inter-site distance and either (1) COD or (2) installed capacity. This suggests that there is no best practice or rule of thumb for site spacing adopted by project sponsors or permitting agencies across the countries studied in Europe.

As explored in section 5, inter-site distances of less than roughly 40 rotor diameters are likely to result in some reduction in array efficiency at the downwind OWF caused by wakes from the upwind farm, with significant impacts occurring at distances of less than 20 rotor diameters. This implies that project sponsors have either factored the impact of upwind wakes in their energy yield predictions, or, more likely, have entered into a compensation agreement with the operator of the upwind neighboring wind farm.

The two wind farms with a distance greater than 2 nm to their nearest neighbor (Teeside B and Hornsea 3) are more than a decade away from their planned COD in the middle of the next decade and are significantly larger than the other sites in the sample. The Hornsea 3 site has not yet been laid out, and it is likely that the inter-site distance between Hornsea 3 and 2 will change as the project moves through development. As a result, Hornsea 3 should be considered an outlier and its planned inter-site distance is larger than the actual one after COD. However, Teeside B site is fully permitted, and although the exact WTG locations may change between now and COD, it is unlikely that the inter-site distance will change much.

Because of the size of the sites intended for the Areas for Consideration (800 MW), the 2.2 nm inter-site distance between the two Dogger banks sites (Teeside B and Creyke Beck A) could be considered a reasonable minimum distance to use when designing the layouts designs for the indicative WEAs. However, it is anticipated that to reduce wake loss impacts on the downwind site to less than 1%, an inter-site distance of 4 nm would be required, and this is recommended as the base-case distance to use during design of the indicative WTG layouts.

4 Base-Case WTG Layouts

Turbine layouts are required for sites of 800-MW installed capacity each in Area for Consideration East and West, in order to inform the Indicative WEAs identified by NYSERDA. These are termed the base-case layouts. A number of technical design drivers were used in the design of these layouts, including the recommendations in sections 3 and 4 of this report regarding power density and inter-site distance. The layouts are based on a generic 10-MW WTG, which was designed based on data from existing offshore WTGs in the absence of any 10-MW WTGs currently in production.

4.1 Generic WTG Dimensions

Although the layouts are based on a 10-MW generic WTG, dimensions were also requested for the following WTG size options: 8, 10, 12, and 15 MW. A summary of the methodology used, along with the proposed WTG dimensions follows in 4.1.1.

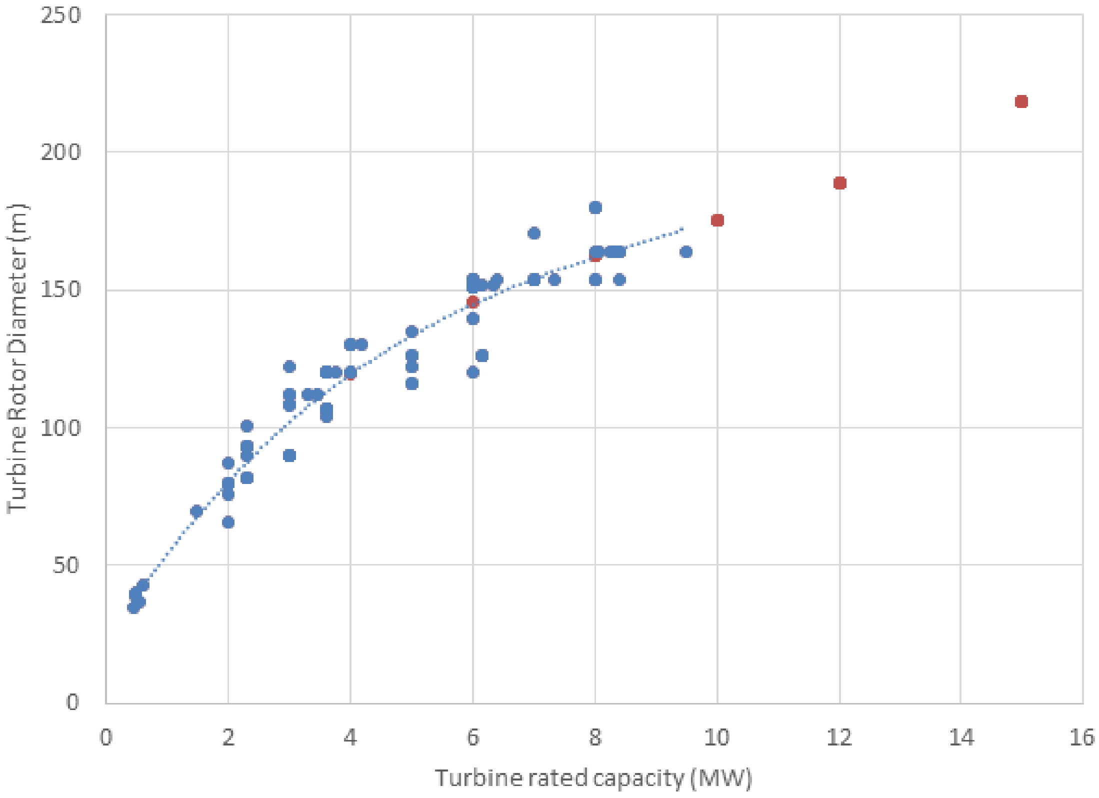
4.1.1 Extrapolation of Existing WTG Dimensions

Dimensions for the 8-MW option are based on the existing MHI Vestas Offshore Wind (MVOW) V164 8-MW WTG, which has already been installed at the UK's operational Burbo Bank Extension wind farm. Dimensions for the others were derived by analyzing the rotor/generator size in relation to WTGs from 69 OWFs and extrapolating to meet the required generator capacity. This was done by plotting rotor diameter against generator capacity and drawing a regression-fit line through the data. The line was then extended out and the corresponding rotor sizes read off the line for 10, 12, and 15 MW generator sizes. The results of this analysis are shown in Table 11.

The UK consultancy Everoze Ltd reviewed the predicted dimensions and provided separate predictions using a different methodology. Power curves were selected from a handful of modern WTGs of the size of interest, and a generic power coefficient (Cp) curve was derived. The generic Cp curve was then used to produce power curves for different rotor diameters, thereby allowing an estimate of rated capacity versus rotor diameter. WTG manufacturers are known to start with a given rotor diameter and increase the generator size over time, so a range of rotor diameters were derived by this method. Everoze's analysis agreed closely with the predicted dimensions.

Table 11. Rotor Diameter and Rated Capacity of WTGs

Dataset (Blue) and Extrapolated Data (Red)



4.1.2 Proposed Wind Turbine Dimensions

The proposed dimensions are presented in Table 12. The rotor diameters for the 10, 12, and 15 MW WTGs represent a “middle case” design that is deemed likely to reflect the rotor diameter associated with each model platform midway through its production lifetime.

The hub height and tip height were derived by first estimating the air gap between the bottom of the rotor disc and the sea surface. The largest existing WTG, the MVOW V164-9.45 MW, has a quoted tip height of 187 m and an air a gap of 23 m, giving a blade/air gap ratio of 0.14. The air gaps for the remaining WTGs were chosen to maintain this ratio.

No analysis has been carried out as to whether fatigue loading issues may be associated with the hub heights proposed for the WTGs in Table 12.

Table 12. Proposed Dimensions of the WTG Options

	8 MW	10 MW	12 MW	15 MW
Rotor diameter (m)	164	177	194	217
Tip Height (m)	187	202	222	247
Hub Height (m)	105	113.5	125	138.5
Water to blade clearance (m)	23	25	28	30
Based on	V164-8MW	Extrapolation	Extrapolation	Extrapolation
Rotor/Air Gap ratio	0.14	0.14	0.14	0.14

4.2 Indicative Wind Energy Area (WEA) Layouts

Indicative WTG layouts were created using the generic 10 MW WTG presented above, with a rotor diameter of 177 m and a hub height of 110 m. This hub height was chosen due to the availability of modelled wind data at this height, which is deemed close enough to the 113.5m stated in Exhibit 14 to have no significant effect on the wake results. Two site layouts of 800 MW each were created for Area for Consideration East (named “D1” and “D2”). In Area for Consideration West, seven sites were created under two different options: 4 x 800-MW and 3 x 800-MW sites (names “E1” to “E7”). These are presented in Figures 3 and 4.

Figure 3. Site Areas for Area for Consideration West (Option 1) and East

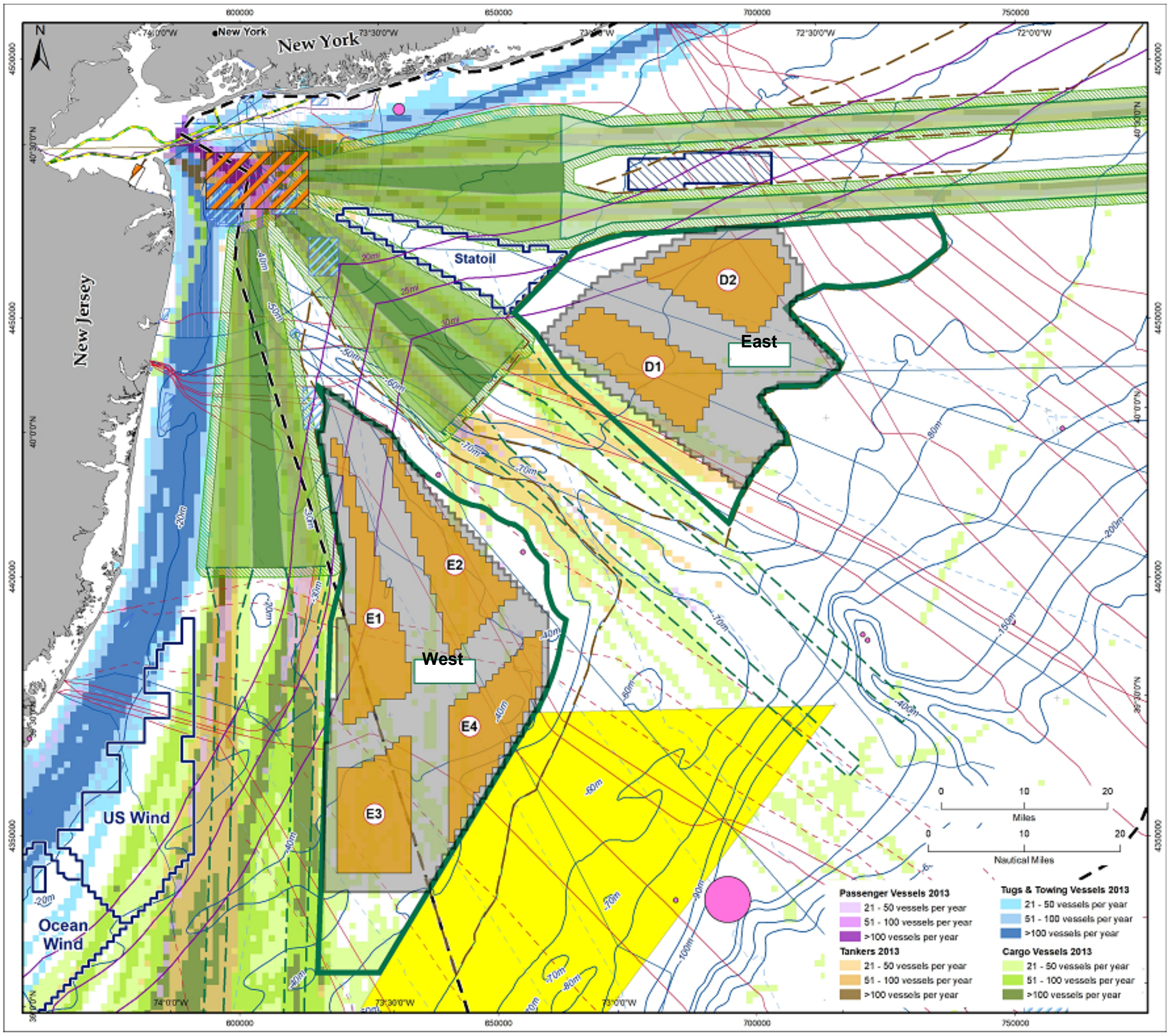
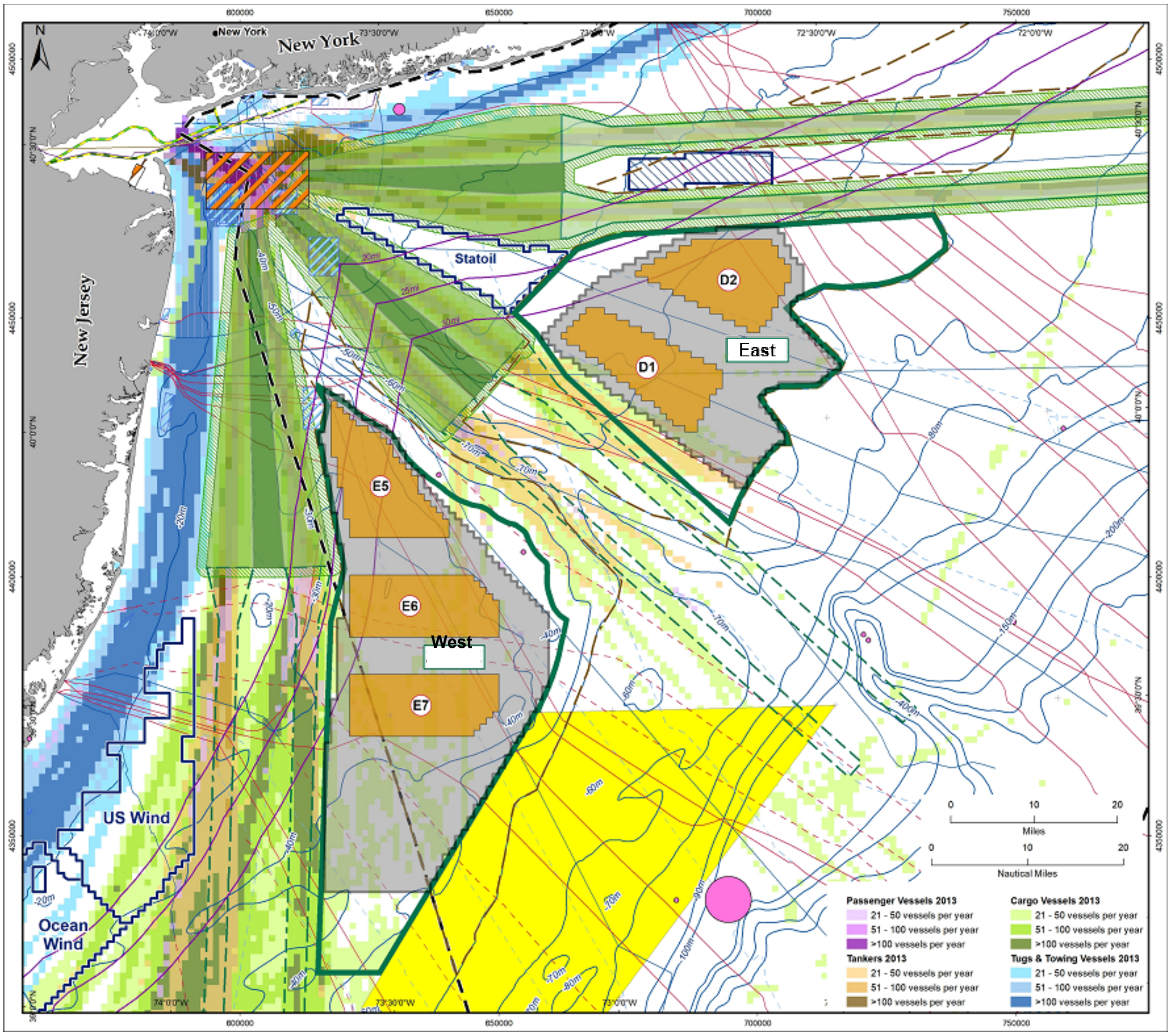


