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Image of an offshore wind farm

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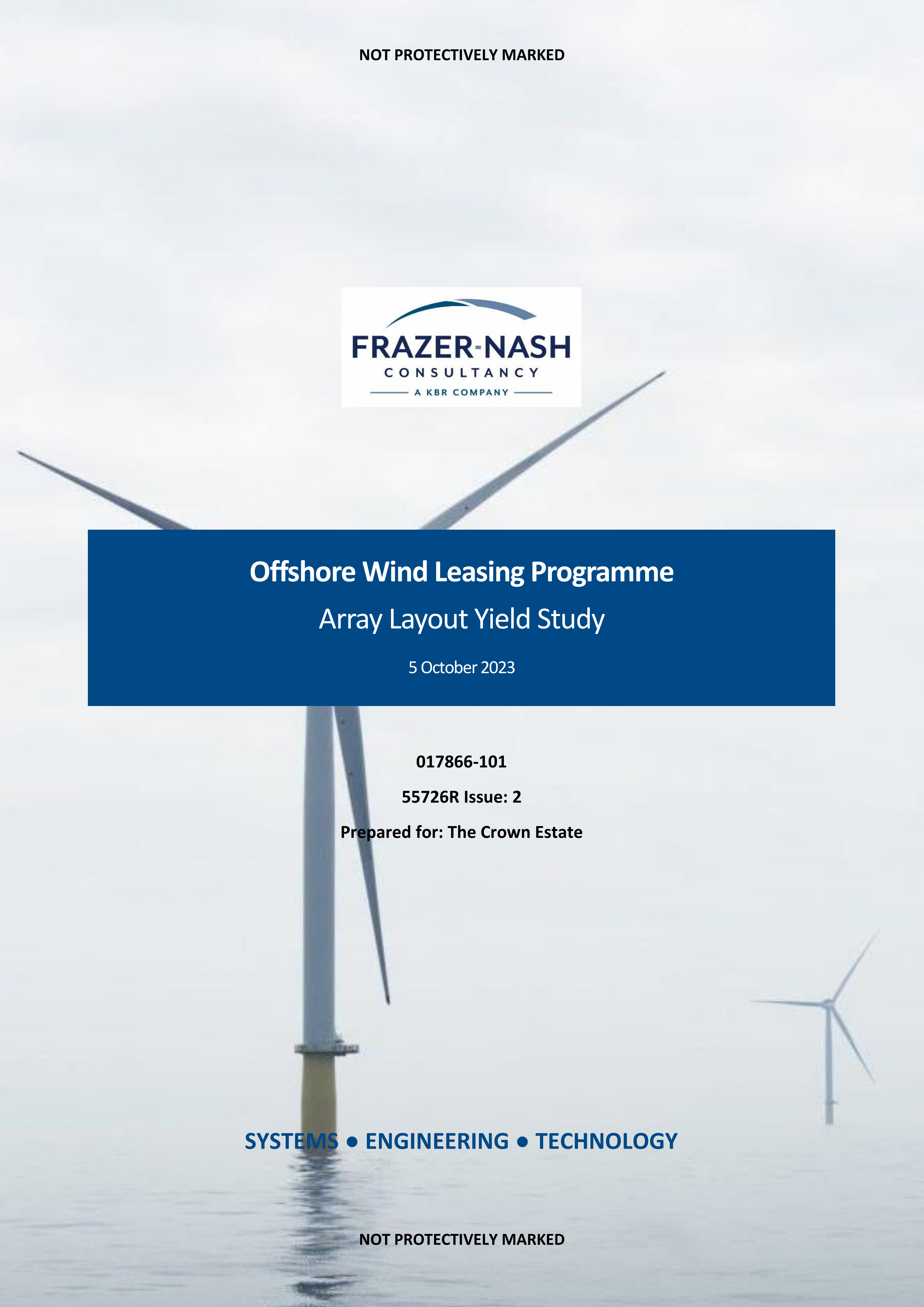
Mona Offshore Wind Ltd.

Prepared for:

Mona Offshore Wind Ltd.



FRAZER-NASH CONSULTANCY
A KBR COMPANY

Offshore Wind Leasing Programme

Array Layout Yield Study

5 October 2023

017866-101

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Prepared for: The Crown Estate

SYSTEMS • ENGINEERING • TECHNOLOGY

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Originating Office: FRAZER-NASH CONSULTANCY LIMITED
Hill Park South, KBR Campus, Springfield Drive, Leatherhead, Surrey, KT22 7LH

Contents

1 Introduction

1.1 Background

The Crown Estate (TCE) is responsible for leasing the seabed for a range of activities including the construction and operation of offshore wind farms. To help optimise the use of the seabed, TCE wishes to designate offshore wind project development areas (PDAs) to maximise the energy production from the portfolio of existing and future wind farms, whilst balancing environmental and other requirements. To better understand how portfolio offshore wind farm production varies with PDA design, TCE have commissioned Frazer-Nash to assess wakes and blockage production losses for a number of generic wind farm configurations.

1.2 Objectives

Previous studies using standard engineering wake models (such as PARK2) have identified a number of key PDA design parameters which influence portfolio wind farm production. The objective of this present study is to provide generic evidence to support TCE's design of future offshore wind leasing programmes from an aerodynamic loss perspective. Specifically, the influence of key PDA design parameters on wind farm production are assessed using an updated engineering wake model with more realistic accounting of farm-to-farm wake and farm blockage effects.

The modelling results in this report are relevant to:

- Build-out density – the spacing between adjacent wind turbines within a single wind farm.
- Buffer distance – the spacing between neighbouring wind farms
- Seabed efficiency – the distribution of wind farms within a fixed seabed area, including the impact of introducing separation between projects whilst reducing their developable area.

2 Methodology

This section discusses the inputs and approach to the assessment. The wind farm layouts modelled in each of the build-out density, separation distance, and seabed efficiency studies are discussed in Section 2.1. The wakes and blockage models are described in Section 2.2. The input wind resource is treated in Section 2.3 and turbine attributes are discussed in Section 2.4.

2.1 Wind Farm Layouts

The influences of build-out density, buffer distance between projects, and seabed utilisation were examined by assessing the 21 individual configurations summarised in Table 1. In each study, a 1 GW wind farm comprised of a 7 x 7 array of 20.4 MW turbines is used as a basis. The wind farm layouts considered for each sensitivity are discussed further in Sections 2.1.1 – 2.1.3.

Table 1: Wind farm configurations assessed.

Sensitivity	Run #	Layout	Spacing between wind farms (km)	Build-out Density (MW/km^2)
Build-out Density	1	A single square orthogonal 1GW array	n/a	3
	2			4
	3			5
	4			6
	5			7
	6			8
Buffer	7	A and B square orthogonal 1GW arrays separated along northing direction	2.0	6
	8		3.0	
	9		4.0	
	10		5.0	
	11		7.5	
	12		10	
	13		15	
	14		20	
Seabed efficiency	15	Fixed seabed area and seabed aspect ratio. Varying wind farm aspect ratio.	5.269	4.36
	16		7.904	4.80
	17		10.539	5.33
	18	Fixed seabed area and wind farm aspect ratio. Varying seabed aspect ratio.	2.635	4
	19		10.015	5
	20		16.134	6
	21		21.410	7

2.1.1 Build-out Density

Increases in wake loss with decreasing turbine spacing are well understood using conventional wake models. In this study, to revisit this question considering more recent developments in these methods, a single 1 GW wind farm is modelled in isolation for typical build-out densities in the range of 3 to 8 MW/km^2. As shown in Figure 1 and Figure 2, this was achieved by varying the turbine spacing uniformly in both Northing and Easting directions between 10.9 and 6.7 rotor diameters, respectively. Density values throughout this report are based on the area enclosed by the square perimeter of the wind turbine locations.

