

FIVE ESTUARIES OFFSHORE WIND FARM

10.64.1 RESPONSE TO EAST ANGLIA TWO'S DEADLINE 7 SUBMISSIONS AND THE EXAMINING AUTHORITY'S RULE 17 REQUEST TO THE APPLICANT

Application Reference: EN010115 Document Number: 10.64.1

Revision: A

Pursuant to: Deadline 8
Eco-Doc Number: 005753621-01
Date: March 2025

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Revision	Date	Status/Reason for Issue	Originator	Checked	Approved
Α	Mar 25	Deadline 8	VEOWF	VEOWF	VEOWF

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1. BACKGROUND / RELATED DOCUMENTS

1.1.1 A summary of the related documents is provided for ease:

Examination Library Reference	Author	Name / Drainage
REP6-079	East Anglia TWO	East Anglia TWO Limited's Deadline 6 Submission – Wake Loss Assessment
PD-031	ExA	Rule 17 Request for MWh assessment of wake by East Anglia 2
PD-034	ExA	Rule 17 Request for MWh assessment of wake by Five Estuaries
REP7-117	East Anglia TWO	East Anglia TWO Limited's Deadline 7 Submission – Response to Examining Authority's Rule 17 Letter
REP7-087	Five Estuaries	Five Estuaries Response to East Anglia TWO's Wake Loss Assessment
REP7-116	East Anglia TWO	East Anglia TWO Limited's Deadline 7 Submission – Response to Applicant's Written Summary of Oral Case for Issue Specific Hearing 6 [REP6-045]

2. INTRODUCTION AND CONTEXT

- 2.1.1 This document sets out the Applicant's response to the Examining Authority's rule 17 request seeking further information on the estimated annual generating output for the Proposed Development, in addition to the Applicant's comments on the response submitted by East Anglia TWO Limited at deadline 7 (examination library references REP7-116 and REP7-117).
- 2.1.2 This document should also be read in conjunction with the Applicant's previous submissions on this matter [REP3-024 (at section 2.20), REP5-073 (at section 9), REP6-045 (at paragraphs 1.8.1 to 1.8.18), REP6-047 and REP7-087].
- 2.1.3 This response is submitted without prejudice to the Applicant's position that an assessment of wake effects is not required under the energy National Policy Statements, or that the Applicant is required to take account of any wake effects on the East Anglia TWO project as an additional design consideration for the Project.

2.2 CONTEXT

- 2.2.1 The Examining Authority has requested both the Applicant and East Anglia TWO Limited to provide information as to the estimated annual generating output for their respective projects, and in the case of East Anglia TWO Limited for the estimated annual generating output both with and without the Proposed Development.
- 2.2.2 The Applicant wishes to emphasise at the outset, as set out in the Applicant's deadline 7 submission [REP7-087 at 2.1.12 and 2.3.3], the erroneous premise of the exercise of seeking to consider any wake impacts that the Proposed Development may have on the annual generating capacity of the East Anglia TWO project. This is because East Anglia TWO Limited is not an existing, operational project, and for the reasons explained in REP7-087 it is not appropriate in this context to proceed to consider the 'without Proposed Development' scenario as a reasonable baseline.
- 2.2.3 The circumstances of the Proposed Development and East Anglia TWO are clearly distinguishable from the Awel y Môr case, which related to claimed wake effects on an existing, operational project. The Applicant reiterates that it is not appropriate to regard East Anglia TWO as akin to an existing, operational project.
- 2.2.4 Further, if the purpose of requesting this information from the Applicant and East Anglia TWO Limited is to enable the Examining Authority and Secretary of State to assess whether there is a sufficient impact from the Proposed Development on the East Anglia TWO project which is considered to require either the consideration of mitigation measures or the imposition of a requirement, the Applicant submits that there are several fundamental flaws in this approach, both for the wider reasons set out in its Deadline 7 response (REP7-087) and in the light of material submitted by East Anglia TWO Limited at Deadline 7, for the additional reasons set out below.

