Study into Levelized Cost of Energy

of variants for wind farm site boundaries of Hollandse Kust (west)

From:	BLIX Consultancy BV & partners
Reference:	WOZ2180196
To:	Netherlands Enterprise Agency

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Version:	Final – V1.0
Date:	6 August 2020

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MANAGEMENT SUMMARY

1.1 Introduction and approach

BLIX Consultancy & partners performed a study in 2018 to investigate the Levelized Cost of Energy (LCoE) of different variants for the wind farm site boundaries of the roadmap 2030 areas.

RVO requested BLIX to perform additional LCoE calculations for newly-defined variants A, B, C, D, E, F, G and H and compare the results with the current reference wind farm layout based upon the definitive Memorandum Scope and Level of Detail ('Notitie Reikwijdte en Detailniveau' or 'NRD')[1]. With these additional variants it is possible to quantify the impact of different options (such as taking into account the helicopter traffic zones, width of maintenance zones, width of shipping passages etc.) and support further decisions on the final boundaries of these wind farm sites.

This report describes the results.

The approach was to define indicative layouts for each alternative. The LCoE was modelled per individual turbine with yield simulations and a financial model based on recent market prices. The results provide insight into the main factors governing the LCoE.

1.2 Overview of considered variants

The modelled variants are described in Table A. Note that each individual wind farm site is assumed to be overplanted to a maximum capacity of 756MW (63 x 12MW).

Table A: Description of the variants NRD and A through E.

Variant	Assumption
NRD	Reference case - as described in paragraph 5.2
A	Based on NRD with modified shipping passage width to 1500m
B	Based on variant A without helicopter traffic zone around platform P06-A
C	Based on variant B where the shipping passage between site VI and VII fully coincides with the site boundaries area
D	Based on B with exclusion of maintenance zones around the telecom cable, and of the maintenance zones around pipelines connected to P06-A
E	Based on D with equal distribution of the net area of site VI, VII and VI (alternative)

Based on intermediate results and new insights by the Working Group a new reference variant F was defined and new variants G, H were added, see Table B.

[1]https://www.rvo.nl/sites/default/files/2019/11/DEF%20Vaststellen%20NRD%20Kavelbesluiten%20VI%20en%20VII%20HKW%20voor%20de%20website.pdf

Table B: Description of the variants F through H

Variant	Assumption
F	Based on variant C with modified shipping passage width to 1050m [#1], 2x150m maintenance zones around pipelines connected to P06-A [#5] and an east to west orientation of shipping passage between site VII and VI (alternative) [#7]
G	Based on variant F taking site VI (alternative) into account [#8]
H	Based on variant G with equal LCoE output of site VI, VII and VI (alternative) through displacement of shipping passage between site VI / VII and VII / VI (alternative) [#7]

1.3 Results

The resulting differences in LCoE per variant are shown in Figure A and B:

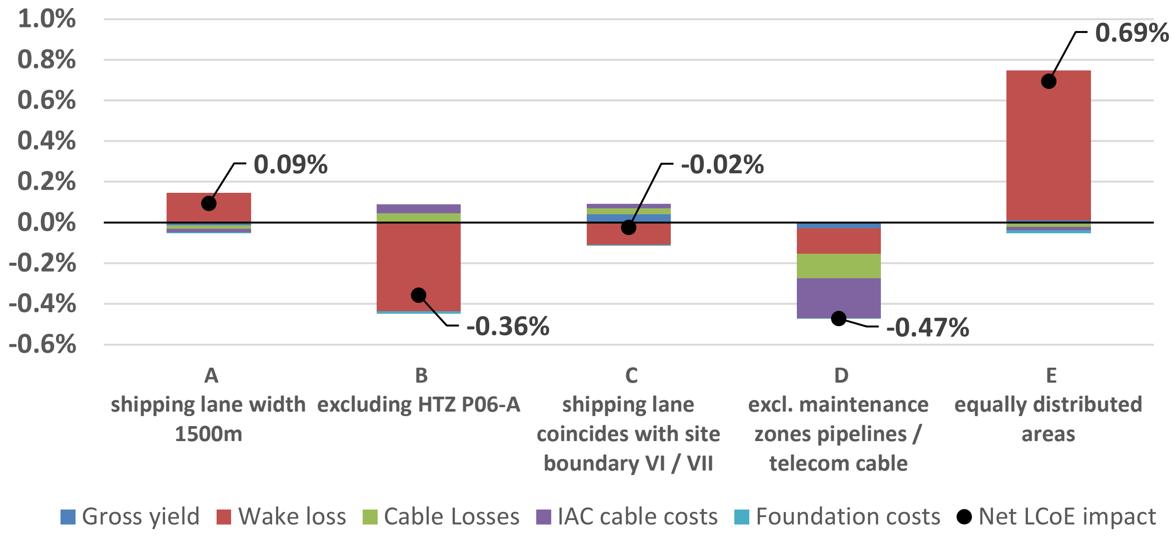


Figure A LCoE impact of changes in the site boundaries of variants A through E.

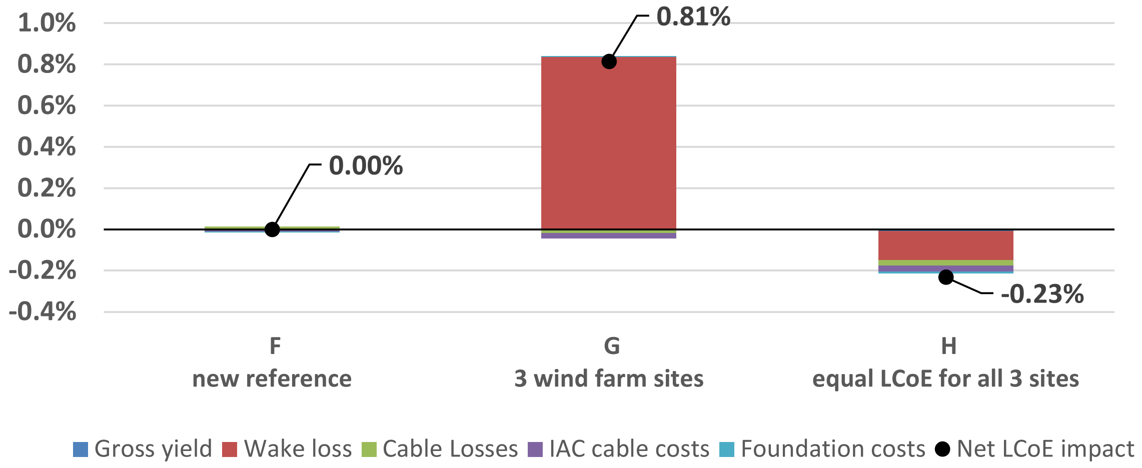


Figure B LCoE impact of changes in the site boundaries of variants F through H.

Table C below shows the deviations per site of the variants G, H and the sensitivity analyses to investigate the robustness of the results of variant H.

Table C: Deviations of the LCoE per site compared to the mean of the variants G, H and the sensitivity analyses.

Variant	VI	VII	VI (alternative)
G	-1.15%	+1.89%	-0.74%
H	-0.43%	0.29%	0.14%
WindPro layout sensitivity	-0.17	0.26%	-0.08%
15MW layout sensitivity	-0.10%	0.20%	-0.09%

1.4 Conclusions

The following main conclusions are drawn based on the results of the LCoE study:

1. The results of this study are comparable to the 2018 study results. At that time, significant differences in LCoE were seen between the variants in which the total available surface of HKW was used for two or three wind farms, comparable to the current result of variant G.
2. Differences in the configuration of the site boundaries were analyzed resulting in limited to moderate differences in LCoE compared to the NRD reference, except when the areas of the three sites is equally distributed, which cause a significant increase in LCoE.
3. Wake losses are closely related to the wind farm density. However, the cause of the difference in density is very important here; an increase in density due to maintenance zones that fit within the turbine spacing have only a small effect on the wake losses, while increasing the density caused by shifting a site boundary has a large effect on the wake losses.
4. The wake effects have the greatest impact on the net LCoE differences, the impact of the other parameters is limited.
5. Broadening the shipping passage (variant A) has limited impact on the LCoE.
6. Excluding the HTZ around P06-A (variant B) has a moderate positive LCoE impact.
7. Adding the southwestern part of site VI to site VII with the shipping passage between site VI and site VII that coincides with the site boundaries of sites VI and VII (variant C) has a negligible LCoE impact.
8. Excluding the maintenance zones of the northern telecom cable and around pipelines connected to P06-A (variant D) cause a moderate decrease in LCoE.
9. Equally distributing the net areas of site VI, VII and VI (alternative) (variant E) and thereby reducing the net areas of site VI and VII compared to the reference increases the LCoE significantly.
10. Installing an additional 756MW of wind energy capacity (variant G) will increase the average LCoE of all three sites significantly by the substantial increase in wake losses.
11. For variant H, the site boundaries by the shipping passages are placed in such a way that the LCoE is similar for all three sites.
12. The sensitivity analyses show that the results of variant H with equal LCoE for all three sites are robust for variations in the wind farm layout.

2 INTRODUCTION

2.1 Background

BLIX Consultancy & partners performed a study in 2018 to investigate the Levelized Cost of Energy (LCoE) of different variants for the wind farm zone boundaries of the roadmap 2030 areas.

The Roadmap 2030 comprises the following wind farm zones (see Table 1):

Table 1: Wind farm development scheme of Roadmap 2030.

Wind farm zone	Abbreviation	Capacity	Year of tender
Hollandse Kust (west)	HKW	1,400 MW	2020/2021
Ten noorden van de Wadden-eilanden	TNW	700 MW	2022
IJmuiden Ver	IJV	4,000 MW	2023 – 2025

The final report from 2018 described the results of the layouts and LCoE modelling of Hollandse Kust (west) and Ten noorden van de Waddeneilanden. For IJmuiden Ver, only yield calculations were performed (no cost calculations).

For wind farm zone Hollandse Kust (west), new variants of wind farm site boundary alternatives have been developed by the Netherlands Enterprise Agency (RVO), the Ministry of Economic Affairs and Climate Policy and Rijkswaterstaat (defined in the remainder of this document as the Working Group), as a result of the 2018 LCoE study results and discussions between the Working Group and various other stakeholders.

RVO requested BLIX to perform additional LCoE calculations for these variants, defined as A, B, C, D, E, F, G and H and to compare the results with the current reference wind farm layout of the Hollandse Kust (west) wind farm zone, based upon the definitive Memorandum Scope and Level of Detail (Dutch: 'Notitie Reikwijdte en Detailniveau' or 'NRD')[2]. Figure 1 shows the layout of the HKW wind farm zone and its subdivision into three sites (Dutch: 'kavels'), namely site VI, site VII and site VI (alternative). This report describes the results.

2.2 Study objective

The study objective was to assess the Levelized Cost of Energy (LCoE) of various wind farm site boundary alternatives for future wind farm zone Hollandse Kust (west), with a similar approach as was used in the 2018 LCoE study by BLIX and partners, to support further decisions on the final boundaries of these wind farm sites.

The sub objectives were as follows:

1. Determine the relative impact on LCoE of different site boundary choices;
2. Determine which parameters cause the largest influence on the LCoE;
3. Determine the placement of the shipping passages between the sites to achieve equal LCoEs for all three sites.

2 https://www.rvo.nl/sites/default/files/2019/11/DEF%20Vaststellen%20NRD%20Kavelbesluiten%20VI%20en%20VII%20HKW%20voor%20de%20website.pdf