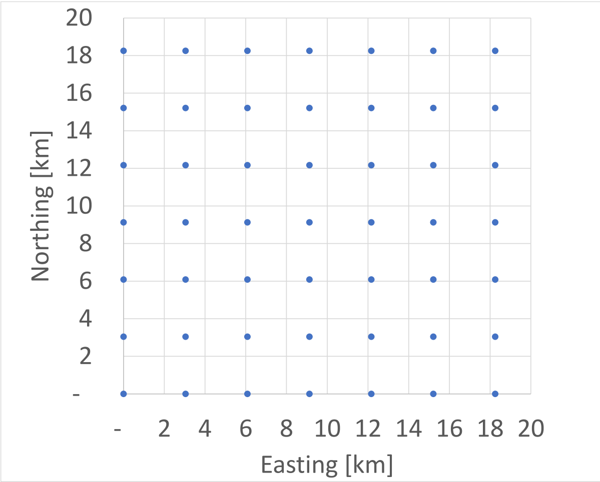

Figure 1: Wind farm layout with 3 MW/km^2 build-out density (run ID 1).

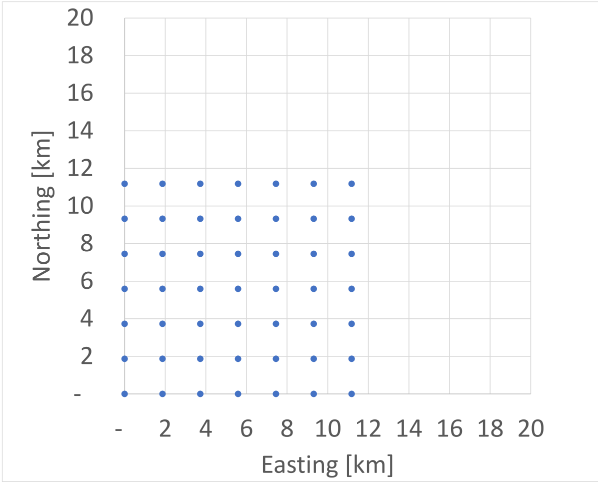

Figure 2: Modelled wind farm layout with 8 MW/km^2 build-out density (run ID 6).

2.1.2 Buffer Distance

To examine the sensitivity of farm-to-farm wake loss to separation distance between wind farms, two 1 GW wind farms of 6 MW/km^2 build-out density were modelled with a separation between 2 and 20km as shown in Figure 3 and Figure 4, respectively. Turbine spacing is measured between the nearest turbine rows of the respective wind farms and the farms are spaced along the North – South axis. The case with 2km turbine spacing (run ID 7) is equivalent to a single contiguous 2GW wind farm (for a build-out density of 6 MW/km^2).

It is expected that the absolute production of this configuration of wind farms would depend, to an extent, on the alignment of the wind farms with respect to the prevailing wind direction. However, different layout orientations are not considered in this study as the separation distance rather than direction is expected to be dominant.

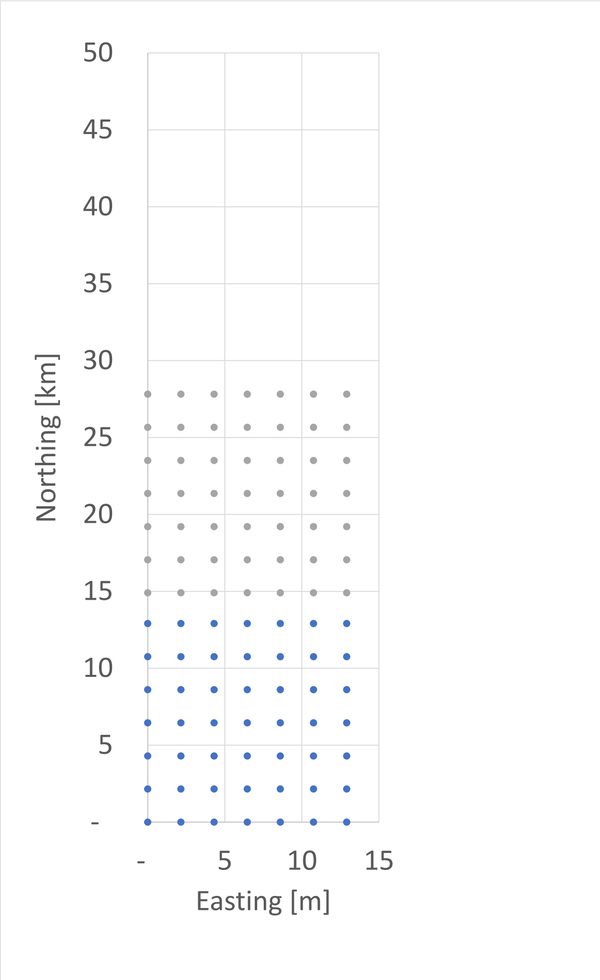

Figure 3: Wind farm layout with 6 MW/km² and 2 km spacing between wind farms (run ID 7).

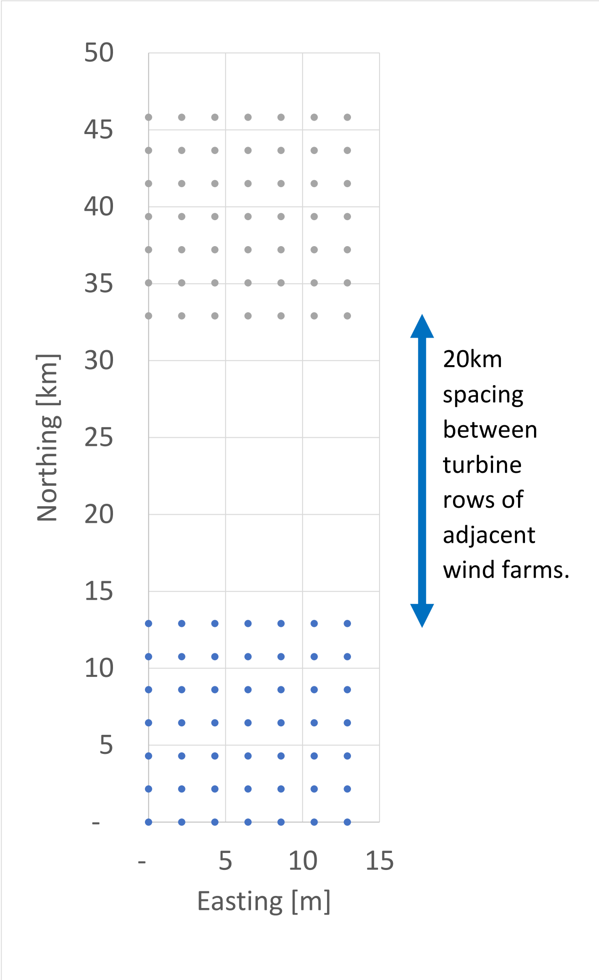

Figure 4: Wind farm layout with 6 MW/km² and 20 km spacing between wind farms (run ID 14).