3. RESPONSE TO EXAMINING AUTHORITY'S RULE 17 REQUEST TO THE APPLICANT (PD-034)

- 3.1.1 The following section provides the Applicant's response to the Examining Authority's request in PD-034 for an estimate of the annual generating output of the Proposed Development.
- 3.1.2 With respect to the Examining Authority's request for information regarding load factors; as the Applicant has not finalised the layout of the wind farm yet, it is not appropriate to quote a single figure for predicted capacity ("load" factor). This information is also commercially sensitive.

Instead of providing calculations based on a single number Five Estuaries present a range of indicative values that the predicted capacity factor is expected to be within. This is presented in Table 1 below.

Table 1 Range of total output of Five Estuaries in GWh

Total Annual							
Output (GW)	Assumed Capacity Factor						
Project Size (MW)	46.0%	47.0%	48.0%	49.0%	50.0%		
1080	4352.0	4446.6	4541.2	4635.8	4730.4		
1040	4190.8	4281.9	4373.0	4464.1	4555.2		
1000	4029.6	4117.2	4204.8	4292.4	4380.0		
960	3868.4	3952.5	4036.6	4120.7	4204.8		
920	3707.2	3787.8	3868.4	3949.0	4029.6		

3.1.3 The calculations are made on the following basis:

Equation1:

Total Annual Output (GWh) = Project Size (MW) × hours per year (8760h) × Capacity Factor × 0.001 (to convert from MWh to GWh)

4. APPLICANT'S COMMENTS ON EAST ANGLIA TWO LIMITED'S RULE 17 RESPONSE (REP7-117)

- 4.1.1 This section sets out some brief comments on East Anglia TWO Limited's response to the Examining Authority's rule 17 request for further information (examination library reference REP7-117).
- 4.1.2 Further to the Applicant's comments set out at section 1.2 above and at 2.1.12 and 2.3.3 of REP7-087 at 2.1.12 and 2.3.3 as to the fallacy of equating the East Anglia TWO project with existing, operational wind farms, the approach taken by East Anglia TWO Limited to assessing the claimed wake effects of the Proposed Development is fundamentally flawed.
- 4.1.3 The East Anglia TWO assessment of Wake Loss contains a central estimate of a yield reduction of 1.3% which is claimed to be as a result of the Proposed Development with a range of ±0.8% to the 95% Confidence Interval which equates to approximately a lower bound of 0.5% and upper bound of 2.1% % of impact. Please see REP7-087 section 2.3.37 for an explanation of Confidence Intervals.
- 4.1.4 As per its comments in REP7-087 the Applicant wishes to highlight that the assessment carried out by East Anglia TWO Limited, from which the annual generation capacity estimates have been derived, is excessively conservative (i.e. it provides an unrealistically high estimate) of the impact of the Proposed Development on East Anglia TWO as it does not consider North Falls, or the other operational wind farms "up wind" in the prevailing direction which will also be impacting the wind resource in the "up wind" prevailing direction. These additional wind farms that have not been modelled will further reduce the East Anglia TWO capacity factor in both the "without Five Estuaries" and "with Five Estuaries" calculations.

Table 2 Summary of the East Anglia TWO generating capacity estimate

EA2 Capacity	960	MW
h/year	8760	h
East Anglia TWO without Five		
Capacity Factor	%	
Total Annual Generation GWh	4028.2	GWh

^{*} not including other wind farms "up wind" in the prevaling direction

4.1.5 The Applicant notes that in the estimate of the impact of wake on the East Anglia TWO wind farm only values for the mean and upper bound confidence interval are presented. In Table 3, the Applicant has set out in accordance with best practice the lower, central and upper estimates are provided including the reduction compared to the "un waked" prediction.

Table 3 Variation in East Anglia TWO's wake loss estimates

	Additional Loss Revised Capacity		Total Annual	Reduction in
Estimate	%	Factor	Generation GWh	GWh
Lower Bound 95% Confidence Interval	0.5%	47.7%	4008.1	20.1
Central Estimate	1.3%	47.3%	3975.8	52.4
Upper Bound 95% Confidence Interval	2.1%	46.9%	3943.6	84.6

^{*} differences between the above and the East Anglia TWO values are anticipated to be due to rounding

4.1.6 The Applicant notes that the range of the predictions to 95% confidence interval provided is 64.5 GWh (84.6 GWh minus 20.1 GWh). This value does not account for the uncertainty in the inputs (layout, turbine selection, and additional wind farms "up wind" in the prevailing direction etc). This is larger than the central estimate of 52.4MWh presented. This is noted to highlight the uncertainty in the wake assessment presented by East Anglia TWO.