Figure 4. Site areas for Area for Consideration West (Option 2) and East



4.2.1 Layout Design Drivers

The various design drivers used to create the layouts are presented in subsequent discussions, followed by an analysis of the wake losses associated with the WTG layouts.

4.2.1.1 Power Density

Based on the results presented in section 3, a recommended power density of between 0.02 and 0.03 MW/acre was taken as the starting point. The lower value is based on the power density of the largest and latest OWF reviewed (Horns Rev 3), which has a power density of 0.02 MW/acre and is considered to represent industry best practice, given the experience of its designers and operators in the offshore wind market. The WTG spacing associated with this density (13 D x 10 D) is generous. For comparison, the 27 European OWFs reviewed had an average downwind and crosswind spacing of 7.5 D and 5.9 D, respectively.

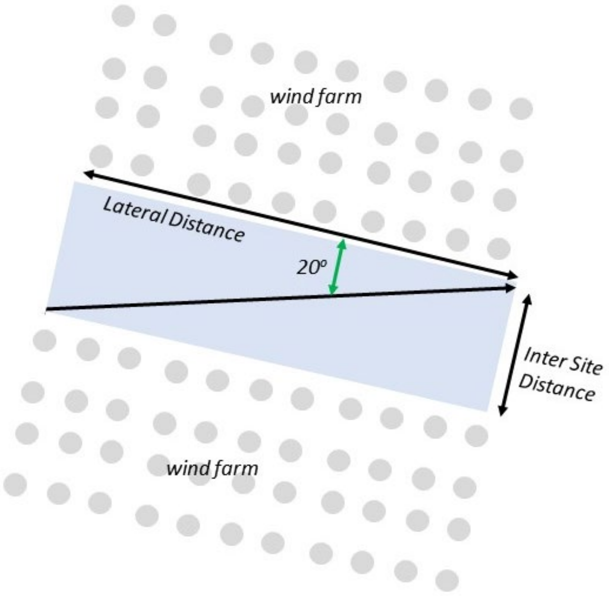
However, in line with the recommendations of section 3.4, a power density of 0.01 MW/acre has been used to inform decisions around the area required. Although lower than the majority of European OWFs reviewed, this power density allows ample space for project sponsors to apply their own layout design preferences, which is important, given these areas are at a much earlier stage of the planning process than the European OWFs. This power density also allows for a "packing factor" as explained further in section 5.2.3. It is comparable to the power density of the Forewind Creyke Beck C and D wind farms (0.009 MW/Acre), which at 1,200 MW each are the largest consented OWFs to date and comparable in size to the 800-MW sites proposed here. As such, 0.01 MW/acre is deemed a reasonable design driver for the Indicative WEAs.

4.2.1.2 Shipping and Navigation

The Shipping and Navigation Study presents guidelines published by International Regulations for Preventing Collisions at Sea (COLREGS). A vessel's captain is required to consider all navigation and collision risks when determining an appropriate Closest Point of Approach (CPA) to another vessel, and a CPA of 0.5 nm to 1 nm is considered acceptable under normal conditions, although this can be extended in poor conditions to ensure safe passage. The New York State Offshore Wind Master Plan Shipping & Navigation Study[2] recommends WEA setbacks of at least 1 nm from shipping and navigation lanes for this reason.

While approaching a wind farm boundary presents its own risks to a mariner, passage between wind farms requires additional considerations to avoid collision. The UK Maritime and Coast Guard Agency (MCA) has issued Marine Guidance Note (MGN) 543 which highlights that a ship's track could deviate as much as 20 degrees or more during transit, and for a vessel transiting along a row of turbines, this deviation could influence the minimal distance calculation. The U.S. Coast Guard has adopted previous guidance from the MCA to develop a methodology to help classify potential impacts to safe navigation,[3] and may do the same with MGN 543. The inter-site distances for the Indicative WEAs were therefore derived by applying the "20-degree" guidance illustrated in Figure 5.

Figure 5. Application of "20-Degree" Guidance to Inter-site Distance

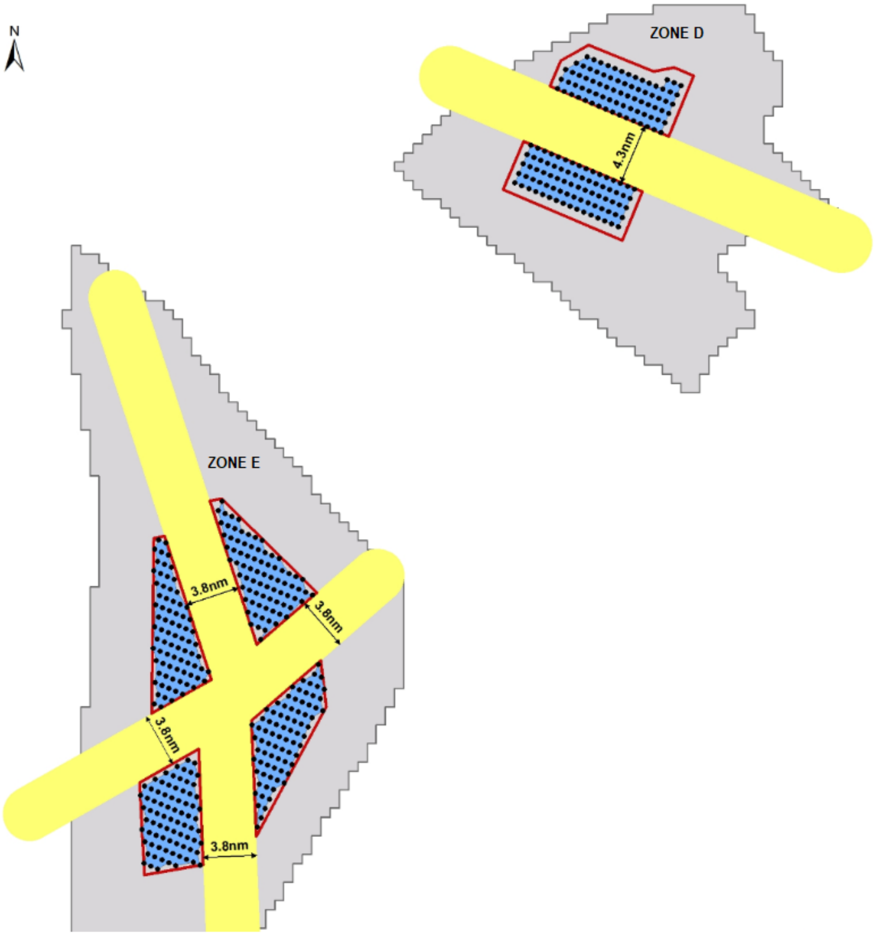


4.2.1.3 Inter-site Distance

Given the lack of a clear trend between inter-site distance and the age, size, or layout of the OWF, as presented in section 4.1, the design driver for inter-site distance was based on the recommendations contained in NYSERDA's Shipping and Navigation Study, as outlined previously. However, the recommended minimum distance of 2.2 nm contained in section 4.4 was also considered.

For the sites in Area for Consideration East, an inter-site distance of 4.3 nm was used. For Area for Consideration West, the distance was reduced to 3.8 nm since it was not possible to fit all sites into the Area for Consideration boundary using 4.3 nm. In some cases, the 4.3 nm inter-site distance does not reflect a strict adherence to the 20-degree guidance; however, given the size of the layouts and the scope for WTGs larger than 10 MW to be adopted by project sponsors, it is considered a prudent distance to apply in order to maintain sufficient distance, should such larger WTGs be used. Larger WTGs would result in larger site areas being required to maintain the power density and would therefore reduce the inter-site distances. Figure 6 shows the approach taken when defining inter-site distances.

Figure 6. Illustration of Inter-site Distance Measurement

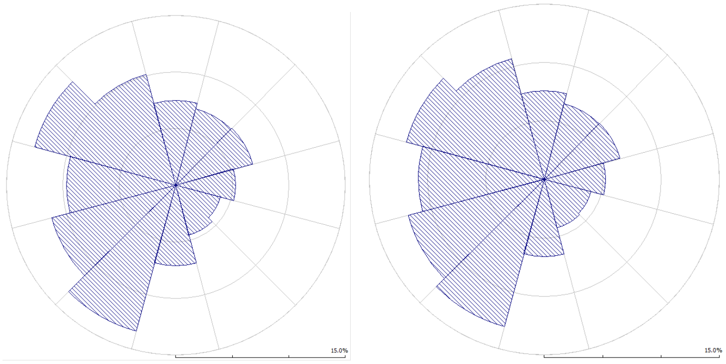


4.2.2 Design Characteristics of Indicative WEA Layouts

A layout design tool was used to establish the inter-WTG spacing required to achieve the power densities needed. A diagram showing wind direction, a wind rose, for each Area for Consideration was used to inform the inter-row and inter-column spacing chosen. As shown in Figure 7, the wind roses for both Area for Consideration East and West have a south-southwesterly prevailing wind direction; therefore, the WTG rows were aligned to 200 degrees. A significant northwesterly component is also present; therefore, ample spacing was allowed between WTG columns, as well as between WTG rows.

Figure 7. Wind Roses

For Area for Consideration West (Left) and East (Right) Used in the Modeling.



Based on the review of power density, inter-site distance, navigation design drivers, and the wind roses for each zone, the indicative WEA layouts have the following common characteristics:

- Power density of 0.01 MW/acre for the 10 MW-177 m option.
- Turbine spacing of 13 rotor diameters (13 D) in the prevailing wind direction and 10 D in the cross-wind direction for the 10 MW-177 m WTG option. This equates to a spacing of 11 D x 8 D for the 15 MW-217 m WTG option.
- Rows aligned perpendicular to a prevailing wind direction of 200 degrees, based on AWS Truepower analysis.
- Site boundaries cut to aliquots, resulting in additional space (packing factor) of 15–20%.
- A minimum distance of 3.8 nm maintained between each 800-MW site through the application of the 20-degree guidance to initial layout designs.