2.1.3 Seabed Efficiency

The purpose of this study is to examine whether there is any net benefit or penalty in production from introducing a buffer separation between two projects that are constrained within a fixed seabed area. The seabed area modelled in this study is approximately 34.3km (North-South) by 15.8km (East-West) in extent.

On one hand, introducing a buffer distance reduces any farm-to-farm interaction losses. However, due to the fixed seabed area, introducing such a buffer requires an increase in density for each individual farm which carries the penalty of increased internal wake loss. Two different approaches were taken to investigate the net result of these effects recognising the strengths and drawbacks of each:

- In the first approach (run ID 15 – 17), shown in Figure 5 and Figure 6, both seabed dimensions and area were preserved. This required varying the wind farm aspect ratio as buffer area was increased and resulted in wind turbine layouts of anisotropic spacing, thereby increasing potential dependency on wind resource directionality.
- In the second approach (run ID 18 – 21), shown in Figure 7 and Figure 8, seabed aspect ratio is allowed to vary and farm build-out density is varied such that the farms occupy the full width of seabed, as shown in Figure 7 and Figure 8. Whilst not considering a seabed of fixed dimensions, this approach maintains isotropic spacing and limits any potential dependency on wind resource directionality.

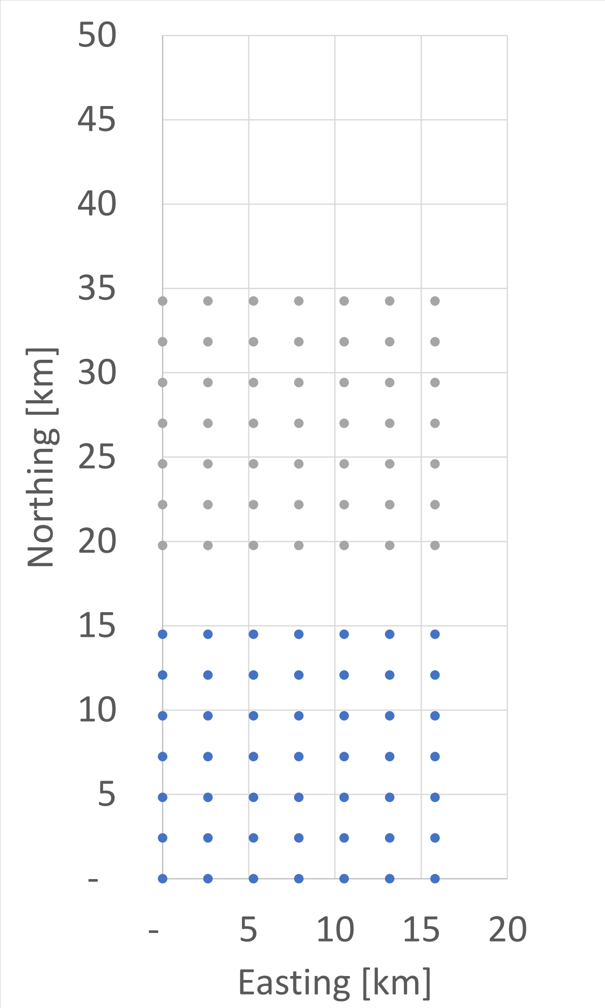

Figure 5: Layout with 4 .36 MW/km^2 build-out density (for each farm) and 5.269 km spacing within a fixed seabed area (run ID 15).

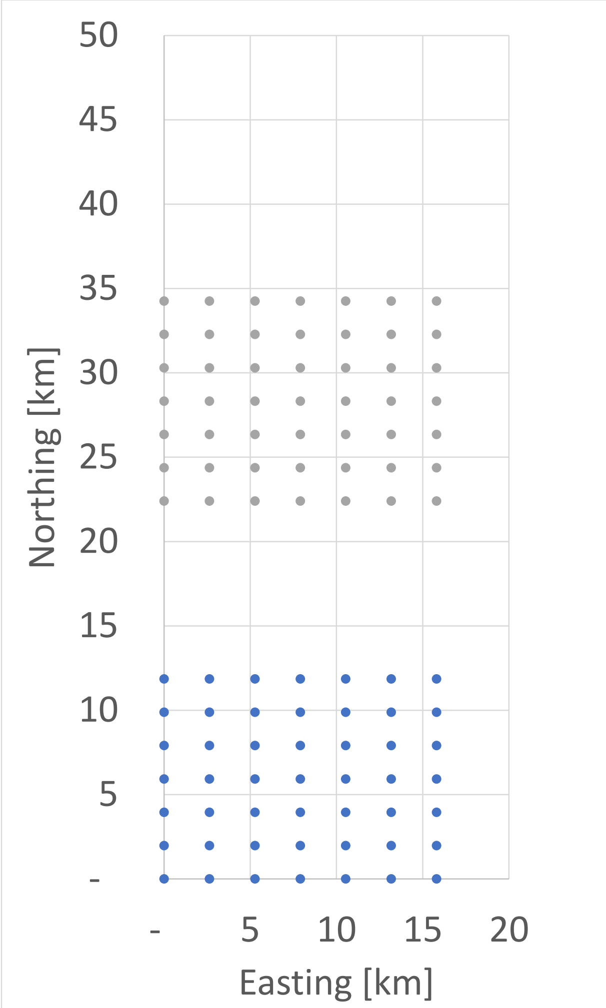

Figure 6: Layout with 5.33 MW/km^2 build-out density (for each farm) and 10.539 km spacing within a fixed seabed area (run ID 17).

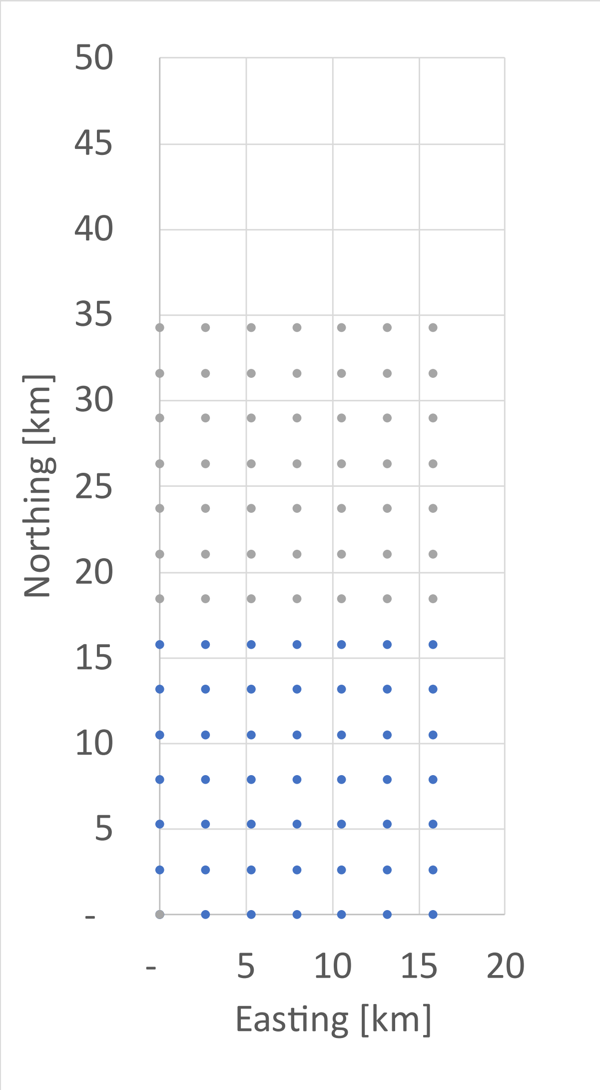

Figure 7: Layout with 4 MW/km² build-out density (for each farm) and 2.635 km spacing between farms (run ID 18).