RECIPROCAL IMPACT OF EAST ANGLIA TWO ON FIVE ESTUARIES

- 4.1.7 Following on from the discussion presented in section 2.3.6 to 2.3.11 of REP7-087 regarding the reciprocal impact of East Anglia TWO on Five Estuaries. The Applicant provides an approximation of the range of wake impact that the presence of East Anglia TWO is anticipated to have on Five Estuaries Annual Energy Production (AEP).
- 4.1.8 Considering the uncertainties in the layout, turbine size and project size the Applicant notes that the following assessment is intended as an approximation for the Examination Authority to understand the order of magnitude of the reciprocal impact expected.
- 4.1.9 Table 4 contains a range of wake impacts that may be expected caused by the presence of East Anglia TWO on Five Estuaries when the wind is blowing in the non-prevailing direction while wind speed is below the rated capacity. A range is presented as to present a single value is considered by Five Estuaries to be misleading considering the uncertainty.

Table 4 Example of range of reciprocal impacts of wakes caused by East Anglia TWO on Five Estuaries AEP

Five Estuaries						
Project Size (MW)	47.9%	0.2%	0.4%	0.6%	0.8%	1.0%
1080	4531.7	9.06	18.13	27.19	36.25	45.32
1040	4363.9	8.73	17.46	26.18	34.91	43.64
1000	4196.0	8.39	16.78	25.18	33.57	41.96
960	4028.2	8.06	16.11	24.17	32.23	40.28
920	3860.4	7.72	15.44	23.16	30.88	38.60

4.1.10 The Applicant notes that the magnitude and the range of the impacts are the same order of magnitude to the impacts predicted by the East Anglia TWO wake loss assessment in REP6-079 from Five Estuaries on East Anglia TWO.

5. APPLICANT'S COMMENTS ON EAST ANGLIA TWO LIMITED'S DEADLINE 7 SUBMISSION (REP7-116)

5.1.1 This section responds briefly to East Anglia TWO Limited's Deadline 7 response (examination library reference REP7-116). For convenience the same subheadings as used in East Anglia TWO Limited's submission have been adopted.

POLICY

5.1.2 The Applicant has conducted a Greenhouse Gas Assessment APP-094. It is noted in this assessment that there is uncertainty in relation to project design, generating capacity and specifically load factors. It is for these reasons a sensitivity analysis has been conducted (included in section 1.4.17 to 1.4.22). The range of load factors explored is 45-53%; this is translated into GWh in Table 5. East Anglia TWO indicate in the section 1.5 of REP7-116 that they consider that the "net effect of the Project as a whole on greenhouse gas emissions that should be assessed". The Applicant highlights that the range of wake impact predicted by East Anglia TWO and shown in Table 3 is well within the range that the sensitivity assessment has already considered and hence no further assessment is necessary. As a consequence there are no implications for the benefits, planning policy or HRA cases which the Applicant has made.

Table 5 Sensitivity testing of AEP assumptions in Greenhouse Gas Assessment

MW	1080	1080	
Load Factor	45%	53%	
Hours / year	8760		
GWh	4257.4	5014.2	
Sensetivity Range Tested			
756.9	GWh		

- 5.1.3 The Applicant does not propose to repeat the policy arguments which it has already made in this Examination.
- 5.1.4 It is notable that East Anglia TWO, despite what it argues that the Applicant should do in relation to their project, continues to remain silent on the points the Applicant has made about EA2's failure to have consideration of its wake effects on existing offshore wind farms (and on Five Estuaries and North Falls as projects with Crown Estate Agreements for Lease which it has known about since 2018) and the obvious questions of fairness which arise.