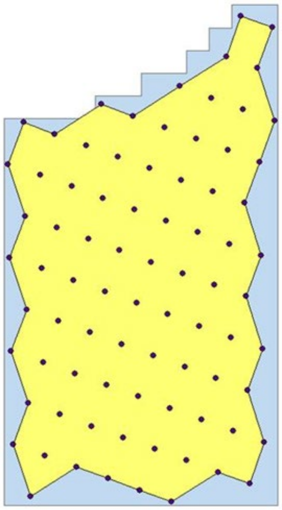
4.2.3 Packing Factor

The boundaries of the indicative WEAs were drawn to align with aliquot boundaries, to allow for an additional “packing factor” area of between 15 and 20%. The packing factor ensures that an adequate margin is applied during the planning stage in case some parts of the WEAs are found not to be unsuitable for WTGs due to other constraints. When drawing the perimeter boundary to calculate the area and therefore the power density for the layouts, the aliquots were used. The power density of the WEA areas is therefore slightly lower than the 0.0125 MW/acre density of the actual WTG layouts in each WEA.

Figure 8 illustrates this for site E3 within Area for Consideration West. The yellow area is drawn between perimeter WTGs and has a power density of 0.0125 MW/acre. The blue area is aligned with the aliquot boundaries and in this example, represents a power density of 0.01 MW/acre. Aliquot area is 20% larger than the perimeter area, representing a packing factor of 20% in this case.

Figure 8. Aliquot Area

(Blue) and Perimeter Area (Yellow) for Area for Consideration West, Site 3.



4.3 Wake Modeling of Indicative WEAs

Preliminary wake modeling of the 10 MW WTG layouts was performed to confirm that the wake losses are acceptable, both for each site individually as well as taking into account the cumulative wake impacts from upwind sites.

4.3.1 Methodology

Wake modeling was undertaken using the WA^{S}P 11 and FUGA 2 software applications. WA^{S}P is an industry standard wind atlas application, and FUGA 2 is an industry leading offshore wake modeling application with a proven track record in accurately predicting wake losses on large OWFs.[4]

The wind data used in the modeling was provided by AWS Truepower (AWST) via NYSERDA for nominal locations within Area for Consideration East and Area for Consideration West, as per AWST's Metocean study. No variation in wind speed across the either Area for Consideration was assumed.
A roughness value of z0 = 0.0001 was used within FUGA 2, which is the manufacturer's recommended value for a typical offshore site with neutral atmospheric stability conditions. The value is the stability state assumed in this study and while it is noted that more stable conditions may result in higher wake losses, in the absence of site-specific atmospheric stability data, the recommended value cannot be investigated.

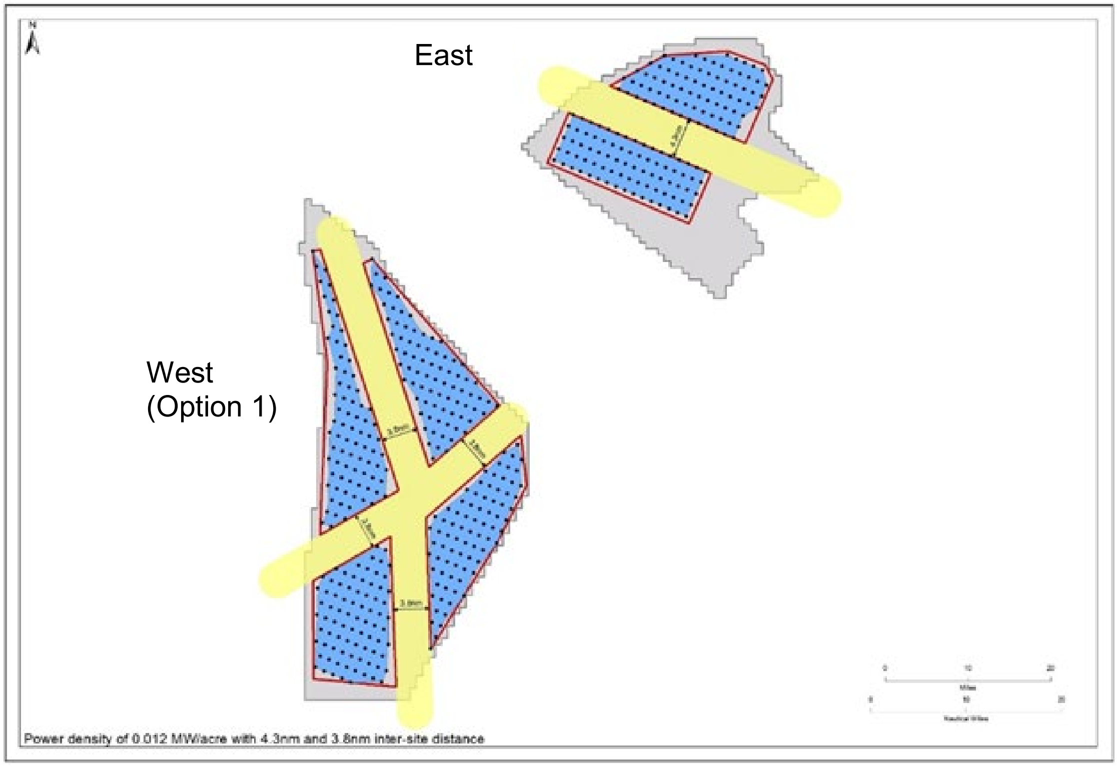
A generic power curve was created for the 10-MW 177 m rotor WTG based on standard assumptions around rotor diameter, thrust coefficient, and offshore turbulence intensity. The WTGs were modelled for a 110 m hub height, and the neighboring sites were activated and de-activated within the model to enable cumulative wake effects to be calculated. No other proposed OWFs were included in the wake modeling.

4.3.2 Turbine Layouts

The WTG layouts as modelled in WA^{S}P and FUGA are presented in Figures 9 and 10.

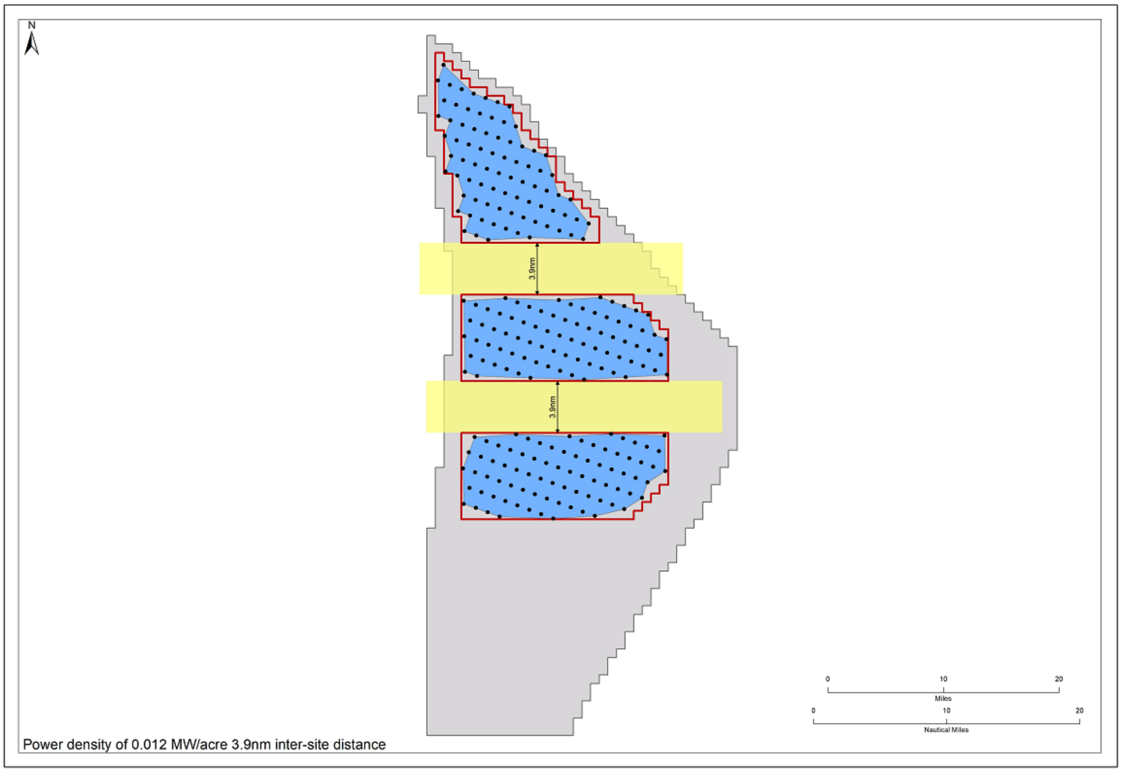
Figure 9. WTG Layouts for

Area for Consideration West (Option 1) and Area for Consideration East



Power density of 0.012 MW/acre with 4.3nm and 3.8nm inter-site distance

Figure 10. WTG Layouts for Area for Consideration West (Option 2)



4.3.3 Results

Table 13 shows the wakes calculated for each site in isolation and the wakes when all the other sites are included in the modeling. The final column shows the difference between these two figures, representing the increase in the wake effects caused by the upwind sites in each case. The variance in the "Wake Loss–Stand-alone" column is driven solely by the orientation and shape of the layouts relative to the wind rose. The variance in the "Increase due to neighboring sites" column is driven by the position of the sites relative to each other and the wind rose.

Table 13. Wake Losses for Area for Consideration

West (Both Options) and Area for Consideration East Indicative WEA Layouts

West (Option 1) Inter-site distance: 3.8 nm	Wake Loss–Stand-alone	Wake Loss–All sites included	Increase due to neighboring sites
E1	4.0%	5.0%	1.0%
E2	4.3%	6.0%	1.7%
E3	5.0%	5.7%	0.7%
E4	4.7%	6.7%	2.0%

Table 13 Continued

West (Option 2) Inter-site distance: 3.8 nm	Wake Loss– Stand-alone	Wake Loss– All sites included	Increase due to neighboring sites
E5	4.8%	5.5%	0.7%
E6	4.7%	6.5%	1.8%
E7	4.8%	5.8%	1.0%

East Inter-site distance: 4.3 nm	Wake Loss– Stand-alone	Wake Loss– All sites included	Increase due to neighboring sites
D1	4.5%	5.1%	0.7%
D2	4.9%	5.9%	1.0%

4.4 Discussion

The indicative site layouts in the Area for Consideration report used a power density of 0.01 MW/acre, resulting in inter-WTG spacing larger than that seen at many European OWF's. This density allows for a 15–20% packing factor to account for unbuildable areas as well as provides ample space for project sponsors to apply different layout designs. The use of an inter-site distance of 4 nm on average results in negligible wake effects between neighboring sites, thereby maintaining efficient projects.

Wake losses of less than 10% are generally considered satisfactory, while wake losses greater than 12% indicate excessively tight WTG spacing and would require justification from the project sponsor. The stand-alone wake losses associated with the indicative site layouts appear reasonable given the size, density, and orientation of the site layouts. This is principally due to the generous spacing applied in the design of each site (13 D in the prevailing wind direction, 10 D in the cross-prevailing direction). Despite the generous inter-site distances applied in the design (driven by the recommended minimum distance for navigational purposes), the cumulative wake losses are significant in some cases and may warrant some form of wake compensation agreement or negotiated by the project sponsors.

There is scope for project sponsors to use higher power densities and smaller inter-site distances than has been assumed in the indicative WEAs, but a sensitivity analysis was deemed necessary in order to understand at what point the wake losses associated with such changes become excessively high.

5 Sensitivity Analysis

A two-part sensitivity analysis was carried out to demonstrate the risk (in wake loss terms) of installing the capacities of Area for Consideration East and West in smaller areas. The first part involved creating additional WEA layouts for both East and West, with higher power densities than the indicative layouts reported in section 5 (hereafter referred to as the "base-case" scenario layouts). The second involved decreasing the inter-site distance. In total, layouts with three different power densities were created, with a combination of three different inter-site distances, making a total of nine scenarios, of which one (the base-case scenario) has already been modelled and reported in section 5. Wake loss calculations were then performed for each scenario.

Table 14 provides an overview of the layout scenarios modelled. Area for Consideration East comprises two sites of 800-MW installed capacity. Area for Consideration West comprises four sites of 800-MW installed capacity, as per option 1 modelled in section 5. All layouts are presented in appendix F.

Table 14. Overview of Layout Scenarios Modelled in Sensitivity Analysis

		Inter-site Distance (nm)		
		3.8 (West) / 4.3 (East)	**2.0**	**0.0**
Power Density (MW/acre)	**0.01**	Base case	NEW	NEW
	0.02	NEW	NEW	NEW
	0.04	NEW	NEW	NEW

5.1 Design Characteristics of Additional Layouts

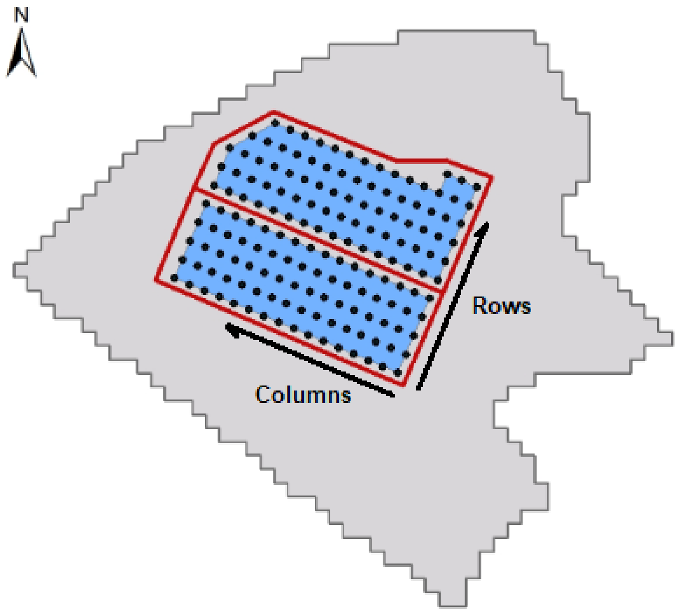
In order to control as many variables as possible, the same methodology detailed in section 5 was followed in the sensitivity analysis. The same generic WTG with 10-MW rated capacity, 177 m rotor diameter and 110 m hub height was assumed when creating the layouts, and the same input wind data from AWST were used in the wake modeling. The same prevailing wind direction was assumed when aligning WTG rows as previously, and the general shape and alignment of the layouts were maintained.