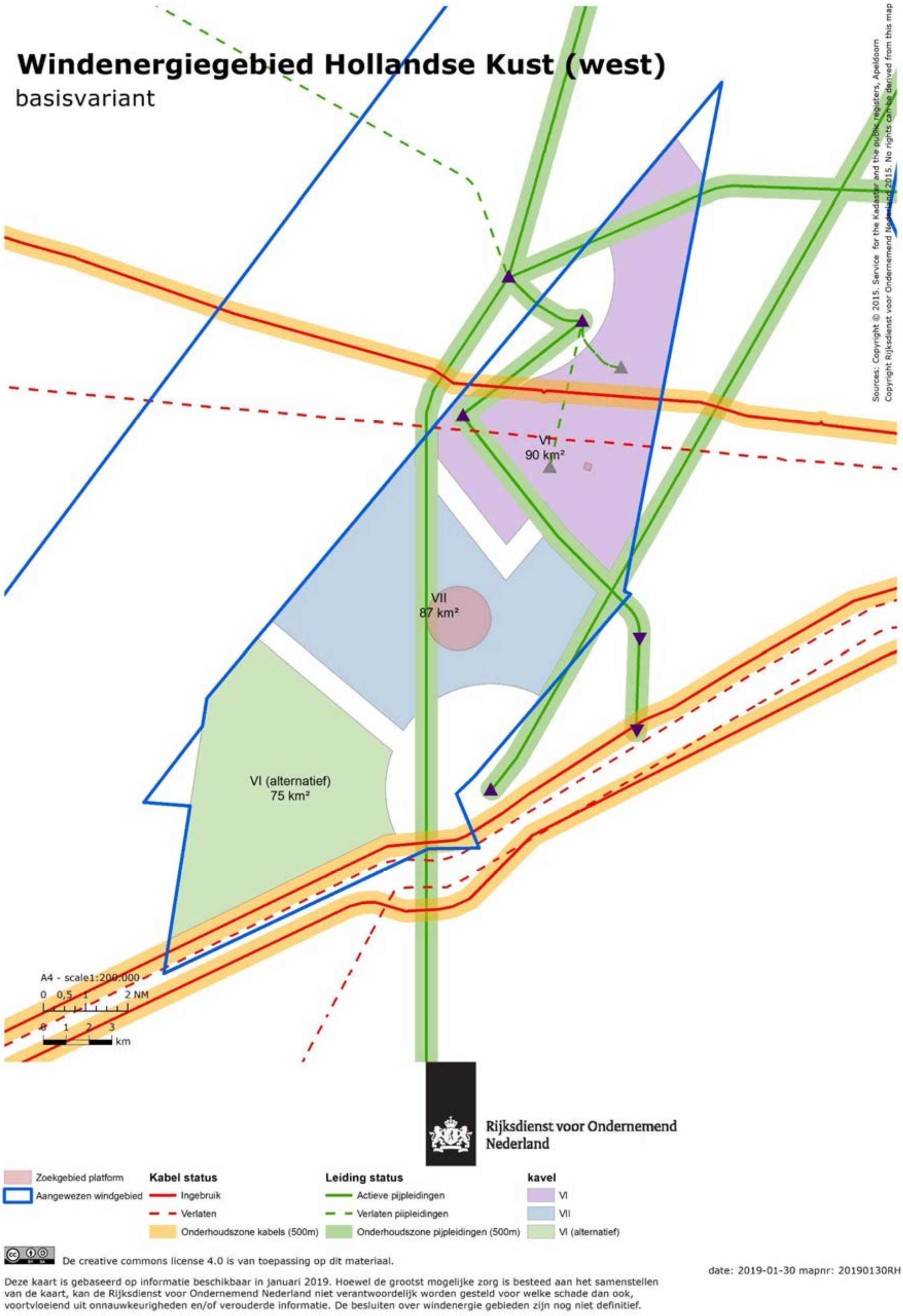


Figure 1 Site subdivision for Hollandse Kust (west) as presented in the NRD.

2.3 Structure of report

Chapter 3 describes the approach and the project team. The starting points and assumptions are described in Chapter 4. In Chapter 5, the variants and layouts are presented. Chapter 6 contains an analysis of the yield. Finally, the overall LCoE associated with each variant and the relative LCoE per turbine is described in Chapter 7, followed by a discussion in Chapter 8 and conclusions in Chapter 9.

3 APPROACH

3.1 Team & partners

The objective of the project was to extend the LCoE study conducted in 2018 by BLIX and partners with a similar approach.