MITIGATION

5.1.5 Within East Anglia TWO's response REP7-116 in Section 2 "Mitigation" point 2.1 it is suggested that an 8km buffer between the wind farms would result in a 0.2% (i.e. from 1.3% to 1.1%) reduction in predicted wake loss. This appears to be on the assumption that the adverse impact of the 8km buffer would be borne entirely by Five Estuaries, without regard to mitigation available to East Anglia TWO. The Applicant notes that it is not explained what assumptions have been made in relation to this calculation and why the buffer is proposed at 8km rather than some other distance. Nevertheless it comments below.

- 5.1.6 The Applicant notes that East Anglia TWO's predicted reduction is less than the presented uncertainty in the predictions and equates to a 8.1GWh per year increase in generation for East Anglia TWO. This alone substantially undermines the case for an increased buffer.
- 5.1.7 Figure 1 illustrates how such an 8km proposal could, in theory, be achieved with three scenarios for increasing the existing buffer to 8km. Scenario A shows that the buffer would affect 10 East Anglia TWO WTG locations i.e. where the buffer is achieved entirely by East Anglia TWO. Scenario B shows that the buffer would affect 12 Five Estuaries WTG locations i.e. where the buffer is achieved entirely by Five Estuaries. Scenario C achieves the buffer by affecting both projects and shows 4 EAT WTG locations are affected and 3 Five Estuaries WTG locations are affected. The Five Estuaries WTG locations are assumed from the coordinates presented in the East Anglia TWO wake assessment and are fictitious for illustrative purposes only. The total resulting loss of WTGs ranges from 7 (Scenario C) to 12 (Scenario B) x 15 MW WTGs. (The alternative of compressing the WTG layout is considered in the next section.)
- 5.1.8 Adopting this approach would hence result in reductions shown in Table 6. To calculate these values the capacity factor of East Anglia TWO 47.9% has been used.
- 5.1.9 Five Estuaries note that this is a simplistic assessment and there are many unknowns not fully accounted for, however the purpose of this assessment is intended to highlight the point made in Five Estuaries' submission REP7-087 2.3.25 that such an approach results in a net loss of generation capacity that is much larger than any perceived benefit to East Anglia TWO. As already pointed out, the perceived benefit to East Anglia TWO is itself within the range of uncertainty in East Anglia TWO's wake loss calculations.

Table 6 Impact of 8km buffer options on total wind farm output

Reduction in 15 MW WTGs	Loss of geeration capacity GWh
10	629.4
12	755.3
7	440.6

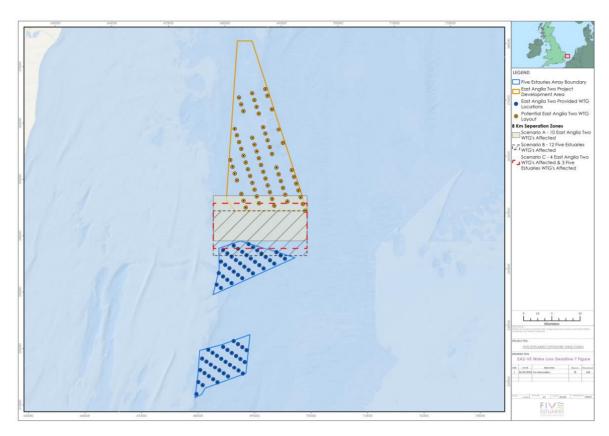


Figure 1 Impact of "an 8km buffer" between Five Estuaries and East Anglia TWO

- 5.1.10 If the option of increasing the buffer by compressing the wind turbines within each site closer together were to be suggested by East Anglia TWO (as described in REP7-087 section 2.3.24 as a theoretical possibility), Five Estuaries would point to an independent consultant for The Crown Estate provided in Appendix A. In this study the impact of increasing "build out density" (i.e. moving the WTGs closer together) and increasing buffer distances is explored. The conclusions of "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."" indicates that internal wakes are more significant compared to the wind farm to wind farm wakes. Because these internal wakes are more significant than external wakes, attempts to reduce wind farm to wind farm wakes by increasing buffer distances will result in aggregate reduction in energy as the internal wakes (which are more significant) will increase. The underlying principle governing this is that within a wind fam the WTGs are typically 4 to 5 rotor diameters apart which for a 15 MW WTG is 4 to 5 times 236m (944-1,180m) and this distance is much less than the Crown Estate lease area buffers (5km as applied between Five Estuaries and East Anglia TWO); hence the internal wakes will be higher than external ones between the Two projects.
- 5.1.11 This highlights that in the impact of the increased wake within each wind farm has a greater reduction in total generation compared to reducing the intra wind farm wakes.