5.1.1 Power Density

The new power densities were chosen by referring to the findings of section 3. The medium-density scenario (0.02 MW/acre) is based on the recommended density stated in section 3.5, which takes into account the large (approximately 800 MW) size of the sites expected by NYSERDA. The power density used in the high-density scenario (0.04 MW/acre) is the same as the average reported in section 3.4 and, given the size of the sites expected by NYSERDA, is expected to produce losses by excessively high wakes. This layout is shown in Figure 11.

Figure 11. Example Layout Design

Area for Consideration East, 0.02 MW/acre, 0 nm Buffer Scenario



The inter-WTG spacing used was as follows:

- 0.01 MW/acre scenario: 13 D between rows, 10 D between columns
- 0.02 MW/acre scenario: 10 D between rows, 8 D between columns
- 0.04 MW/acre scenario: 7.5 D between rows, 5.5 D between columns

For the new layouts, the site perimeters were not aligned with aliquots and, as such, no packing factor was allowed for in the new site areas.

5.1.2 Inter-site Distance

For the largest inter-site distance scenario, the distance was kept at 4.3 nm between the sites within Area for Consideration East, and 3.8 nm between the sites within Area for Consideration West, as per the base-case modeling. This was done to control the inter-site variable, and therefore, allow a valid comparison of the effect of different power densities on wakes, which would not be possible using a different inter-site distance to that used in the base-case analysis from section 5.

For the medium-distance scenario, a distance of 2 nm was chosen for both East and West, based on the recommendation in section 4.5. The shortest distance scenario (0 nm) has no buffer distance between sites so the inter-site distance is equal to the inter-WTG distance in each site. These distances are as follows:

- 1.29 nm for 0.01 MW/acre scenarios
- 0.96 nm for 0.02 MW/acre scenarios
- 0.72 nm for 0.04 MW/acre scenarios

In the 0 nm scenarios the sites appear as one continuous project, as shown in Figure 11. Although this concept is unlikely to be feasible due to the need for navigation channels, the scenario was conceived to present the worst case from a cumulative wake-loss point of view. The lack of a buffer provides no opportunity for the wakes from the upwind site to dissipate before impacting the downwind sites.

5.2 Wake Modeling

The same wake modeling methodology detailed in section 5 was followed. Neighboring sites were activated and de-activated within FUGA to enable cumulative wake effects to be calculated as well as stand-alone wakes. No other proposed OWFs were included in the wake modeling.

5.3 Results

A subset of results is presented in this section, along with bar charts to illustrate the trends seen. A full list of the wake-loss results is provided in appendix G. Additional data on the WTG spacing, distance to shore, and average water depth for each scenario is provided in appendix H.

5.3.1 Power Density Alone

Table 15. Graph of Stand-Alone Wake Losses for Each Site for Each Power Density Scenario

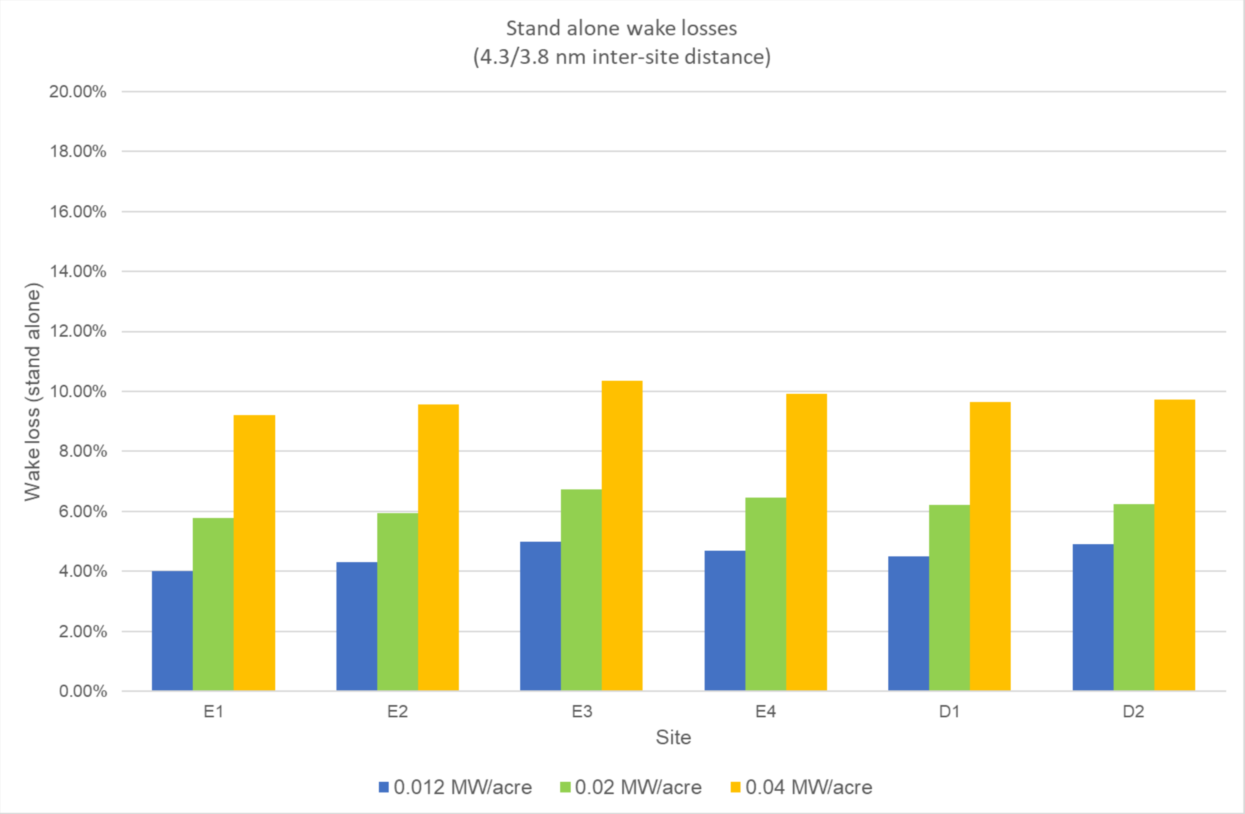


Table 15 presents the stand-alone wakes for all six sites for the base-case, inter-site distance. Each column represents a different power density, and as expected, wake losses increase as power density increases. The site-by-site trend is similar for each density, an outcome which is reasonable, given that the base-case (low density) sites were essentially minimized to create the medium- and high-density versions, with no changes made to the number of rows or columns. The variation in wake losses is purely driven by site design, in terms of shape and number of rows. Stand-alone wake losses for the other inter-site distance scenarios are identical or very similar and have therefore not been plotted here.

Table 16. Graph of Cumulative Wake Losses

For Area for Consideration East (Average of all Sites)

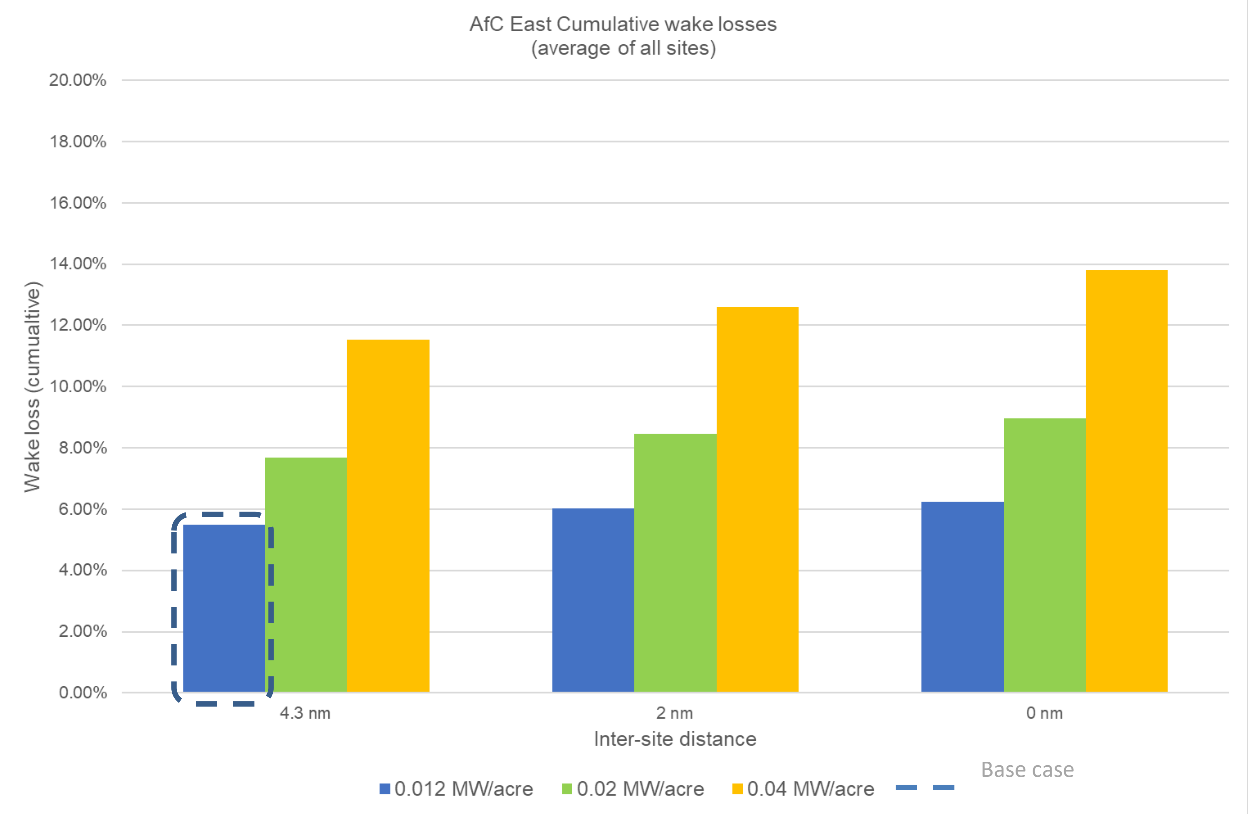


Table 17. Table of Cumulative Wake Losses

For Area for Consideration East (Average of Both Sites)

		Inter-site Distance (nm)		
		4.3	**2.0**	**0.0**
Power Density (MW/acre)	**0.01**	5.50 %	6.03 %	6.23 %
	0.02	7.68 %	8.45 %	8.97 %
	0.04	11.53 %	12.60 %	13.80 %

5.3.2 Power Density and Inter-site Distance

Tables 16 and 17 present the average cumulative wake losses for Area for Consideration East and show clearly that wake losses increase as inter-site distance decreases. The relatively small increase in wake losses from 2 nm to 0 nm for the lowest density scenarios is due to the 0 nm scenario actually having an inter-site distance of 1.29 nm, very close to 2 nm. This is explained in more detail in section 6.1.2. In all cases, the cumulative wakes at D1 are significantly less than at D2 given its position upwind of D2 in the prevailing wind direction, which has the effect of pulling the average wake loss for the zone down.

Despite this, wake losses exceed 8% (which is deemed an acceptable level) in two of the medium-density scenarios and all three of the high-density scenarios. If wake losses exceed 12%, they are likely to have a significant impact on project returns, and as wake losses increase further, so too does the risk of excessive fatigue loading on WTG components due to wake induced turbulence. This can reduce the lifetime of the WTG and in extreme cases may result in WTG original equipment manufacturers (OEM) refusing to provide a WTG warranty for a given layout. Wake losses for the 2 nm and 0 nm scenarios are considered to fall within this category for the high-power density scenarios. For the medium- and low-power density layouts, wake losses are still reasonable even with no buffer distance. This is likely due to the sufficiently large inter-WTG spacing, which allows some dissipation of wakes between the two sites.