BLIX Consultancy worked together with Pondera to achieve this goal, with the support provided by Energy Solutions and KCI the engineers for the 2018 study. The roles of all parties are described below:

1. **BLIX Consultancy BV**: project leader and cost modelling
2. **Pondera**: design of wind farm layouts and yield calculations
3. **Energy Solutions**: electrical expertise
4. **KCI the engineers**: design expertise

3.2 Study approach

The study was based on the following approach, which is similar to the approach taken in the 2018 LCoE study:

1. Define variants for the HKW wind farm zone

   Most of the variants were provided by the Working Group, some were proposed by the BLIX project team. The variants consisted of a reference variant and variants with excluding a helicopter traffic zone, excluding the maintenance zones for some of the pipelines, telecom cables and oil & gas platforms, including and widening or narrowing of shipping passages, displacement of the site boundaries and use of the wind farm zone for a capacity of 2 x 756MW or 3 x 756MW.

2. Provide baseline wind farm layouts and yield calculations for each variant

   Next, indicative wind farm and cable layouts were provided for each variant, based on a schematised approach with a regular turbine spacing. Then, the energy yield was determined for each wind farm layout with dedicated software tools (WASP for the wind climate and WindPRO for yield calculations) considering the local wind climate and the wake effects associated with each of the layouts.

3. Setup financial model schematisation

   The next step was to update the BLIX financial model (used for the LCoE project in 2018) for the analysis of the new variants. At the time, KCI provided indicative foundation designs for several water depths, based on which a relation was developed for foundation cost against water depth and various wave heights. A relation for cable losses, considering the number of WTGs on a string, was provided by Energy Solutions. All other costs were estimated based on the then most recent market prices insight of BLIX in North Sea tenders.

4. Calculate the LCoE of each variant

Finally, the LCoE was calculated for each variant and compared with the reference variant. The relative yield and relative LCoE per turbine were analysed and conclusions were drawn regarding the overall LCoE of different variants.

3.3 Assessment of results

In consultation with the Working Group, it has been determined that the results of the LCoE impact analysis will be rated as "limited", "moderate" or "significant" according to the table below.

Table 2: Assessment of LCoE impact results

LCoE impact	Rate
Less than 0.3%	“limited”
Between 0.3 – 0.6%	“moderate”
More than 0.6%	“significant”

4 STARTING POINTS AND ASSUMPTIONS

4.1 Introduction

This chapter describes the main starting points and assumptions for the study. First the starting points are described, followed by an assessment of the main parameters that vary between the variants and influence the LCoE. Then, the local site conditions (wind climate, hydrodynamic and soil parameters) and the technical assumptions are elaborated.

4.2 Starting points

The following starting points were agreed with the Netherlands Enterprise Agency:

1. The aim of the LCoE modelling is to compare relative differences, not obtain realistic absolute values of the LCoE. Therefore, only relative differences are shown in the present report.
2. The wind farm layouts should be considered indicative (not optimised) and based on a schematised regular pattern to allow fair comparison between variants. In reality, there may be optimisations possible based on more detailed assessments and more available site data. These optimisations are not part of the scope of the present study.
3. The cost modelling is based on the same price levels and assumptions for wind farm design as were used in the 2018 report to enable comparison of results. BLIX has been involved in tender preparations for developers and wind farms all over the world, including in the North Sea. These insights were used in the LCoE study of 2018 to make realistic assumptions for these parameters.
4. The cost modelling excludes the substation and export cable. Although these costs are important, for the present study the position and costs of the substation and export cable do not vary between variants and would therefore not lead to differences between variants.

4.3 Main parameters that vary between variants

In 2018, as a first step of the model schematisation, an assessment was performed of the parameters that differ between variants and their qualitative impact on the LCoE, as described below in Table 3.

Table 3: Main parameters varying between variants

Parameter	Importance	Description
Turbine locations	High	Differs between variants; influences the wake losses, water depth and cable length.
Wake losses	High	Differs between variants; influences the net yield.
Water depth	High	Depends on turbine location so differs between variants; affects the cost of the foundations particularly in case of large water depth variations.
Infield cable length	Medium	Depends on turbine location so differs between variants; influences the cable installation cost.
Number of cable crossings	Medium	Depends on turbine location so differs between variants; influences the cable installation cost.
Cable losses	Medium	Limited differences between variants; string length and number of turbines on string influence the transmission losses.

Wave and current conditions	Low	Very limited differences between variants; affects the cost of the foundations. Assumed negligible.
Mean wind speed	Low	Very limited gradient across site, leading to minor differences per variants.
Distance to port	None	Influences the cost of the operations and maintenance. No difference between variants.