5.1.12 In summary, and bearing in mind the various methodological caveats the Applicant has highlighted, the mitigation as suggested by East Anglia TWO in section 2.1 of REP7-116 can be expected to reduce the UK's total offshore wind generation capacity and would be in conflict with government policy for renewable energy policy in EN-3 and more broadly.

6. **RECOMMENDATION**

- 6.1.1 A requirement of the type imposed in Awel y Môr, would fail the legal tests for planning requirements, in particular the tests of necessity, enforceability, precision and overall reasonableness.
- 6.1.2 The Applicant has highlighted in its previous submissions fundamental issues regarding:
 - a. the fact Five Estuaries has respected The Crown Estate's buffer distance of 5km for Extension projects;
 - b. the fact that EA2 is not constructed or in operation, which creates a range of uncertainties around what that project may, in fact be (assuming it is constructed) and related wake considerations;
 - c. the unfairness of EA2 seeking mitigation measures from Five Estuaries when it will itself (if and when constructed) cause wake effects on other existing (and emerging) offshore wind projects, which it proposes to do nothing to address;
 - d. the fact that any mitigation measures imposed on Five Estuaries would reduce the AEP of Five Estuaries, when the overarching energy and EN-3 policies are to maximise aggregate generation to meet government targets.
- 6.1.3 The planning case for Five Estuaries has been set out in the Planning Statement (APP-231). There is no need to impose a wake effects mitigation requirement to make the Project acceptable in planning terms. It is apparent from what has happened across multiple offshore wind applications since the Awel y Môr decision that there are a range of issues relating to wake effects, which require careful policy consideration away from the specific facts of any given application and Examination for new offshore wind projects.
- 6.1.4 This includes what, exactly, any type of obligation to seek to mitigate wake effects in different scenarios is trying to achieve in policy terms. Putting aside Awel y Môr (where the interpretation of the requirement is open to debate) the norm in offshore wind has been for each project to maximise its AEP to maximise the contribution to renewable energy targets and for commercial reasons. This is the approach which should continue to be followed, with any other issues regarding wake effects resolved outside the planning system.

APPENDIX A – 'OFFSHORE WIND LEASING PROGRAMME ARRAY LAYOUT YIELD STUDY', FRAZER NASH



Offshore Wind Leasing Programme Array Layout Yield Study

5 October 2023

017866-101

55726R Issue: 2

Prepared for: The Crown Estate

SYSTEMS • ENGINEERING • TECHNOLOGY

NOT PROTECTIVELY MARKED



Offshore Wind Leasing Programme

Array Layout Yield Study

Client: The Crown Estate

Client Ref.: PO 3296228

Date: 5 October 2023

Classification: NOT PROTECTIVELY MARKED

Project No.: 017866-101 Compiled By:

Document No.: 55726R **Verified By:**

Issue No.: 2 Approved By:

Signed:



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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.



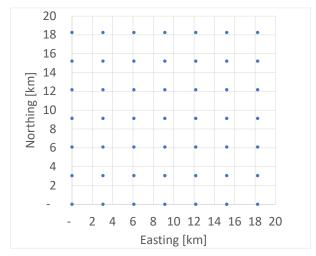
Table 1: Wind farm configurations assessed.

Sensitivity	Run #	Layout	Spacing between wind farms (km)	Build-out Density (MW/km²)
	1		-	3
	2			4
Build-out Density	3	A single square orthogonal	n/2	5
Bulla-out Delisity	4	1GW array	n/a	6
	5			7
	6			8
	7		2.0	
	8		3.0	
	9	A and B square orthogonal 1GW arrays separated along northing direction	4.0	
Buffer	10		5.0	C
Buller	11		7.5	6
	12		10	
	13		15	
	14		20	
	15	Fixed seabed area and seabed	5.269	4.36
	16	aspect ratio. Varying wind farm	7.904	4.80
	17	aspect ratio.	10.539	5.33
Seabed efficiency	18	Fixed seebed area and wind	2.635	4
	19	Fixed seabed area and wind	10.015	5
	20	farm aspect ratio. Varying seabed aspect ratio.	16.134	6
	21	seaved aspect ratio.	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/km². 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.