Table 18. Graph of Cumulative Wake Losses

For Area for Consideration West (Average of All Sites)

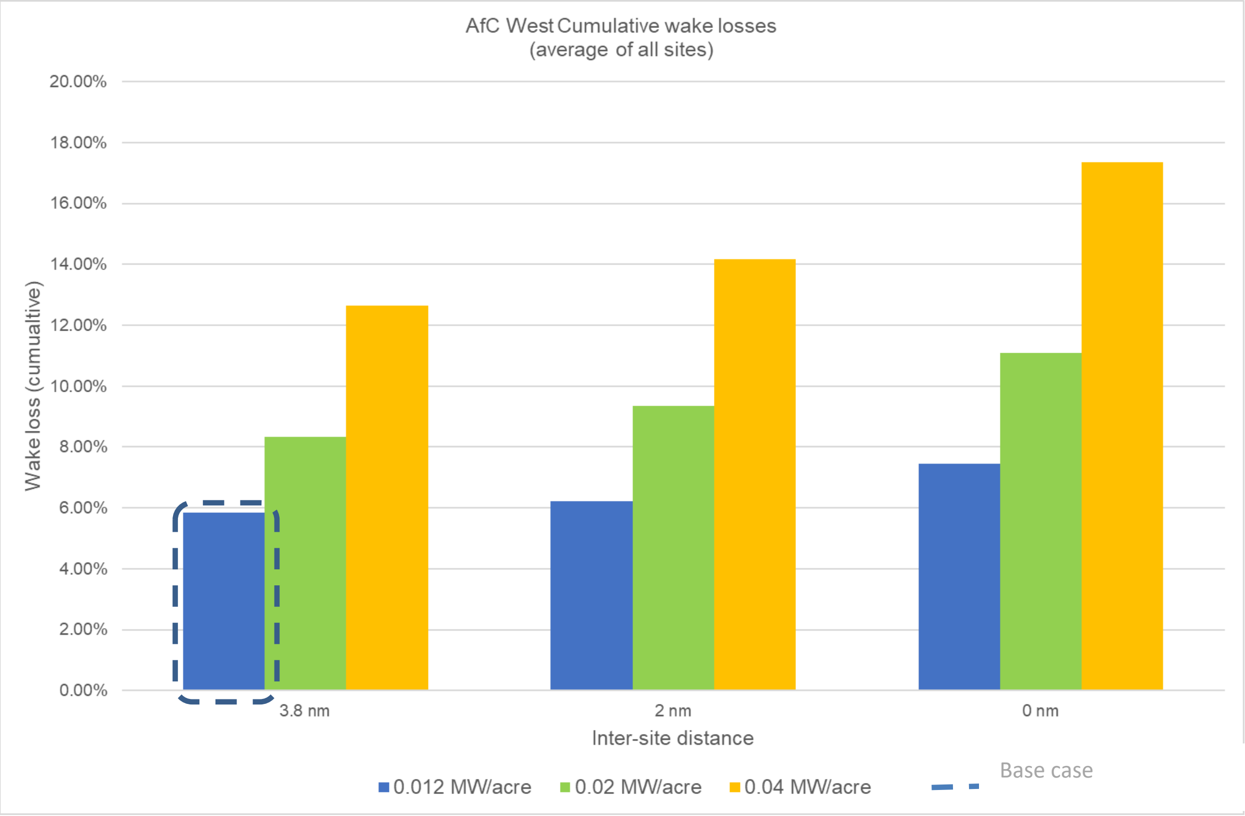


Table 19. Table of Cumulative Wake Losses

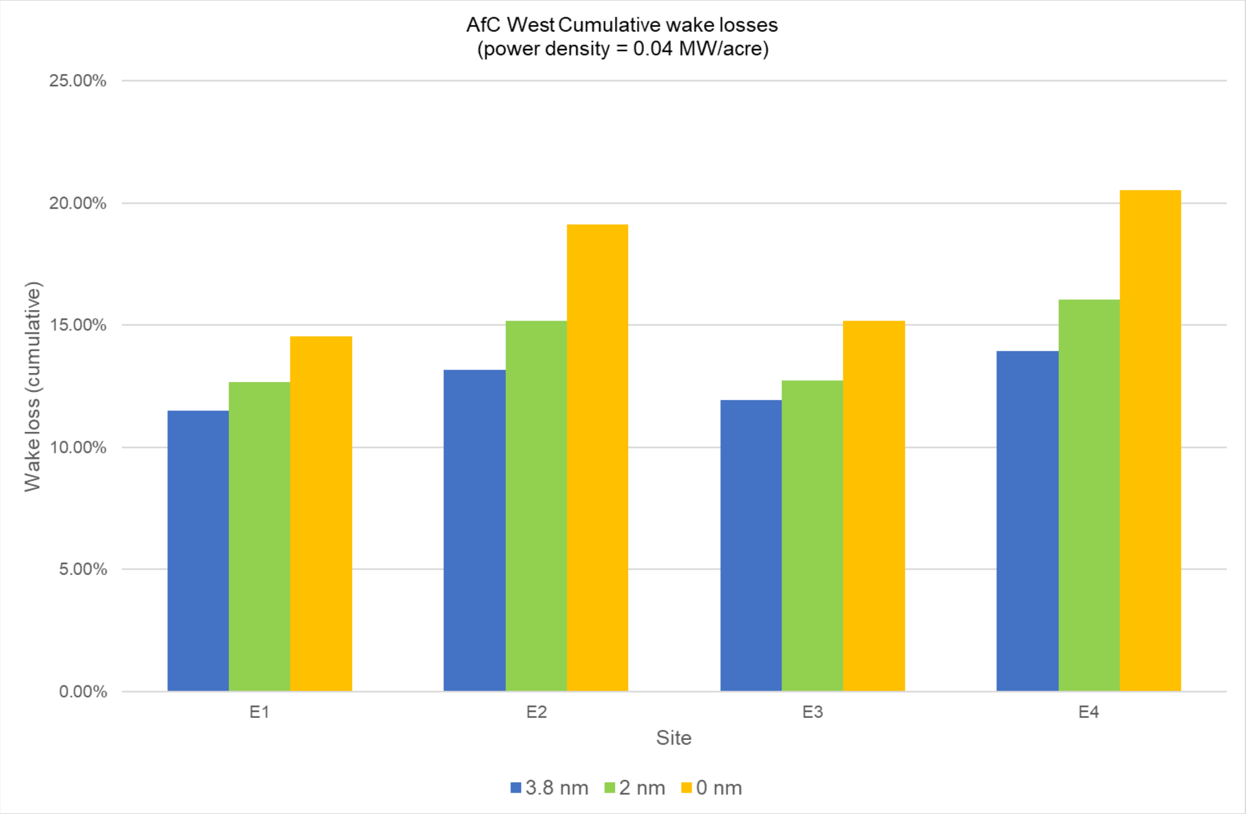
For Area for Consideration West (Average of All Sites)

		Inter-site Distance (nm)		
		3.8	**2.0**	**0.0**
Power Density (MW/acre)	**0.01**	5.85 %	6.21 %	7.44 %
	0.02	8.34 %	9.36 %	11.08 %
	0.04	12.64 %	14.16 %	17.35 %

Tables 18 and 19 present the average cumulative wake losses for the Area for Consideration West sites. Wake losses for all scenarios are higher than the Area for Consideration East sites. This is expected since Area for Consideration West has double the number of sites as Area for Consideration East, and the inter-site distance is 3.8 nm rather than 4.3 nm. Accordingly, wake losses for even the medium-power density scenario exceed 10% when there is no buffer distance applied. The wake losses for all 0.04 MW/acre scenarios are deemed excessively high.

Table 20. Graph of Cumulative Wake Losses

For Area for Consideration West Sites for 0.04 MW/Acre Power Density



The Indicative WEA layouts presented in section 5 were designed with the intention of providing a a situation in which all project sponsors have an equal chance of succeeding; this includes ensuring that no site suffers significantly higher wake losses than the others. It is therefore important to consider the site-specific cumulative wake losses, as well as the all-zone average for Area for Consideration West. Table 20 shows the highest density option for the site-specific cumulative wake losses for this area. It clearly shows that site E4 suffers the highest wakes in all distance scenarios, as would be expected since it is positioned downwind of one or more sites in all wind directions from south to northwest. The difference between E4 and the other sites increases with smaller inter-site distance. For site E4, the cumulative wake losses range from 6.7%for the lowest density/largest inter-site distance scenario to 20.5%for the highest density/smallest inter-site distance scenario (a three-fold increase).

5.4 Impact on Net Capacity Factor

An offshore wind farm's net yield and net capacity factor (NCF) are heavily influenced by wake losses, which are typically the largest single loss factor contained in an energy yield estimate. To illustrate the potential variance in NCF under various scenarios modelled in the sensitivity analysis, indicative annual energy production (AEP) and NCF figures are presented in Table 21 for Site E4 in Zone E, based on the following standard assumptions:

- 1 x 800-MW site, consisting of 80 No. "10-177" WTGs
- WTG and Balance of Plant (BoP) availability of 94% (standard assumption)
- Electrical losses of 3% (standard assumption, covering losses from the inter-array cables only, and not including export cable losses)
- Wake losses (scenario-specific, shown in Table 21)

Table 21. Indicative AEP and NCF Values

For Area for Consideration West Site 4 Under Various Scenarios

	Area for Consideration West, Site 4					
Scenario	0.01 MW/acre, 3.8 nm	0.02 MW/acre, 3.8 nm	0.02 MW/acre, 2 nm	0.04 MW/acre, 3.8 nm	0.04 MW/acre, 2 nm	0.04 MW/acre, 0 nm
Gross AEP (GWh/yr)	3.47	3.47	3.47	3.47	3.47	3.47
Wake loss (%)	6.7	9.4	10.9	13.9	16.0	20.5
Net AEP (GWh/yr)	2.92	2.83	2.79	2.69	2.62	2.48
NCF (%)	41.6	40.4	39.7	38.4	37.4	35.4

The figures in Table 21 are for illustrative purposes only and do not consider additional losses that may be applicable to the WEA or variance in wind speed across the sites. But the trend clearly shows the impact on NCF from the higher wake losses associated with higher power densities and smaller inter-site distances.

6 Conclusions

WTG layouts for the Indicative WEAs within Area for Consideration East and Area for Consideration West have been created to inform the size and orientation of the indicative WEAs and Area for Consideration, based on a review of the power density and inter-site distances at a sample of European offshore wind farms with a range of design characteristics. The WTG spacing in the Indicative WEA layouts accommodates the use of turbines up to 15 MW. Inter-site distances are 3.8 nm or larger, informed by shipping and navigation guidelines aimed at preventing allisions between vessels and wind farms. Wake modeling for the indicative WEA layouts shows the layouts to have relatively low-wake losses individually, although cumulative wake losses from upwind sites are appreciable.

A sensitivity analysis has been performed for both East and West Areas to establish the risk in both wake loss and net capacity factor terms of using higher power densities and smaller inter-site distances. Power densities and closer inter-site distances similar to those seen in Europe were modelled, along with an extreme case featuring no additional buffer space between the sites.

While stand-alone wake losses for each 800-MW site are generally reasonable, wake losses exceed what is deemed sensible in the majority of cases when cumulative effects are considered. The results suggest that cumulative wake losses are likely to exceed 8%if inter-site distance is reduced to 2 nm and power density increased to 0.02 MW/acre; this is a sensible wake loss level in light of the uncertainties over the shape of future developments. Pursuing even higher power densities and smaller inter-site distances is not recommended if large impacts on project returns are to be avoided and downwind sites not penalized.

This analysis supports the design criteria used in the Indicative WEA layouts presented in section 5. The generous inter-turbine and inter-site distances, coupled with the packing factor, assumed in the modeling provides confidence that the proposed WEAs are protected for future use. The modeling also provides assurance for the accommodation of significantly larger turbines in the WEAs and/or substantial alterations to the WTG layouts by project sponsors who will later obtain leases to develop.