4.4 Site conditions

4.4.1 Wind climate

The wind climate was assessed as reference for the yield calculations. The same approach has been followed that was used in similar LCoE studies for offshore wind farm zones Borssele, Hollandse Kust (zuid) and Hollandse Kust (noord). As this approach has been approved and the results certified by DNV-GL, this is expected to be a suitable schematization of the wind climate. The method followed the following steps:

- The met mast Ijmuiden dataset was used as the basis for the wind resource assessment for the Hollandse Kust West (HKW). These wind measurements were found to be the most representative, complete and closest to the HKW wind farm zone. The datasets were quality controlled, filtered for errors and anomalies, processed and delimited to four full years.
- The WindPRO measure-correlation-prediction method (MCP) was used in the long-term scaling of the Ijmuiden site measurements. This method applied a Linear Regression analysis between the met mast wind speed measurements and the EMD-ConWx Europe (25 years) mesoscale data in the concurrent measurement periods. The linear regression analysis is applied to all concurrent measured wind speeds considering their corresponding wind directions. The Ijmuiden met mast average wind speed measurement values is corrected for the long-term EMD ConWx-mesoscale average wind speed, which was found to be 2.0 % lower than at the Ijmuiden met mast. The resulting WindPRO Wind Statistics (wws-file) presents the long-term corrected wind climate in 12 directional sectors with a Weibull wind speed distribution.
- To determine the correct horizontal gradient in wind climate within the wind farm zones, the ConWx data-set was used to interpolate the long-term corrected wind climate from the met mast locations to multiple points inside the wind farm zones. This method helped to determine the representative wind speeds at the project sites.

Table 4 summarizes the most important parameters and values found in the wind resource assessment of the wind farm zones. Figures 2 graphically summarizes the wind climate (Weibull distributions and wind roses) at HKW wind farm zone.

Table 4 Wind parameters for Hollandse Kust (west)

Parameter	Hollandse Kust (west)
Met mast used for wind measurements	Ijmuiden
Distance met mast to edge of wind farm zone [km]	25
Met mast measurement time [years]	4
Mesoscale data used for long term correction (years)	EMD-ConWx Europe (25 years)
Scaling factor used for long term correction [%]	-2.0 %
Long-term average annual wind speed at wind farm zone at 130m height [m/s]	10.1