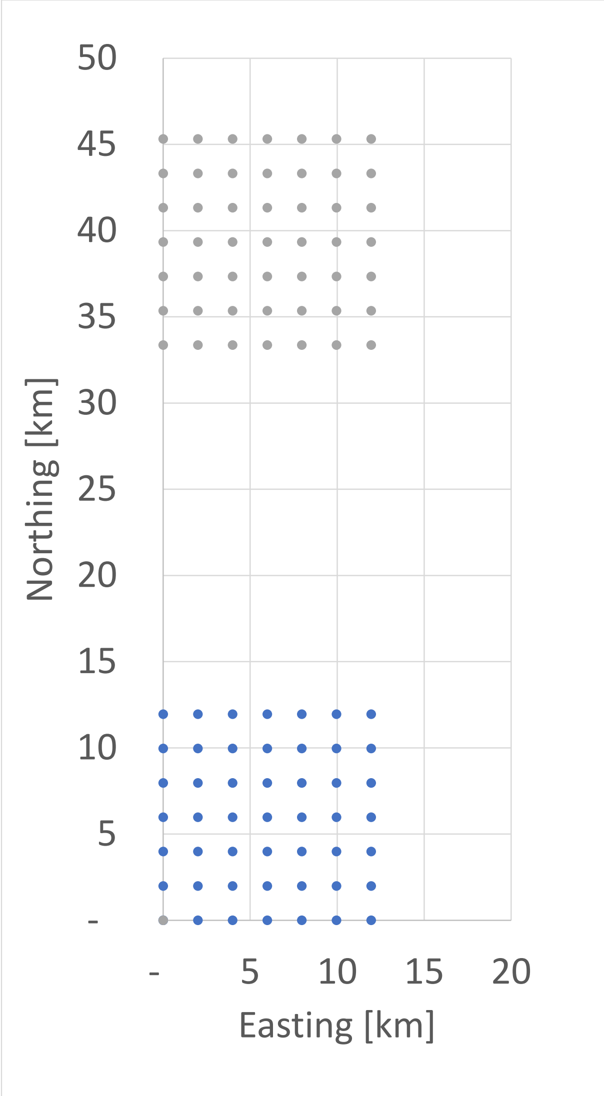

Figure 8: Layout with 7 MW/km² build-out density (for each farm) and 21.410 km spacing between farms (run ID 21).

2.2 Wakes and Blockage Models

The aerodynamic losses were modelled for each wind farm configuration using a Turbulence Optimized Park (TurbOPark) wake model with gaussian deficit profile coupled to the Rankine Half Body with Wake expansion (RHBW) blockage model [1]. Ørsted developed the TurbOPark model and have shown evidence from their own portfolio of offshore wind production data that the method reproduces long range wakes well up to 50km separation [2, 3].

The TurbOPark model was developed and tuned to capture farm-to-farm wake effects as well as internal wakes from the outset. Other wake models have historically been tuned to capture internal wakes only and there is some evidence to suggest that these may under-estimate farm-to-farm wake losses. Although the evidence base is still evolving, TurbOPark is considered to be the most trusted engineering model for farm-to-farm interaction effects on the scales of interest at present.

For the purposes of this study, the TurbOPark model was implemented in version 2.4.0 of the PyWake Python package to replicate the implementation proposed by Ørsted as closely as practicably possible.

2.3 Wind Resource

This section describes the input wind resource data, including the approach taken to sourcing and pre-processing this.

The input wind resource to this study was based on a statistical distribution of wind speeds, wind directions and turbulence data:

- The probability distribution of wind speed and wind direction is illustrated in Figure 9 and Figure 10. This was based on 30-year hindcast model data from the Met Office at a single point in space 110m above sea level [4]. This distribution is typical of a location in UK waters with relatively high mean wind speed and was assumed to apply across all of the modelled domain.
- The wind speed and direction distributions were vertically extrapolated to the requisite hub height using the shear factors shown in Table 2. These were derived for each of the 12 wind direction bins using Equation 1 and mesoscale time-series data from the New European Wind Atlas (NEWA). The mesoscale data was sampled at 100 and 150m above sea level for a 13-year period [5].

Equation 1 Wind Shear Equation.

$$\alpha = \log\left(\frac{v_{150}}{v_{100}}\right) / \log\left(\frac{150}{100}\right)$$

Where α is the power law shear exponent, and v_{100}, v_{150} are the wind speeds at heights of 100m and 150m above sea level, respectively.

Table 2 Shear factors derived from NEWA mesoscale data.

Wind Direction Bin Centre [°]	Shear Factor (-)
0	0.033
30	0.035
60	0.045
90	0.070
120	0.071
150	0.097
180	0.093
210	0.092
240	0.079
270	0.063
300	0.040
330	0.031

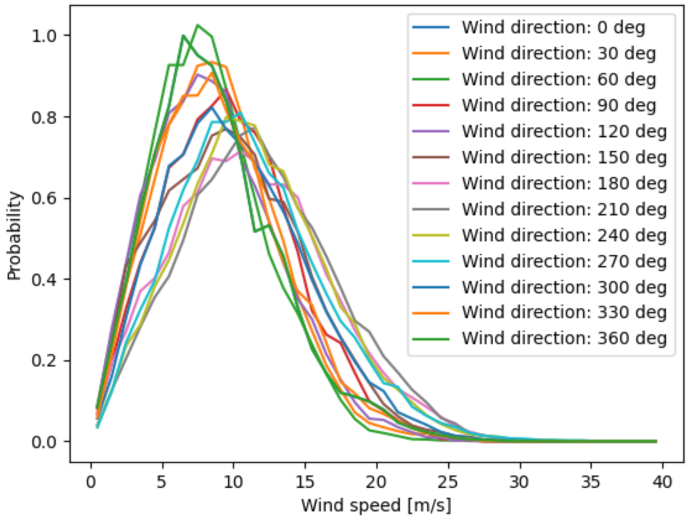

Figure 9 Annual distribution of wind speeds at 110m above mean sea level (AMSL).

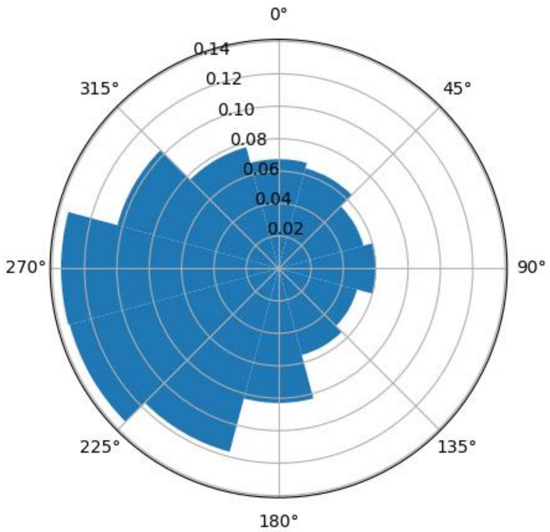

Figure 10 Annual distribution of wind directions at 110m AMSL.