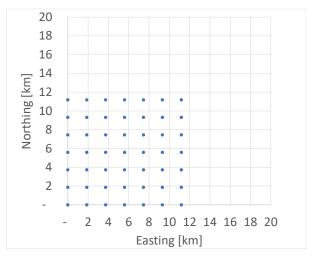


Figure 1: Wind farm layout with 3 MW/km² build-out density (run ID 1).

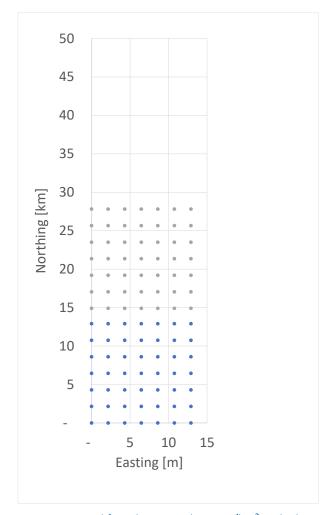
Figure 2: Modelled wind farm layout with 8 MW/km² build-out density (run ID 6).

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/km² 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/km²).

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.





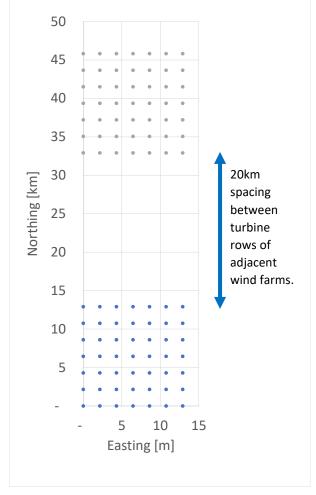


Figure 3: Wind farm layout with 6 MW/km² and 2 km spacing between wind farms (run ID 7).

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

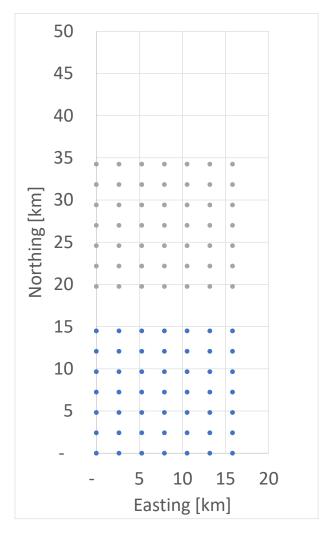
2.1.3 Seabed Efficiency

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.







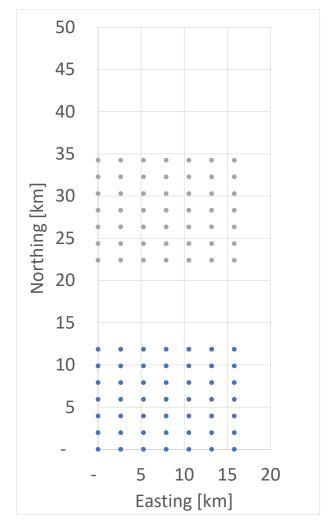


Figure 6: Layout with 5.33 MW/km² build-out density (for each farm) and 10.539 km spacing within a fixed seabed area (run ID 17).



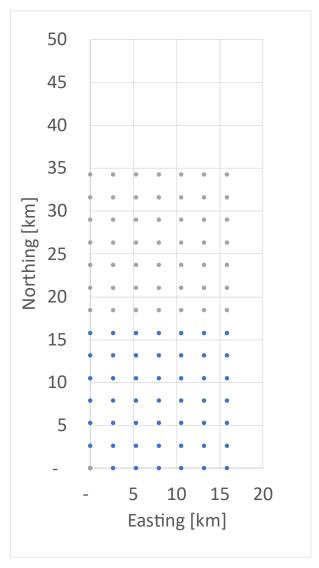


Figure 7: Layout with 4 MW/km² build-out density (for each farm) and 2.635 km spacing between farms (run ID 18).