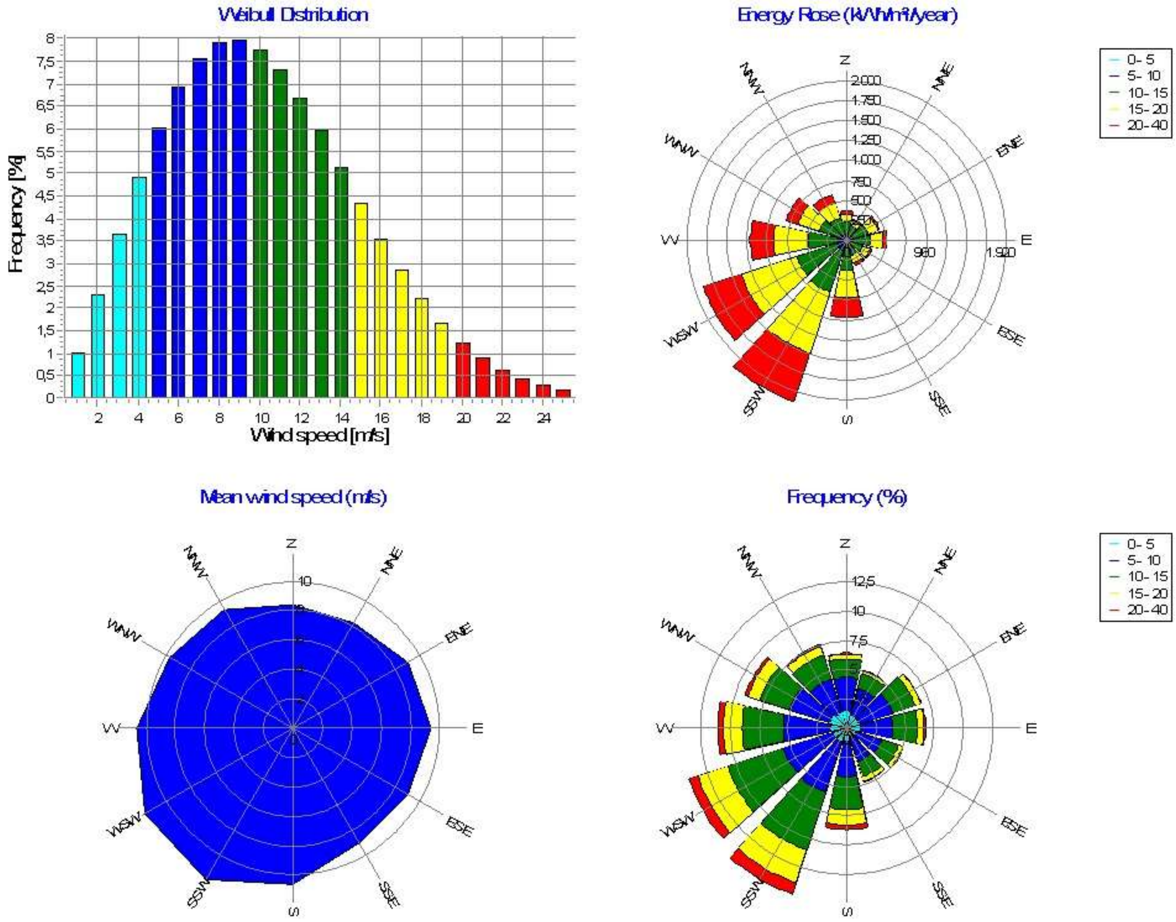


Figure 2 Wind climate summary at a central site data point in the HKW wind farm zone at 130m height.

It should be noted that the HKW metocean measurement campaign had not been finalised at the time of writing, therefore no measurement data from the deployed Floating LiDAR Sea Watch Systems was analysed. This is not considered critical for the outcome of this assessment.

Moreover, with the steps taken, there is an inherent uncertainty to the wind speeds presented. Although with the scope of the present assignment no detailed uncertainty assessment has been performed, given the background of the met mast dataset, filtering & MCP and comparison & scaling to mesoscale data, an indicative uncertainty of 3-4% on the wind speed can be expected as a minimum. The on-site wind measurements, as described in the previous paragraph, are able to reduce the uncertainty of the wind climate. In light of the goal of this current study however, which is to compare variants within the same wind farm zone, the absolute wind speed is not crucial.

4.4.2 Water depths

The water depth at the wind farm zones were used to calculate the foundation length (above seabed) at the turbine locations. The data was derived from bathymetry data provided by Rijkswaterstaat. The bathymetry dataset covers the entire Dutch continental shelf and the data was collected during several different measurement campaigns, during several years. The data was collected and made ready for use by Rijkswaterstaat.

Figure 3 shows the bathymetry for the HKW wind farm zone.