The wake expansion in the TurbOPark model is explicitly dependent on ambient turbulence intensity (TI). The approach taken to obtaining and processing ambient TI data is as follows:

- An average TI of 6.5% at a height of 87m was assumed based on measurement data at 8 different locations over a range of UK waters [6]. The distribution of TI was assumed to apply across all of the modelled domain.
- The turbulence data was scaled to the requisite turbine hub height assuming the standard deviation of wind speed is invariant with height. This assumption is supported by experimental measurements [7] and results in the scaling shown in Equation 2 that is dependent on source height (x), target height (y) and shear factor (γ). This equation is used with the shear factors calculated previously (shown in Table 2) to scale ambient TI to the requisite hub height.

Equation 2 Turbulence intensity.

$$TI\ (y) = \frac{U(x)}{U(y)} TI(x) = TI\ (x) \cdot \left[\frac{y}{x}\right]^{-\gamma}$$

2.4 Turbine parameters

This section describes turbine power curves, thrust curves and dimensions modelled in this study.

The **turbine power curve** used in this study is shown in Figure 11. This is based on the standard IEA 15MW turbine power curve with the following modifications applied:

- Power is scaled linearly to a rated value of 20.4MW as required to construct a 1 GW theoretical array.
- Smoothing around the knee of the power curve was applied to represent real-world turbulence effects.
- A High Wind Ride Through (HWRT) region was added between 25 and 30m/s reference wind speeds as is typical of modern turbine designs.

The turbine **thrust coefficient curve** used in this study is shown in Figure 12 and is also based on the standard IEA 15MW turbine. This was modified to:

- Limit peak thrust (around 10 m/s) similar to real-world controller behaviour.
- Extend turbine operation through the added HWRT region.

A **rotor diameter** of 279.9m was modelled in this assessment. This was obtained by assuming a constant power per unit rotor area equal to that of the standard IEA 15MW turbine. This approach assumes the efficiency of a turbine does not depend on the turbine rotor diameter.

A **hub height** of 169.9m was modelled in this assessment. This was scaled to preserve a minimum 30m gap between blade tip and sea surface.

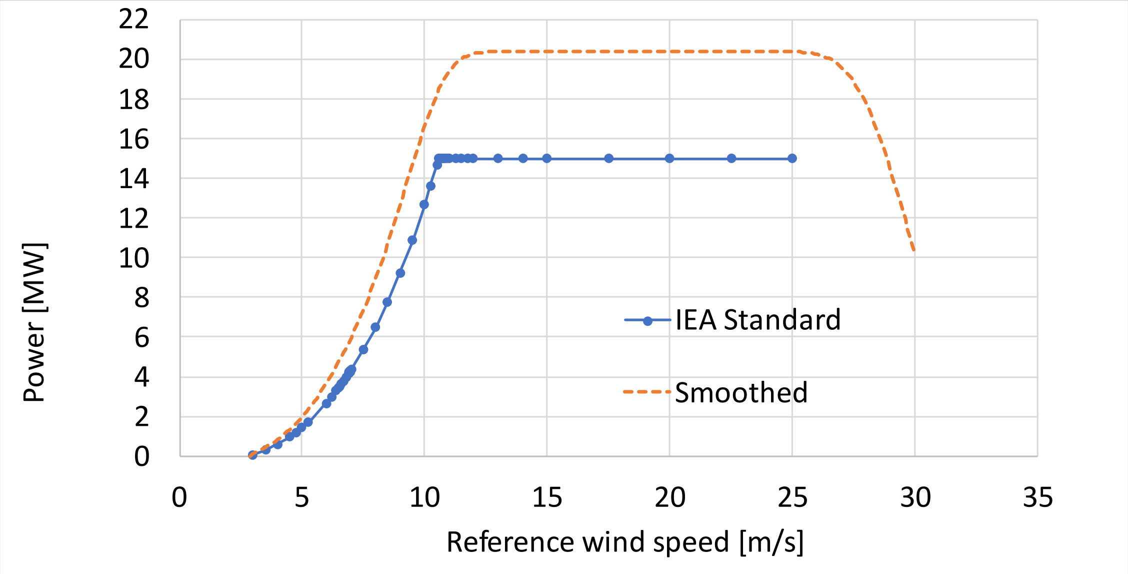

Figure 11 – Modified power curve used in this assessment (orange) and the IEA standard turbine power curve upon which this is based (blue).

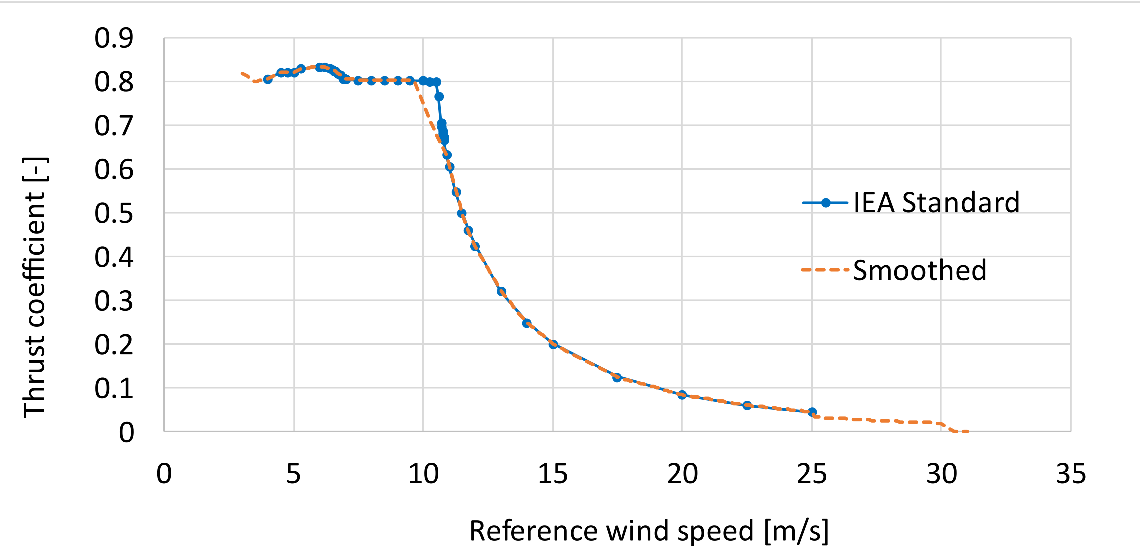

Figure 12 Modified thrust coefficient curve used in this assessment (orange) and the IEA standard turbine thrust coefficient curve upon which this is based (blue).

3 Results and Discussion

This section discusses the metrics of assessment (Section 3.1) as well as the results of each of the studies on build-out density (Section 3.2), buffer distance and seabed efficiency (Section 3.3).

3.1 Metrics

Results throughout this section are presented in terms of the following metrics where appropriate:

- **Gross Annual Energy Production (AEP).** This is defined as the production of the wind farms based on the input wind resource and excluding any aerodynamic losses.
- **Net aerodynamic AEP.** This is defined as the gross AEP minus any losses from wakes or blockage aerodynamic effects and is expressed in GWh.
- **Total interaction loss**. This is the sum of all losses due to internal wakes, farm-to-farm wakes, and blockage expressed as a percentage of gross AEP.
- **Farm-to-farm wake loss**. This is defined as the difference in production between a wind farm operating in isolation and when operating with a neighbouring wind farm present.
- **Internal wakes and blockage loss**. This is defined as the difference between gross and net production when the wind farm is operating in isolation.

The results are typically presented on a portfolio basis considering the AEP and losses of the system of wind farms in each scenario.