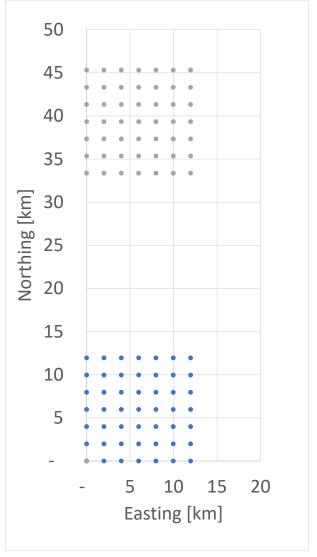


Figure 8: Layout with 7 MW/km² build-out density (for each farm) and 21.410 km spacing between farms (run ID 21).



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



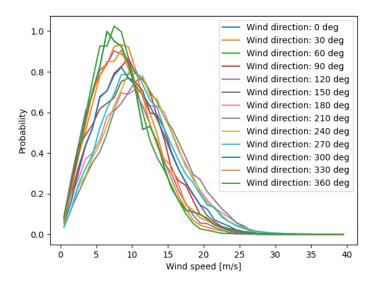


Figure 9 Annual distribution of wind speeds at 110m above mean sea level (AMSL).

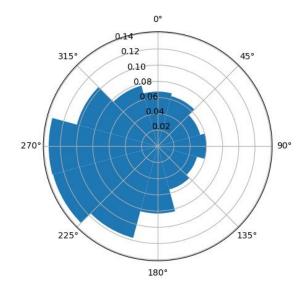


Figure 10 Annual distribution of wind directions at 110m AMSL.



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 (y). 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.



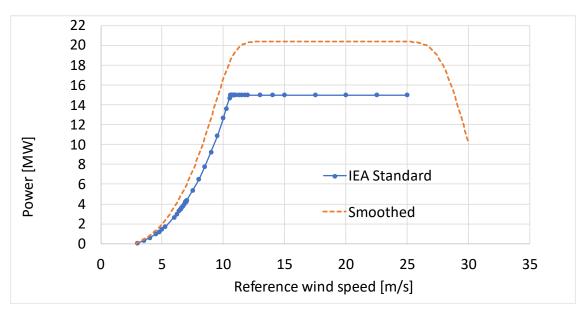


Figure 11 – Modified power curve used in this assessment (orange) and the IEA standard turbine power curve upon which this is based (blue).

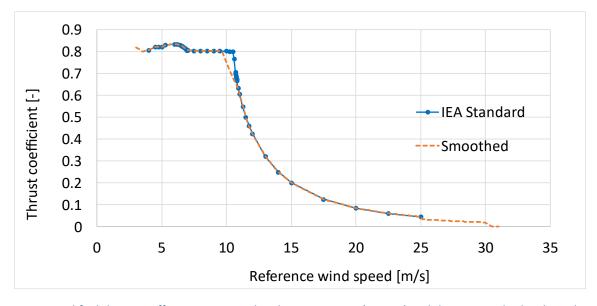


Figure 12 Modified thrust coefficient curve used in this assessment (orange) and the IEA standard turbine thrust coefficient curve upon which this is based (blue).



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/km² (10.9 rotor diameter spacing) to 8 MW/km² (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.



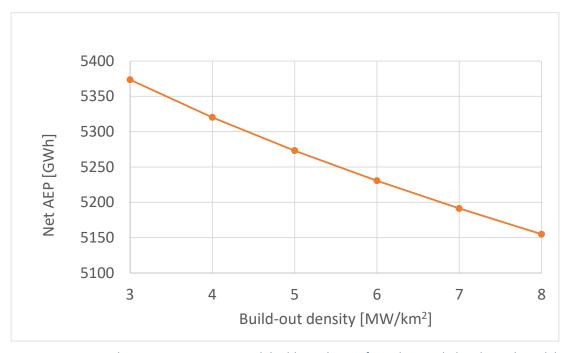


Figure 13: Net aerodynamic AEP variations with build-out density from the coupled TurbOPark model.