7 References

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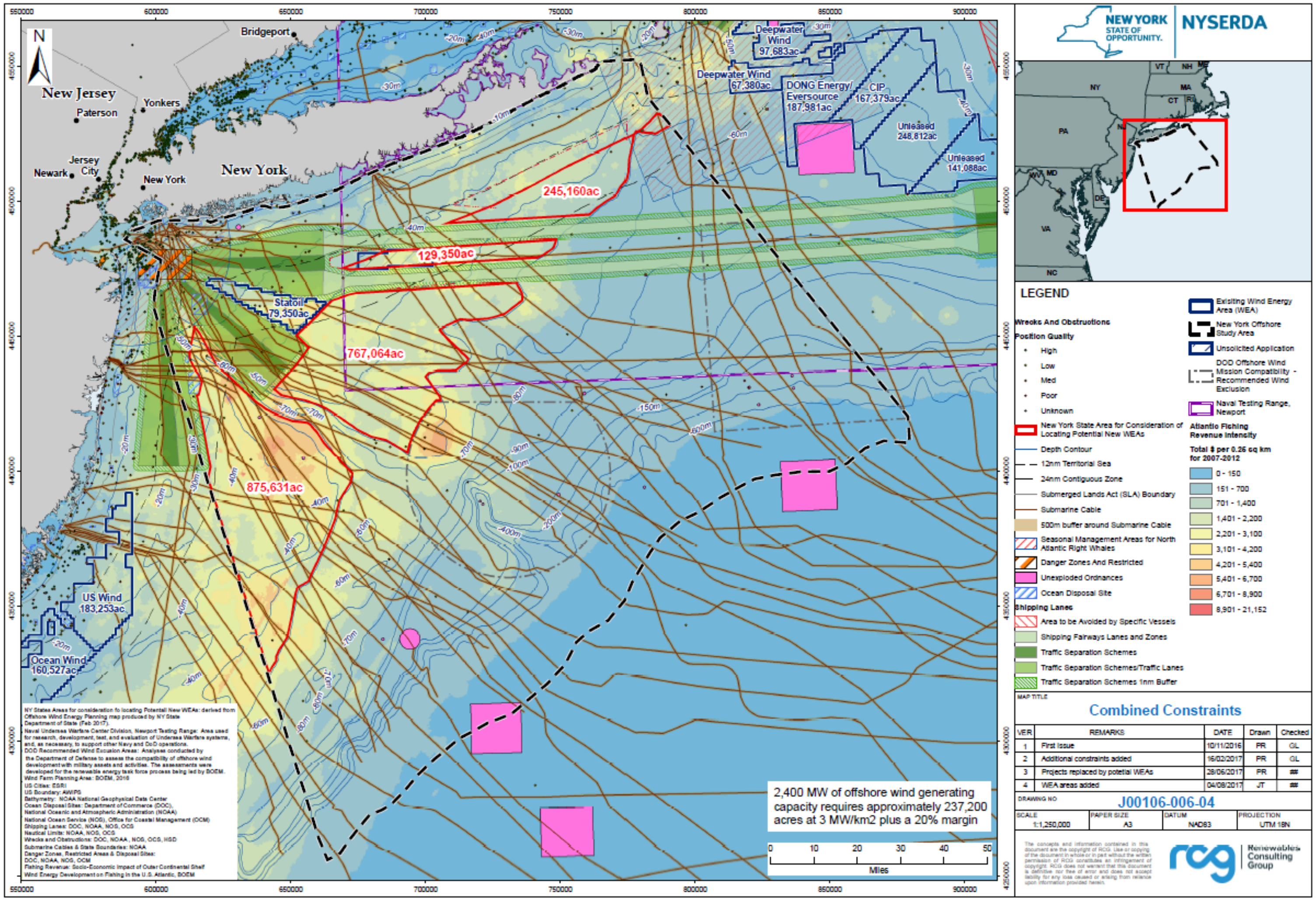
Walker, K., Adams, N., & Gribben, B. (2014). *Predictive Accuracy of Wake Effects Models for Offshore Wind Farms (OWA-W Stage 2 Bankability).*

Appendix A. Map of Offshore Study Area Zones



NY States Areas for consideration fo locating Potentail New WEAs: derived from Offshore Wind Energy Planning map produced by NY State Department of State (Feb 2017).

Naval Undersea Warfare Center Division, Newport Testing Range: Area used for research, development, test, and evaluation of Undersea Warfare systems, and, as necessary, to support other Navy and DoD operations.

DOD Recommended Wind Excusion Areas: Analyses conducted by the Department of Defense to assess the compatibility of offshore wind development with military assets and activities. The assessments were developed for the renewable energy task force process being led by BOEM.

Wind Farm Planning Area: BOEM, 2016
US Cities: ESRI
US Boundary: AWIPS
Bathymetry: NOAA National Geophysical Data Center
Ocean Disposal Sites: Department of Commerce (DOC), National Oceanic and Atmospheric Administration (NOAA)
National Ocean Service (NOS), Office for Coastal Management (OCM)
Shipping Lanes: DOC, NOAA, NOS, OCS
Nautical Limits: NOAA, NOS, OCS
Wrecks and Obstructions: DOC, NOAA, NOS, OCS, HSD
Submarine Cables & State Boundaries: NOAA
Danger Zones, Restricted Areas & Disposal Sites: DOC, NOAA, NOS, OCM
Fishing Revenue: Socio-Economic Impact of Outer Continental Shelf Wind Energy Development on Fishing in the U.S. Atlantic, BOEM

2,400 MW of offshore wind generating capacity requires approximately 237,200 acres at 3 MW/km2 plus a 20% margin

Combined Constraints

VER	REMARKS	DATE	Drawn	Checked
1	First Issue	10/11/2016	PR	GL
2	Additional constraints added	16/02/2017	PR	GL
3	Projects replaced by potetial WEAs	28/06/2017	PR	##
4	WEA areas added	04/08/2017	JT	##

DRAWING NO J00106-006-04

SCALE	PAPER SIZE	DATUM	PROJECTION
1:1,250,000	A3	NAD83	UTM 18N

Appendix B. Dataset for Power Density Review (All Data)

Offshore Wind Farm	Year of 1st Operation	Country	Turbine model	Installed Capacity (MW)	Area (Acres)	Density (MW/Acre)
Kentish Flats 1	2005	UK	V90-3.0	90	1977	0.046
Burbo Bank	2007	UK	SWT-3.6-107	90	1483	0.061
Lynn	2009	UK	SWT-3.6-107	86.4	1483	0.058
Inner Dowsing	2009	UK	SWT-3.6-107	108	1730	0.062
Horns Rev 2	2009	Denmark	SWT-2.3-93	209.3	7660	0.027
Gunfleet Sands II	2010	UK	SWT-3.6-107	64.8	741	0.087
Alpha Ventus 1	2010	Germany	RE-5.0-126	30	988	0.061
Gunfleet Sands	2010	UK	SWT-3.6-107	108	1977	0.055
Belwind 1	2010	Belgium	V90-3.0	165	2965	0.056
Walney 1	2011	UK	SWT-3.6-107	183.6	5683	0.032
Walney 2	2012	UK	SWT-3.6-120	183.6	9637	0.019
Thornton Bank 3	2013	Belgium	6.2M126	110.7	1730	0.064
Thornton Bank 2	2013	Belgium	6.2M126	184.5	2965	0.062
BARD Offshore 1	2013	Germany	Bard-5.0-122	400	14085	0.028
Meerwind	2014	Germany	SWT-3.6-120	288	9884	0.029
West of Duddon Sands	2014	UK	SWT-3.6-120	388.8	14826	0.026
Borkum West 2.1	2015	Germany	M5000-116	200	3954	0.051
Nordsee Ost	2015	Germany	6.2M126	295.2	8649	0.034
Borkum Riffgrund 1	2015	Germany	SWT-4.0-120	308	8896	0.035
Nobelwind (Belwind 2)	2017	Belgium	V112-3.3	165	5683	0.029
Burbo Bank Extension	2017	UK	V164-8.06	257.92	7907	0.033
Nordsee 1	2017	Germany	6.2M126	332.1	7907	0.042
Gode Wind 1	2017	Germany	SWT-6.0-154	330	9637	0.034
Gode Wind 2	2017	Germany	SWT-6.0-154	252	6672	0.038

Galloper	2018	UK	SWT-6.0-154	336	18039	0.019
Merkur Offshore	2019	Germany	GE-6.0-150	396	9637	0.041
Horns Rev 3	2019	Denmark	V164-8.3	406.7	20263	0.020
All Average (27*)						**0.043**
UK Average (11*)						0.045
EU Average (16*)						0.041
All Average (2011 onwards) (18*)						**0.035**
UK Average (2011 onwards) (5*)						0.026
EU Average (2011 onwards) (13*)						0.039

* Number of offshore wind farms in sample

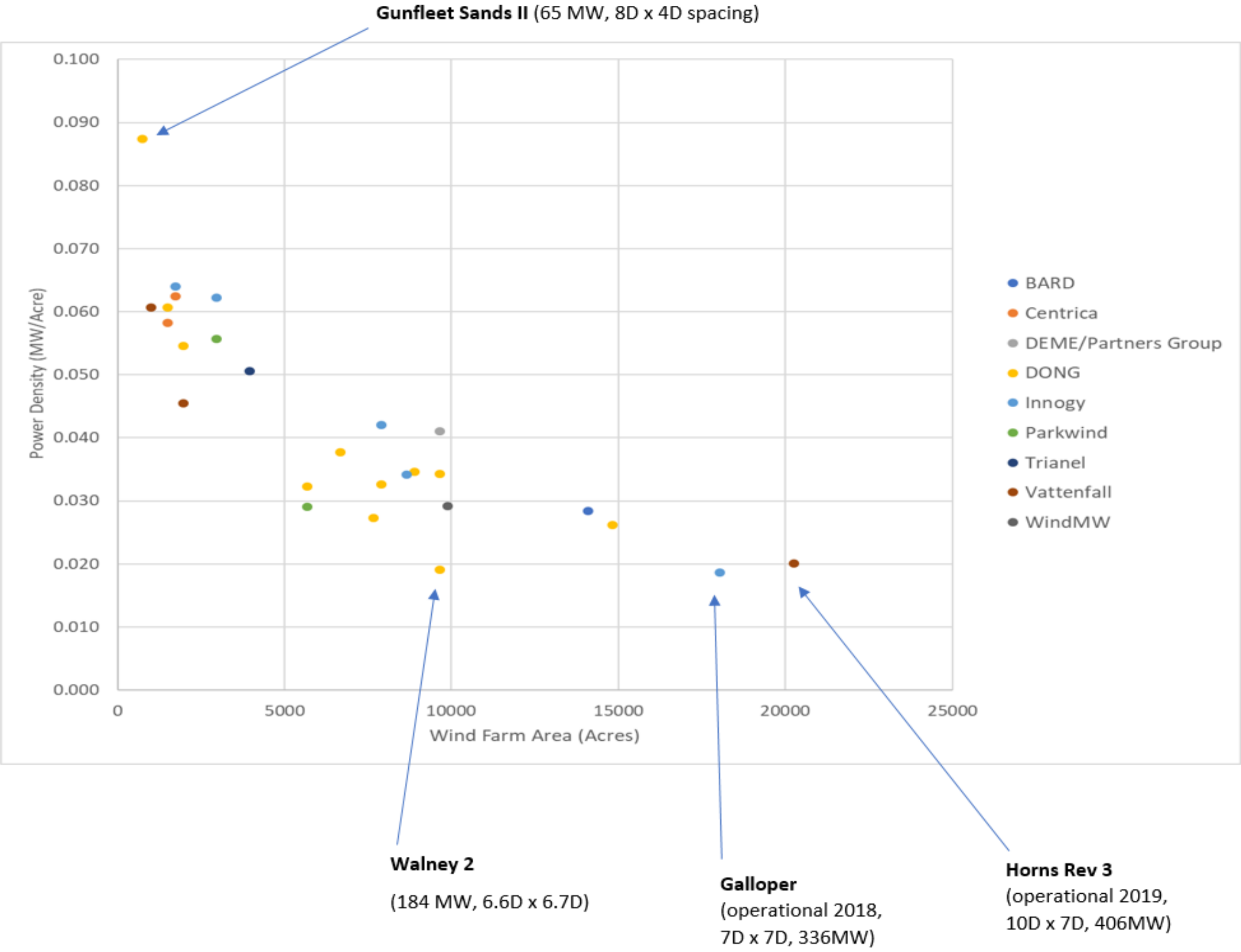
Appendix C. Dataset for Power Density Review (>5,000 Acres)

Offshore Wind Farm	Year of 1st Operation	Country	Turbine Model	Installed Capacity (MW)	Area (Acres)	Density (MW/Acre)
Walney 1	2011	UK	SWT-3.6-107	183.6	5683	0.032
Nobelwind (Belwind 2)	2017	Belgium	V112-3.3	165	5683	0.029
Horns Rev 2	2009	Denmark	SWT-2.3-93	209.3	7660	0.027
Burbo Bank Extension	2017	UK	V164-8.06	257.92	7907	0.033
Nordsee 1	2017	Germany	6.2M126	332.1	7907	0.042
Nordsee Ost	2015	Germany	6.2M126	295.2	8649	0.034
Borkum Riffgrund 1	2015	Germany	SWT-4.0-120	308	8896	0.035
Walney 2	2012	UK	SWT-3.6-120	183.6	9637	0.019
Merkur Offshore	2019	Germany	GE-6.0-150	396	9637	0.041
Meerwind	2014	Germany	SWT-3.6-120	288	9884	0.029
BARD Offshore 1	2013	Germany	Bard-5.0-122	400	14085	0.028
West of Duddon Sands	2014	UK	SWT-3.6-120	388.8	14826	0.026
Galloper	2018	UK	SWT-6.0-154	336	18039	0.019
Horns Rev 3	2019	Denmark	V164-8.3	406.7	20263	0.020
Gode Wind 1	2017	Germany	SWT-6.0-154	330	9637	0.034
Gode Wind 2	2017	Germany	SWT-6.0-154	252	6672	0.038
All Average (16*)						**0.030**
UK Average (5*)						0.026
EU Average (11*)						0.033

* Number of offshore wind farms in sample

Appendix D. Additional Charts (Power Density)

Power density as a function of the wind farm area, with names of highest and lowest density OWFs added.