3.2 Build-out Density

The results for the build-out density sensitivity study are shown in terms of:

- Net aerodynamic AEP in Figure 13, and;
- Compared to previous results generated by Frazer-Nash using the PARK 2 wakes-only model in terms of total interactions loss in Figure 14.

The results metrics above are defined in Section 3.1.

These key findings from these results are:

- Build-out density or turbine spacing within wind farms is a strong driver of internal wake loss. Results from the TurbOPark model indicate that increasing build-out density from 3 MW/km^2 (10.9 rotor diameter spacing) to 8 MW/km^2 (6.7 rotor diameter spacing) results in a 4% increase in total turbine interaction loss.
- Results from the previous study show a similar scaling of interaction loss with build-out density but with different magnitudes. This is likely due to the different methods employed as well as different rotor diameter, thrust and power curves.

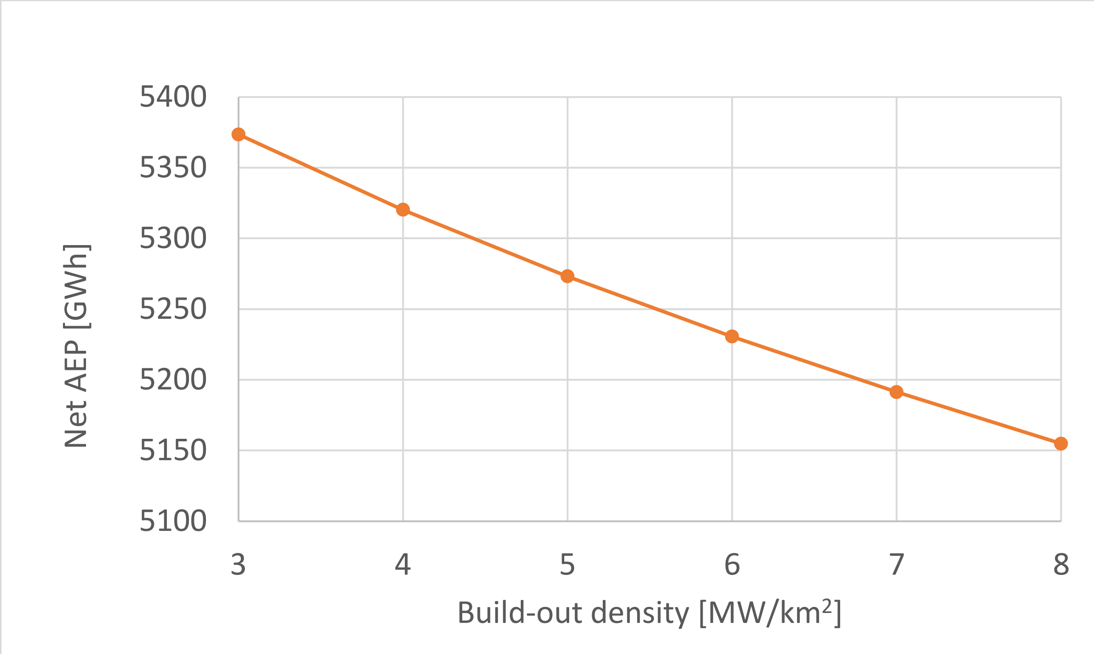

Figure 13: Net aerodynamic AEP variations with build-out density from the coupled TurbOPark model.

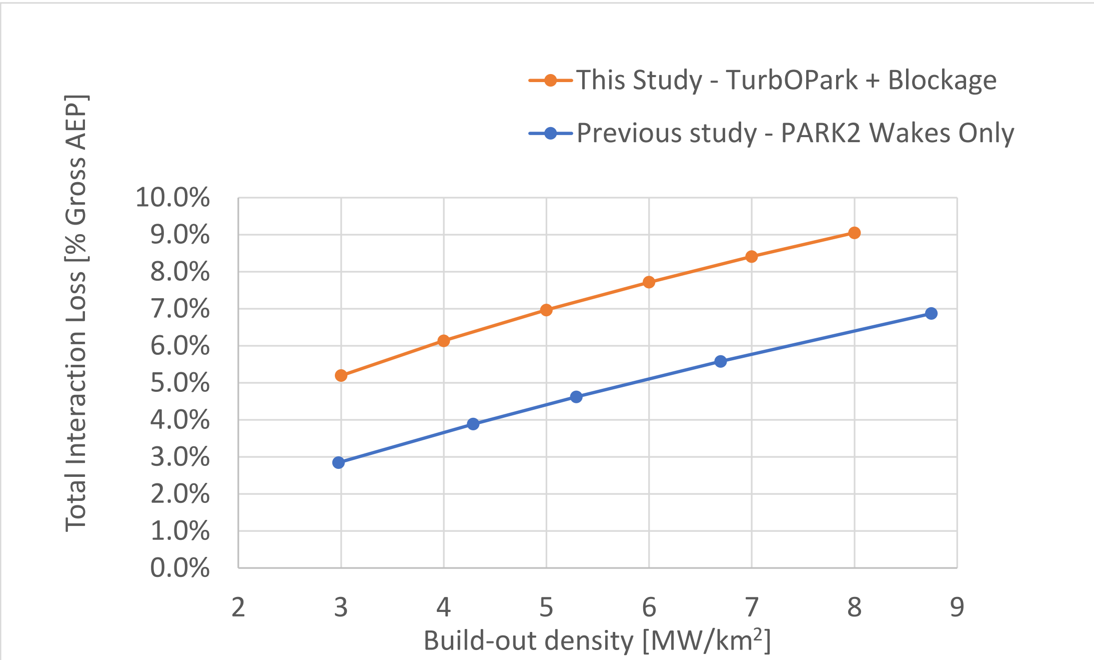

Figure 14: Comparison of total interaction loss variations with build-out density from the coupled TurbOPark model (this study) and the PARK2 wake model (previous study).

3.3 Buffer Distance and Seabed Efficiency

The results for the buffer distance and seabed efficiency studies sensitivity are compared in terms of:

- Portfolio net aerodynamic AEP in Figure 15.
- Total interaction loss in Figure 16.
- Farm-to-farm wake loss in Figure 17.
- Internal wake and blockage loss in Figure 18.

The results metrics above are defined in Section 3.1.

The key findings from these results are:

- Portfolio production increases with buffer distance between wind farms when seabed area is not fixed. This result is expected as farm-to-farm wake losses reduce with increasing buffer distance.
- Beyond approximately 10km separation between wind farms, the TurbOPark model indicates a levelling off of total interaction loss with buffer distance. For separations much larger than 20km, farm-to-farm wake losses will become vanishingly small, and the total interaction loss is expected to asymptote towards the single farm result of 7.7% reported for the 6 MW/km^2 layout in Figure 14.
- The farm-to-farm wake loss results in Figure 17 are between 2.0% and 0.5% of gross portfolio AEP for 2 and 20 km separations, respectively. For even the smallest separations between wind farms (2km or one turbine spacing) farm-to-farm wake loss remains small (2.0% in this case) compared to the loss due to internal wakes and blockage (7.7% in this case).
- However, in typical situations, environmental and other constraints are likely to limit the seabed area available for offshore wind farm usage. Constraining both 1 GW wind farms within a seabed of fixed area (approximately 542 km^2), the TurbOPark model indicates the highest portfolio production is achieved when no buffer is introduced.
- In the case of a constrained seabed, the penalty in production from introducing a buffer is a result of two competing effects: the potential gain in production associated with increased separation and reduced farm-to-farm wakes is outweighed by the penalty associated with reducing turbine spacing. This is shown by comparing the relatively modest decrease in farm-to-farm wakes losses with separation distance in Figure 17 against the sharper rate of increase in internal wake and blockage losses shown in Figure 18 driven by reductions in turbine spacing. This result is the case across both approaches for seabed efficiency considered and consistent with prior modelling assessments performed by Frazer-Nash.
- It is worth noting that the penalty in portfolio production from introducing a buffer in a fixed seabed area remains small for small buffer separations. As shown in Figure 16, this amounts to a decrease of approximately 0.1% in portfolio production when considering buffer separations in the range of 2.6 km (one turbine spacing) to 10.0 km. In this particular case, the TurbOPark model results indicate the increase in internal wake and blockage loss is almost outweighed by the decrease in farm-to-farm wake loss. This finding suggests that introducing buffer separations between projects can be considered alongside a fixed seabed area to satisfy other constraints in the PDA-designation process, but keeping buffers small would avoid introducing excessive aerodynamic loss penalties.