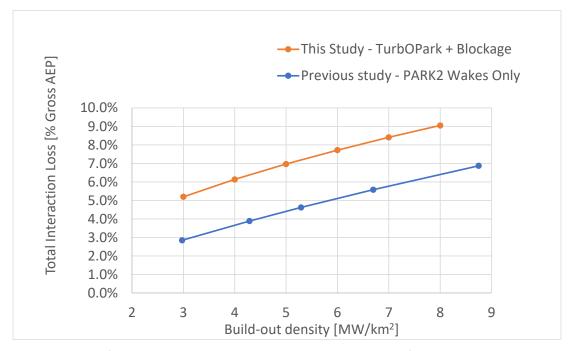


Figure 14: Comparison of total interaction loss variations with build-out density from the coupled TurbOPark model (this study) and the PARK2 wake model (previous study).



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/km² 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 km²), 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.



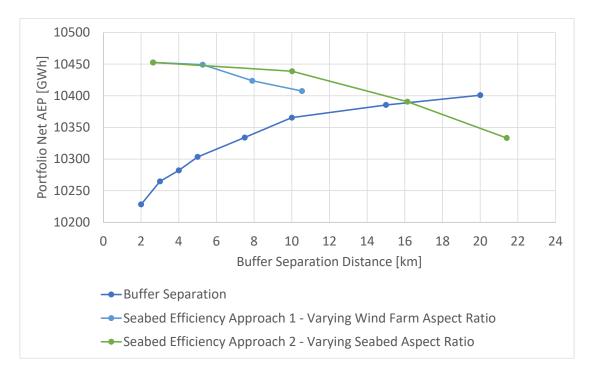


Figure 15: Variation of portfolio net aerodynamic AEP (total production) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).

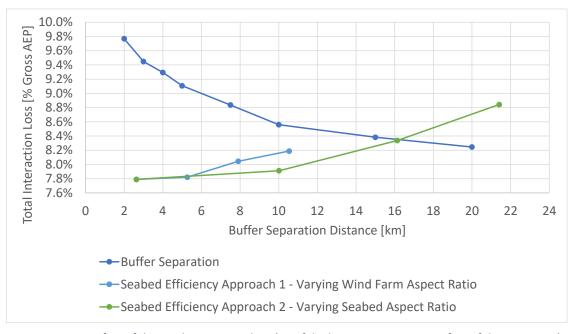


Figure 16: Variation of portfolio total interaction loss (portfolio loss as a percentage of portfolio gross AEP) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).



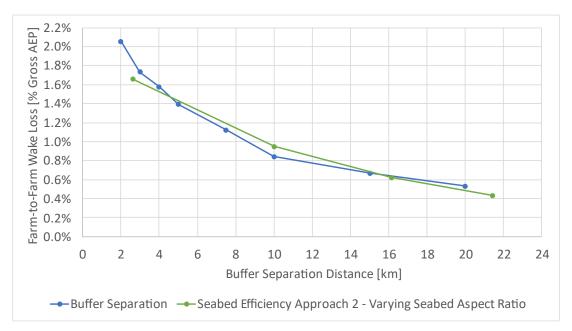


Figure 17: Variation of farm-to-farm wake loss (as a percentage of gross AEP) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).

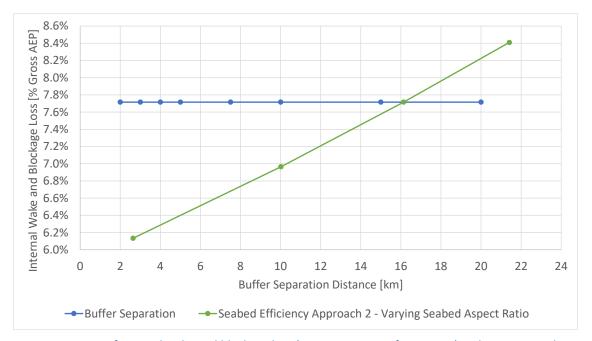


Figure 18: Variation of internal wake and blockage loss (as a percentage of gross AEP) with separation distance considering an infinite seabed area (buffer separation study) and a fixed seabed area (seabed efficiency study).



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/km² 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/km²)	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/km²)	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/km²)	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%



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