Gunfleet Sands II (65 MW, 8D x 4D spacing)

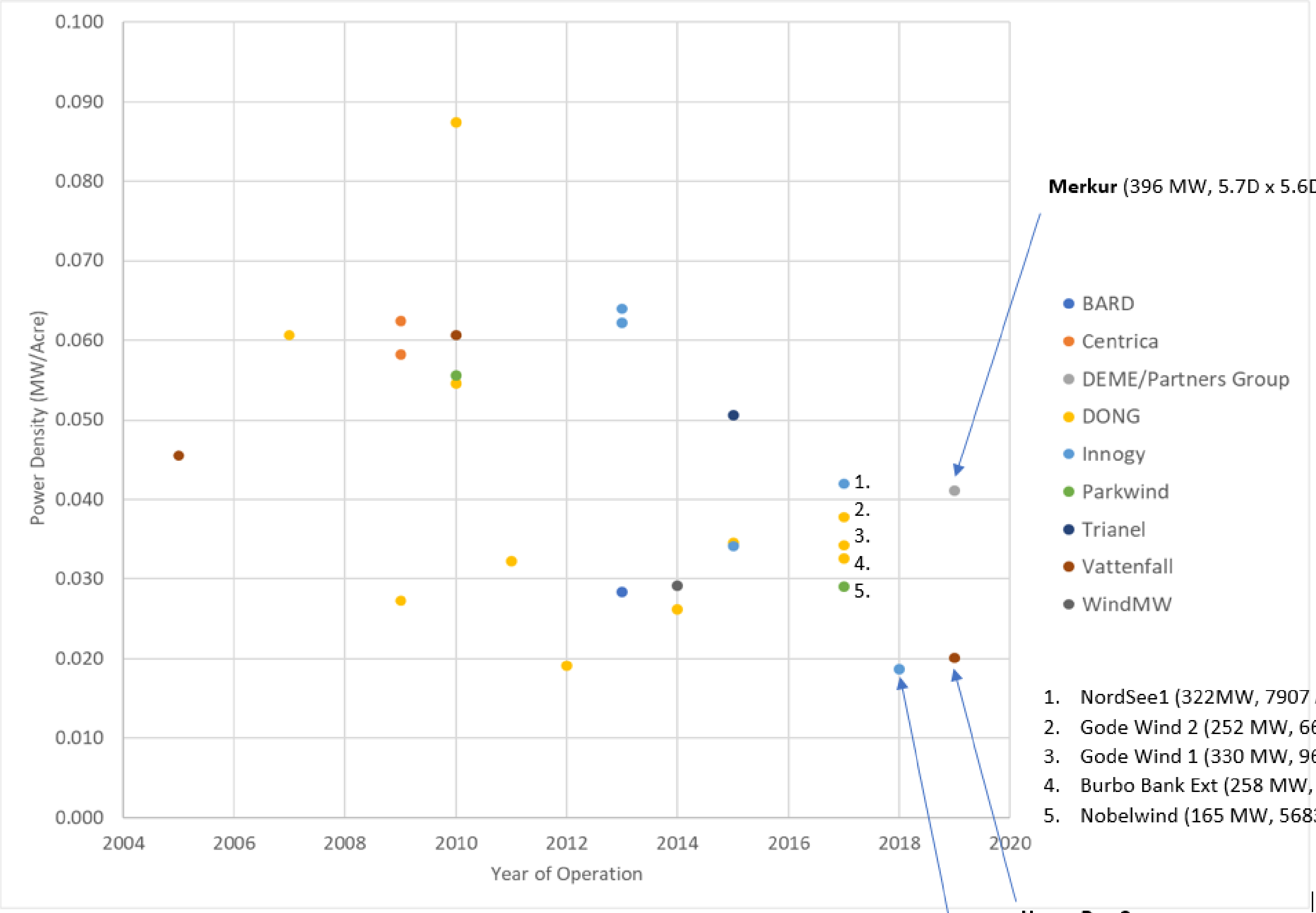
Walney 2

(184 MW, 6.6D x 6.7D)

Galloper
(operational 2018,
7D x 7D, 336MW)

Horns Rev 3
(operational 2019,
10D x 7D, 406MW)

Power density as a function of year of operation, with names of newest OWFs added.



Merkur (396 MW, 5.7D x 5.6D)

1. NordSee1 (322MW, 7907 Acres, 6.7D)
2. Gode Wind 2 (252 MW, 6672 Acres, 6.5D x 6.5D)
3. Gode Wind 1 (330 MW, 9637 Acres, 7.8D x 7.2D)
4. Burbo Bank Ext (258 MW, 7907 Acres, 6.4D x 6.3D)
5. Nobelwind (165 MW, 5683 Acres, 5.6D x 5.0D)

Horns Rev 3
(operational 2019, 10D x 7D,
406MW)

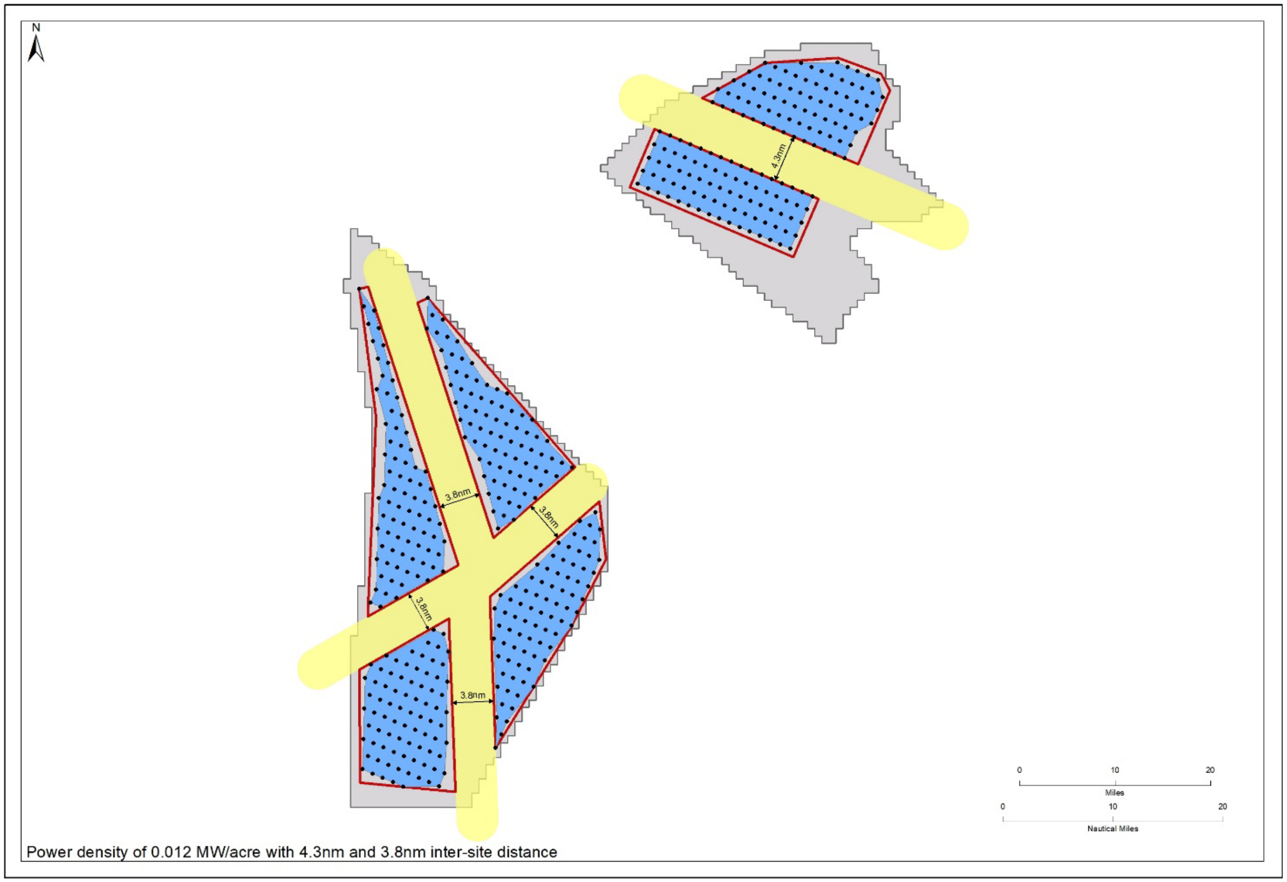
Galloper
(operational 2018, 7D x 7D, 336MW)

Appendix E. Dataset for Inter-Site Distance Review (All Data)

Offshore Wind Farm	Year of 1st Operation	Country	Installed Capacity (MW)	Nearest Upwind Wind Farm	Year of 1st Operation	Installed Capacity (MW)	Distance to nearest WF (nm)	Distance to nearest WF (Rotor Diameters)
Alpha Ventus 1	2010	Germany	30	Merkur Offshore	2019*	396	0.5	6.0
BARD Offshore 1	2013	Germany	400	VEJA MATE	2017	402	1.0	12.3
Borkum Riffgrund 1	2015	Germany	308	Borkum West 2.1	2015	200	0.4	5.3
Burbo Bank	2007	UK	90	Burbo Bank Ext	2017	258	0.8	9.1
Dogger bank Teeside B	2032*	UK	1200	Creyke Beck A	2025	1200	2.2	18.3
Gwynt y Mor East	2015	UK	288	Gwynt y Mor West	2015	288	0.5	5.7
Horns Rev 3	2019*	Denmark	407	Horns Rev 2	2009	209	1.3	25.8
Hornsea 3	2029*	UK	2400	Hornsea 2	2024	1800	4.9	51.3
Inner Dowsing	2009	UK	108	Lynn	2009	86	1.3	22.4
Lincs	2013	UK	270	Inner Dowsing	2009	108	0.7	12.1
Merkur Offshore	2019*	Germany	396	Bokrum West 2.1	2015	200	0.4	5.3
Nobelwind (Belwind 2)	2017	Belgium	165	SeaStar	2025	245	0.5	4.8
Nordsee 1	2017	Germany	332	Nordsee 3	2033*	369	0.4	3.7
Nordsee 2	2033*	Germany	295	Nordsee 3	2033*	369	0.9	7.6
Nordsee 3	2033*	Germany	369	Nordsee 1	2017	332	0.5	7.9
Nordsee Ost	2015	Germany	295	Meerwind	2014	288	0.5	8.3
Rodsand 1	2004	Denmark	166	Rodsand 2	2010	207	1.9	37.6
Thornton Bank 2	2013	Belgium	185	Thornton Bank 3	2013/2009	111/30	0.9	13.5
AVERAGE							**1.1**	**14.3**

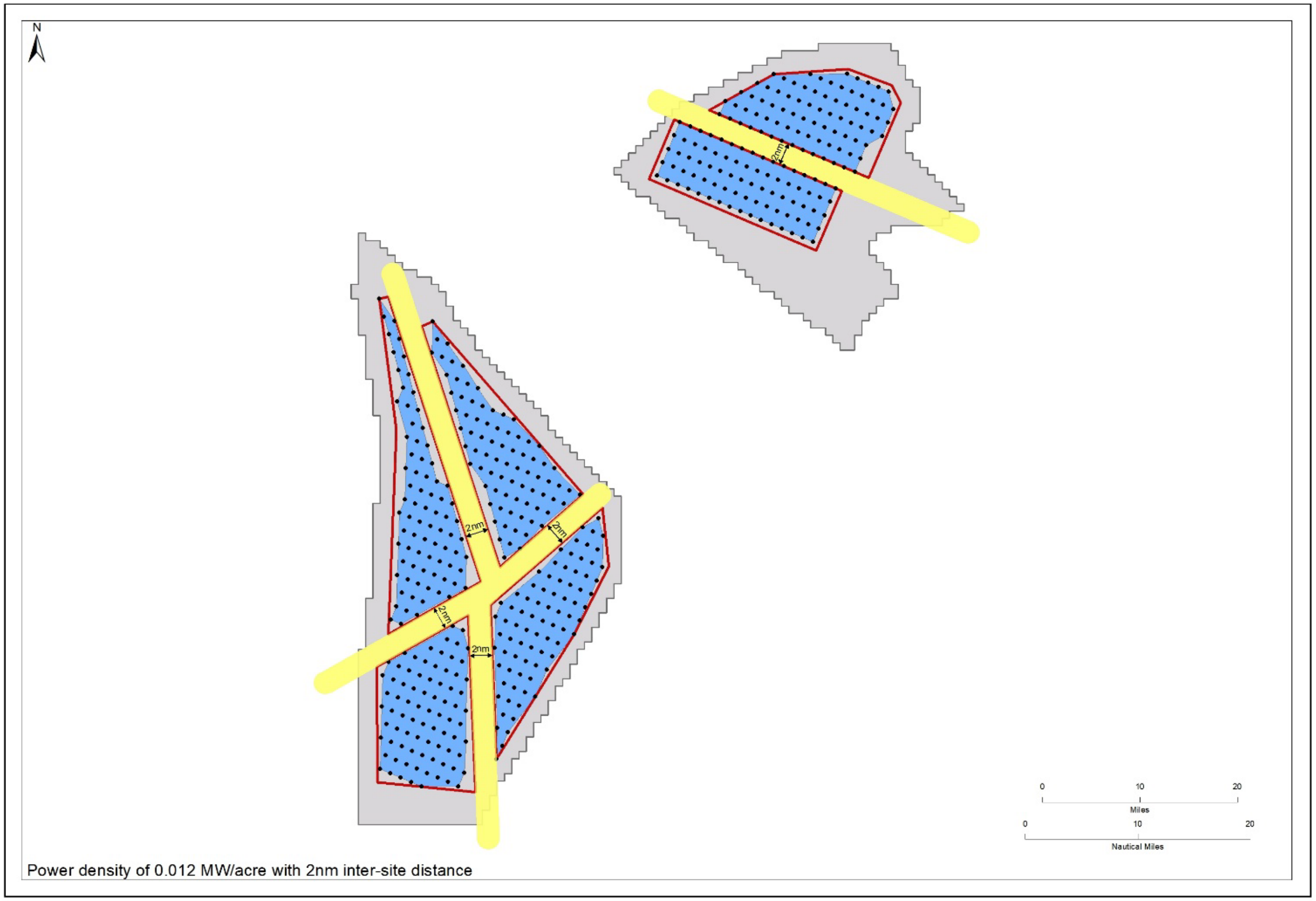
Appendix F. Site Layouts

Scenario 1: 0.01 MM/acre, 4.3 / 3.8 nm inter-site distance.