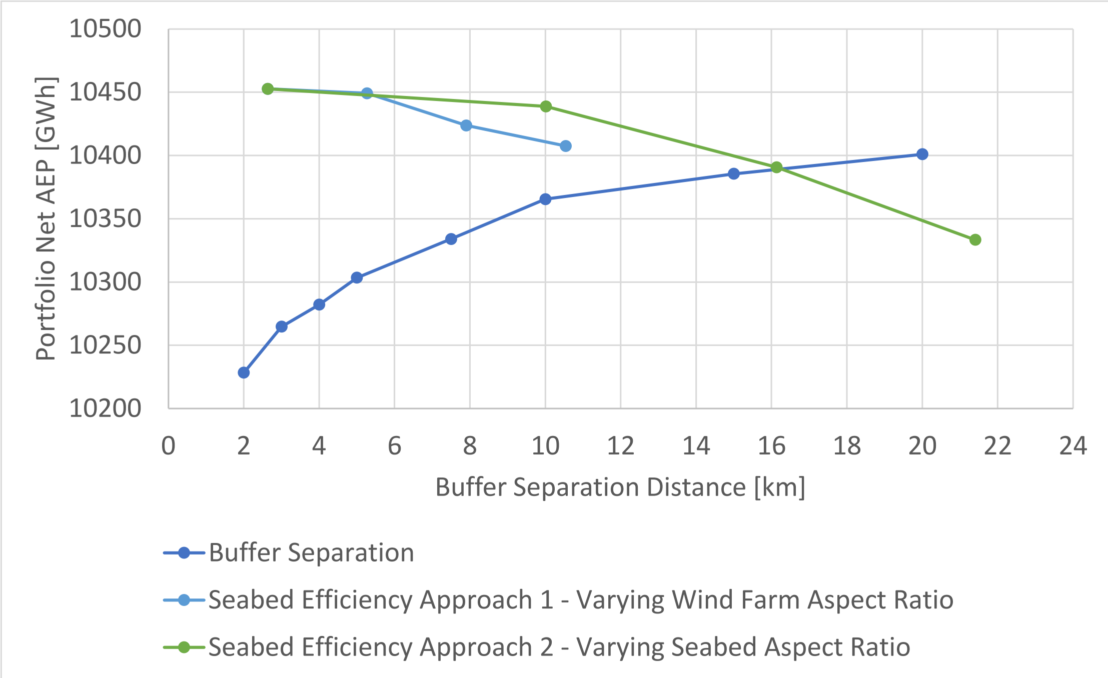

Figure 15: Variation of portfolio net aerodynamic AEP (total production) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).

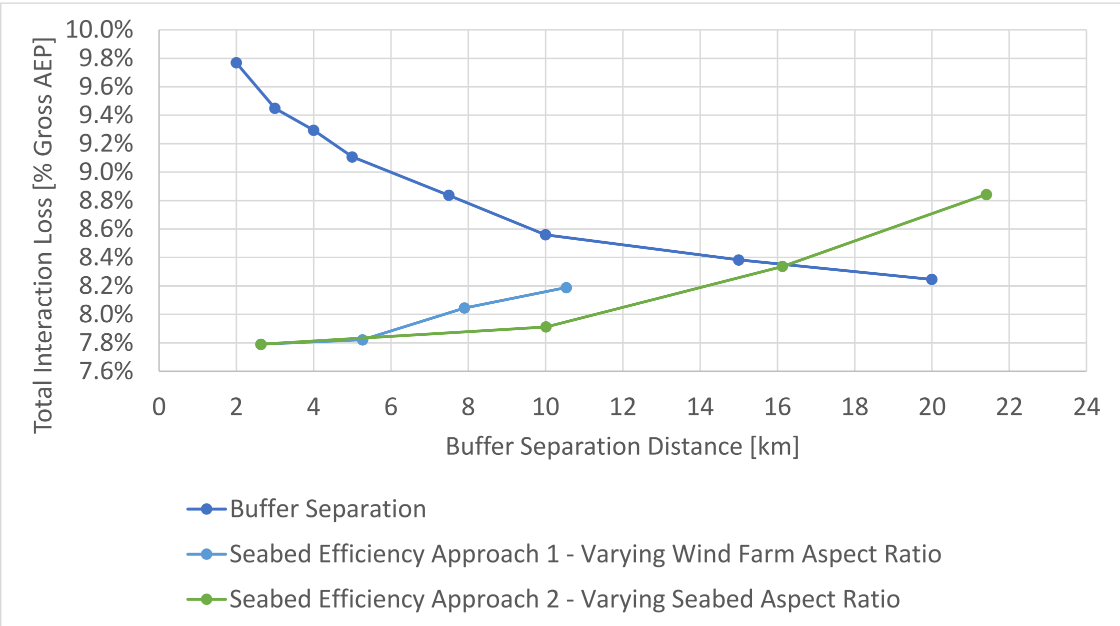

Figure 16: Variation of portfolio total interaction loss (portfolio loss as a percentage of portfolio gross AEP) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).

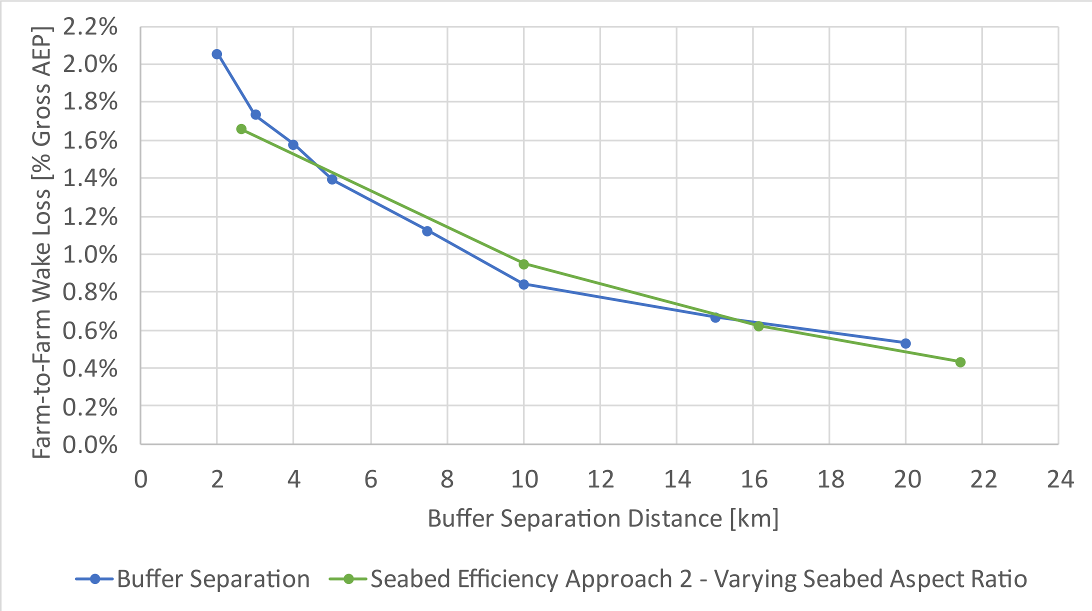

Figure 17: Variation of farm-to-farm wake loss (as a percentage of gross AEP) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).