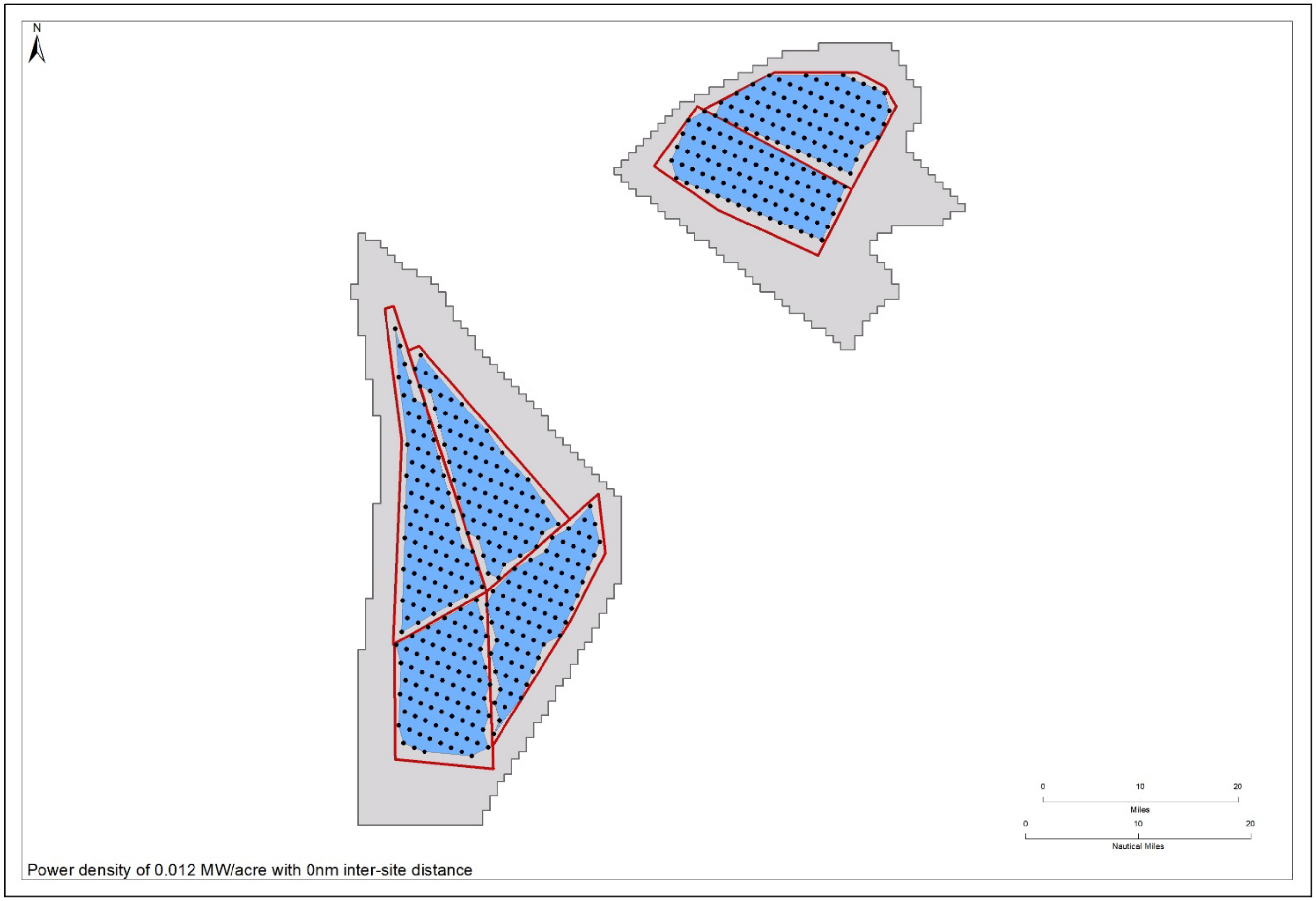
Power density of 0.012 MW/acre with 4.3nm and 3.8nm inter-site distance

Scenario 2: 0.01 MM/acre, 2.0 nm inter-site distance.



Power density of 0.012 MW/acre with 2nm inter-site distance

Scenario 3: 0.01 MM/acre, 0 nm inter-site distance.



Scenario 4: 0.02 MM/acre, 4.3 / 3.8 nm inter-site distance.

Power density of 0.02 MW/acre with 4.3nm and 3.8nm inter-site distance

Scenario 5: 0.02 MM/acre, 2.0 nm inter-site distance.

Power density of 0.02 MW/acre with 2nm inter-site distance

Scenario 6: 0.02 MM/acre, 0 nm inter-site distance.

Scenario 7: 0.04 MM/acre, 4.3 / 3.8 nm inter-site distance.

Power density of 0.04 MW/acre with 3.8nm and 4.3nm inter-site distance

Scenario 8: 0.04 MM/acre, 2.0 nm inter-site distance.

Scenario 9: 0.04 MM/acre, 0 nm inter-site distance.

Appendix G. Wake Analysis Results

("Cumu" = cumulative wakes, from all sites)

	0.01 MW/acre (OLD)								
	4 nm			2 nm			0 nm		
Site	Alone	Cumu	Inc	Alone	Cumu	Inc	Alone	Cumu	Inc
E1	4.00%	5.00%	1.00%	3.75%	5.23%	1.48%	3.91%	6.19%	2.28%
E2	4.30%	6.00%	1.70%	4.11%	6.53%	2.42%	4.17%	8.05%	3.88%
E3	5.00%	5.70%	0.70%	4.71%	5.85%	1.14%	4.73%	6.72%	1.99%
E4	4.70%	6.70%	2.00%	4.41%	7.24%	2.83%	4.50%	8.80%	4.30%
Average	4.50%	5.85%	1.35%	4.25%	6.21%	1.97%	4.33%	7.44%	3.11%
D1	4.50%	5.10%	0.60%	4.39%	5.52%	1.13%	4.38%	5.69%	1.31%
D2	4.90%	5.90%	1.00%	4.61%	6.53%	1.92%	4.61%	6.76%	2.15%
Average	4.70%	5.50%	0.80%	4.50%	6.03%	1.53%	4.50%	6.23%	1.73%

	0.02 MW/acre								
	4 nm			2 nm			0 nm		
Site	Alone	Cumu	Inc	Alone	Cumu	Inc	Alone	Cumu	Inc
E1	5.79%	7.45%	1.66%	5.79%	8.21%	2.42%	5.79%	9.27%	3.48%
E2	5.94%	8.60%	2.66%	5.94%	9.88%	3.94%	5.94%	11.99%	6.05%
E3	6.74%	7.90%	1.16%	6.74%	8.46%	1.72%	6.74%	9.85%	3.11%
E4	6.46%	9.42%	2.96%	6.46%	10.87%	4.41%	6.46%	13.21%	6.75%
Average	6.23%	8.34%	2.11%	6.23%	9.36%	3.12%	6.23%	11.08%	4.85%
D1	6.21%	7.26%	1.05%	6.21%	7.89%	1.68%	6.21%	8.40%	2.19%
D2	6.25%	8.10%	1.85%	6.25%	9.01%	2.76%	6.25%	9.54%	3.29%
Average	6.23%	7.68%	1.45%	6.23%	8.45%	2.22%	6.23%	8.97%	2.74%

Site	0.04 MW/acre								
	4 nm			2 nm			0 nm		
	Alone	Cumu	Inc	Alone	Cumu	Inc	Alone	Cumu	Inc
E1	9.21%	11.51%	2.30%	9.21%	12.68%	3.47%	9.21%	14.55%	5.34%
E2	9.57%	13.18%	3.61%	9.57%	15.18%	5.61%	9.57%	19.12%	9.55%
E3	10.35%	11.93%	1.58%	10.35%	12.74%	2.39%	10.35%	15.18%	4.83%
E4	9.91%	13.93%	4.02%	9.91%	16.04%	6.13%	9.91%	20.54%	10.63%
Average	9.76%	12.64%	2.88%	9.76%	14.16%	4.40%	9.76%	17.35%	7.59%
D1	9.65%	10.96%	1.31%	9.65%	11.84%	2.19%	9.65%	12.90%	3.25%
D2	9.72%	12.10%	2.38%	9.72%	13.35%	3.63%	9.72%	14.70%	4.98%
Average	9.69%	11.53%	1.85%	9.69%	12.60%	2.91%	9.69%	13.80%	4.12%

Appendix H. Additional Layout Data

Power Density (MW/Acre)	Distance Between Sites (NM)	Zone	Site	Mean Depth (MSL)	Closest Distance to NY Shore (NM)	Closest Distance to NJ Shore (NM)
0.01	0	D	D1	-50.18	25	43
0.01	0	D	D2	-52.97	26	46
0.01	0	E	E1	-36.33	38	22
0.01	0	E	E2	-35.80	41	24
0.01	0	E	E3	-41.74	63	29
0.01	0	E	E4	-38.58	57	35
0.01	2	D	D1	-49.72	26	43
0.01	2	D	D2	-53.23	25	47
0.01	2	E	E1	-36.16	37	21
0.01	2	E	E2	-37.98	39	25
0.01	2	E	E3	-43.31	65	29
0.01	2	E	E4	-39.85	58	36
0.01	4.3	D	D1	-49.76	27	42
0.01	4.3	D	D2	-53.10	25	48
0.01	3.8	E	E1	-35.92	36	20
0.01	3.8	E	E2	-39.34	37	25
0.01	3.8	E	E3	-44.23	67	29
0.01	3.8	E	E4	-40.98	58	37
0.02	0	D	D1	-50.49	27	46
0.02	0	D	D2	-52.49	25	47
0.02	0	E	E1	-36.92	47	26
0.02	0	E	E2	-34.99	47	27
0.02	0	E	E3	-39.31	64	31
0.02	0	E	E4	-36.69	58	35
0.02	2	D	D1	-50.34	28	46

0.02	2	D	D2	-52.86	24	48
0.02	2	E	E1	-37.02	47	25
0.02	2	E	E2	-36.32	46	28
0.02	2	E	E3	-42.32	65	30
0.02	2	E	E4	-37.73	60	36
0.02	4.3	D	D1	-50.41	29	46
0.02	4.3	D	D2	-52.79	24	49
0.02	3.8	E	E1	-37.08	46	24
0.02	3.8	E	E2	-37.78	43	28
0.02	3.8	E	E3	-44.21	67	30
0.02	3.8	E	E4	-38.96	60	37
0.04	0	D	D1	-50.32	28	47
0.04	0	D	D2	-52.04	26	48
0.04	0	E	E1	-35.26	53	29
0.04	0	E	E2	-34.86	53	29
0.04	0	E	E3	-35.96	63	32
0.04	0	E	E4	-35.63	60	35
0.04	2	D	D1	-50.17	29	48
0.04	2	D	D2	-52.07	25	49
0.04	2	E	E1	-35.55	52	28
0.04	2	E	E2	-35.62	51	30
0.04	2	E	E3	-38.97	65	32
0.04	2	E	E4	-35.90	61	36
0.04	4.3	D	D1	-49.64	29	47
0.04	4.3	D	D2	-51.54	24	49
0.04	3.8	E	E1	-37.08	51	27
0.04	3.8	E	E2	-36.50	49	31
0.04	3.8	E	E3	-42.25	67	31
0.04	3.8	E	E4	-36.04	62	37

Endnotes

[1] The prevailing wind direction was assumed to be southwesterly, based on data from a number of offshore met masts that are publicly available on the Marine Data Exchange.

[2] NYSERDA (2017). New York State Offshore Wind Master Plan. Shipping and Navigation Study. Report 17-25q. Prepared by: The Renewables Consulting Group LLC. New York.

[3] USCG Marine Planning Guidelines.

[4] http://orbit.dtu.dk/files/6354851/ris-r-1772.pdf

http://orbit.dtu.dk/files/118472784/DTU_Wind_Energy_E_0046.pdf

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