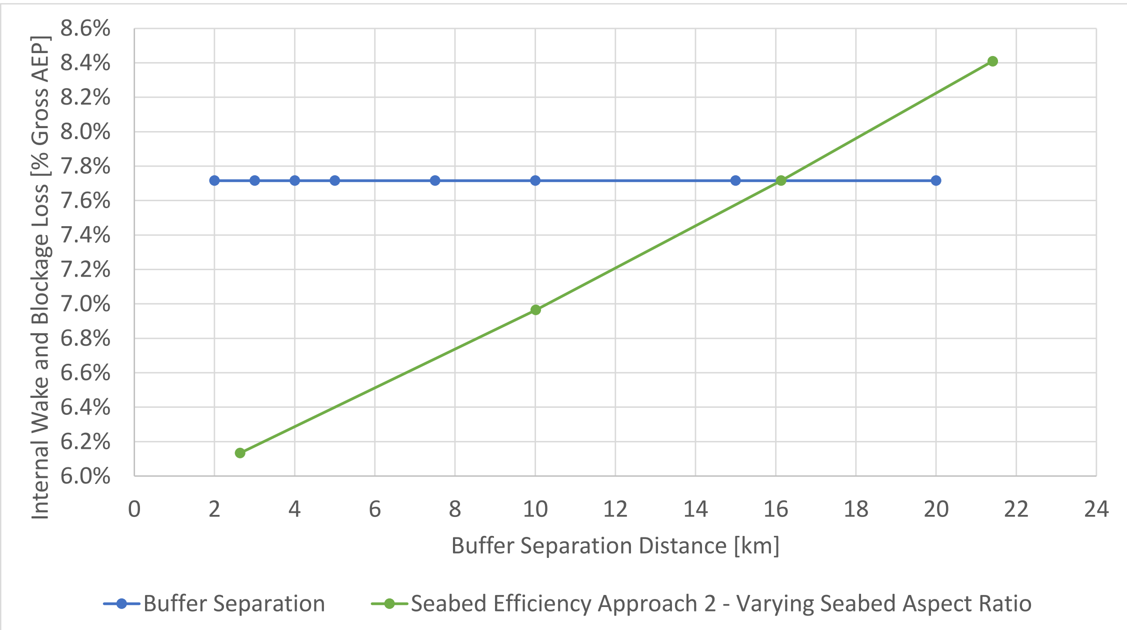

Figure 18: Variation of internal wake and blockage loss (as a percentage of gross AEP) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).

4 Conclusions

The Crown Estate (TCE) is responsible for leasing the seabed for a range of activities including the construction and operation of offshore wind farms. To help design future offshore wind project development areas (PDAs) which maximise the potential for energy production, TCE has commissioned Frazer-Nash to assess the impact on yield of several PDA design parameters.

The production of hypothetical 1 GW wind farms was assessed for different:

- Build-out densities – the amount of installed wind farm capacity per unit area.
- Buffer distance – the spacing between two neighbouring wind farms.
- Seabed efficiency – the distribution of two wind farms within a fixed seabed area, including the impact of introducing separation between projects and reducing their developable area.

To examine the design considerations above, a number of offshore wind farm layout configurations were modelled using the Turbulence Optimized Park (TurbOPark) wake model coupled to a Rankine Half Body with Wake expansion (RHBW) blockage model. This model setup is essentially identical to that developed and tuned against real-world measurement data for 48 offshore wind farms by Ørsted [2].

The key findings from this modelling study are:

- Build-out density (or turbine spacing) within wind farms is a key driver of internal wake loss. Results from the TurbOPark model in this assessment indicated an approximate 1 percentage point increase in total interaction loss (due to wakes and blockage) for every 1 MW/km^2 increase in build-out density which is broadly consistent with prior findings from the PARK 2 model.
- For the generic 1 GW wind farms considered in this study, farm-to-farm wake effects represent a small fraction of the production loss due to internal wakes and blockage for separations between wind farms in the range of 2 to 20 km. The model findings indicate that reductions in farm-to-farm wake loss with increasing buffer separation are more significant at lower buffer separations.
- There is a slight production penalty from introducing a buffer separation between wind farms within a fixed seabed area. This is due to the increase in internal wake loss (due to reduction in turbine spacing) outweighing the decrease in farm-to-farm wake losses from having projects located further apart. However, this production penalty is relatively small for small buffers (0.1% on portfolio production for 1 GW projects less than 10km apart). The findings from this study indicate that buffers between neighbouring offshore wind projects may be used within a fixed seabed area for the purposes of satisfying other PDA design requirements with minimal penalty on aerodynamic losses.

5 References

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Annex A - Results Tables

Table 3: Build-out density study results.

Run ID	Spacing Between Wind Farms (km)	Build-out Density (MW/km^2)	Portfolio Gross AEP (GWh)	Portfolio Net AEP (GWh)	Total Interaction Loss (% Gross AEP)
1	0	3	5,668	5,373	5.2%
2	0	4	5,668	5,320	6.1%
3	0	5	5,668	5,273	7.0%
4	0	6	5,668	5,231	7.7%
5	0	7	5,668	5,191	8.4%
6	0	8	5,668	5,155	9.1%

Table 4: Buffer study results.

Run ID	Spacing Between Wind Farms (km)	Build-out Density (MW/km^2)	Portfolio Gross AEP (GWh)	Portfolio Net AEP (GWh)	Total Interaction Loss (% Gross AEP)
7	2	6	11,336	10,228	9.8%
8	3	6	11,336	10,265	9.4%
9	4	6	11,336	10,282	9.3%
10	5	6	11,336	10,303	9.1%
11	7.5	6	11,336	10,334	8.8%
12	10	6	11,336	10,365	8.6%
13	15	6	11,336	10,386	8.4%
14	20	6	11,336	10,401	8.2%

Table 5: Seabed efficiency study results.

Run ID	Spacing Between Wind Farms (km)	Build-out Density (MW/km^2)	Portfolio Gross AEP (GWh)	Portfolio Net AEP (GWh)	Total Interaction Loss (% Gross AEP)
15	5.269	4.36	11,336	10,449	7.8%
16	7.904	4.80	11,336	10,424	8.0%
17	10.539	5.33	11,336	10,408	8.2%
18	2.635	4	11,336	10,453	7.8%
19	10.015	5	11,336	10,439	7.9%
20	16.134	6	11,336	10,391	8.3%
21	21.410	7	11,336	10,333	8.8%

FRAZER-NASH CONSULTANCY
A KBR COMPANY

Hill Park South
KBR Campus
Springfield Drive
Leatherhead
Surrey
KT22 7LH

fnc.co.uk

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