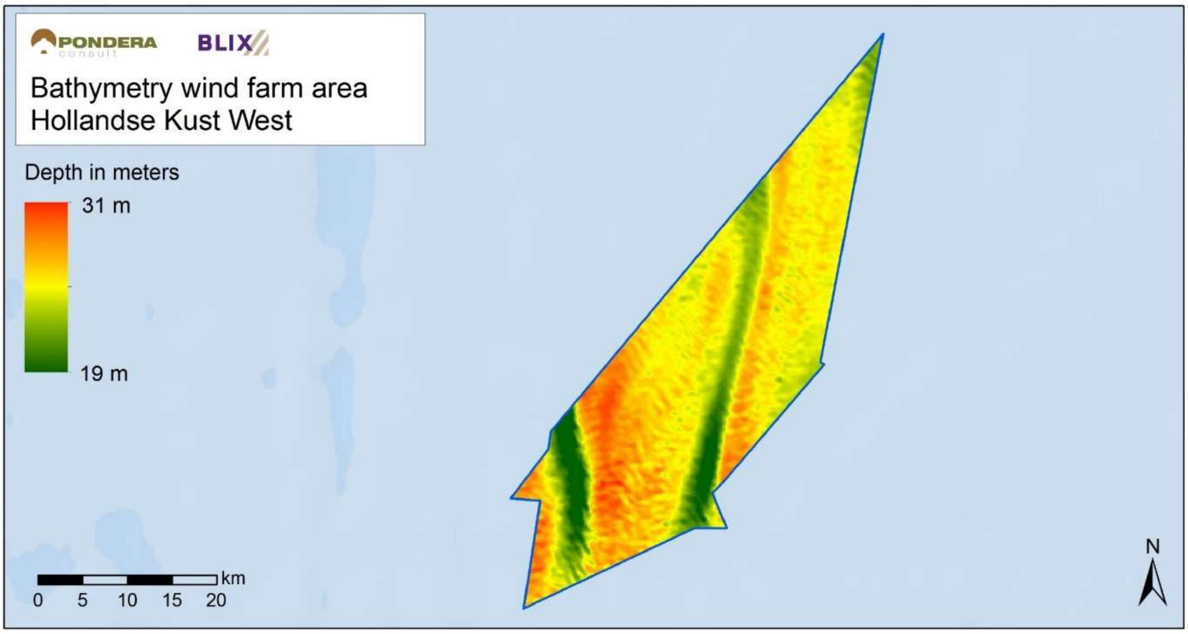


Figure 3 Bathymetry map Hollandse Kust (west).

The HKW site shows two distinct sand banks running north to south across the wind farm zone with a small gradient in depth towards the northeast, where it becomes shallower. Water depths for HKW range from roughly 20 to 30 meters.

4.4.3 Wave conditions

For HKW and TNW, the wave conditions were also used to calculate the foundation cost, since they affect the loads on the foundation. Since no metocean study had been performed for the future wind farm zones, the design storm conditions were estimated based on the DHI metocean report for Hollandse Kust (noord). The assumed values are shown in Table 5.

Table 5: Design conditions with a 50-year return period

Parameter	Hollandse Kust (west)
Significant wave height [m]	7.7
Peak wave period (s)	12.7

The wave heights and currents were assumed to be uniform at each site. In reality they will differ in the order of 0.1 – 0.2m and 0.1 – 0.2s across the site, but these differences were assumed to lead to negligible differences between the LCoE of the variants.

4.4.4 Soil conditions

The soil conditions were used to determine the required foundation depth (below seabed). Based on expert advice from our soil expert (Wind Support), the following values were assumed (see Table 6).

Table 6: Assumed soil parameters

Parameter	Hollandse Kust (west)
Assumed soil profile	uniform medium dense to dense sand
Characteristic friction angle [degrees]	35
Submerged unit weight [kN/m^3]	9.5

Standard API P-y curves for sand were used, which were generated automatically using SACS software.

In reality the soil conditions may differ across the site. Detailed soil information was not available at the time of this study and therefore the soil parameters were assumed to be uniform.

4.4.5 Current obstructions and stakeholders

The shape of the Hollandse Kust (west) zone is mainly determined by the IMO shipping passages running around the wind farm zone. Other important current stakeholders are oil and gas platforms at the north and south of the wind farm zone. The helicopter traffic zones around the platforms are reflected in the different variants that were investigated in this study.

The Hollandse Kust (west) zone has several telecom cables and pipelines running along the site boundaries as well as through the wind farm zone itself. Some of the pipelines are currently out of use. Table 7 provides a description of the infrastructure. Figure 4 shows all relevant obstructions and stakeholders near and in the wind farm zone.

Table 7: Overview of existing obstructions and infrastructure

Item	Hollandse Kust (west)
Nature preservation areas	None
Shipping passages	On all sides of the wind farm zone
Helicopter zones	One north and one south of the wind farm zone
Existing oil & gas platforms	Three north and one south of the wind farm zone; P06-A, P06-B, P06-D, en P09-Horizon
Existing wind farms	None present
Existing telecom cables	Two running through the wind farm zone
Existing pipelines	Numerous running through the wind farm zone
Out of use pipelines	Two: P06-B to P6-C and P06-B to P06-South
Areas used by military	None
Dredging licenses	None

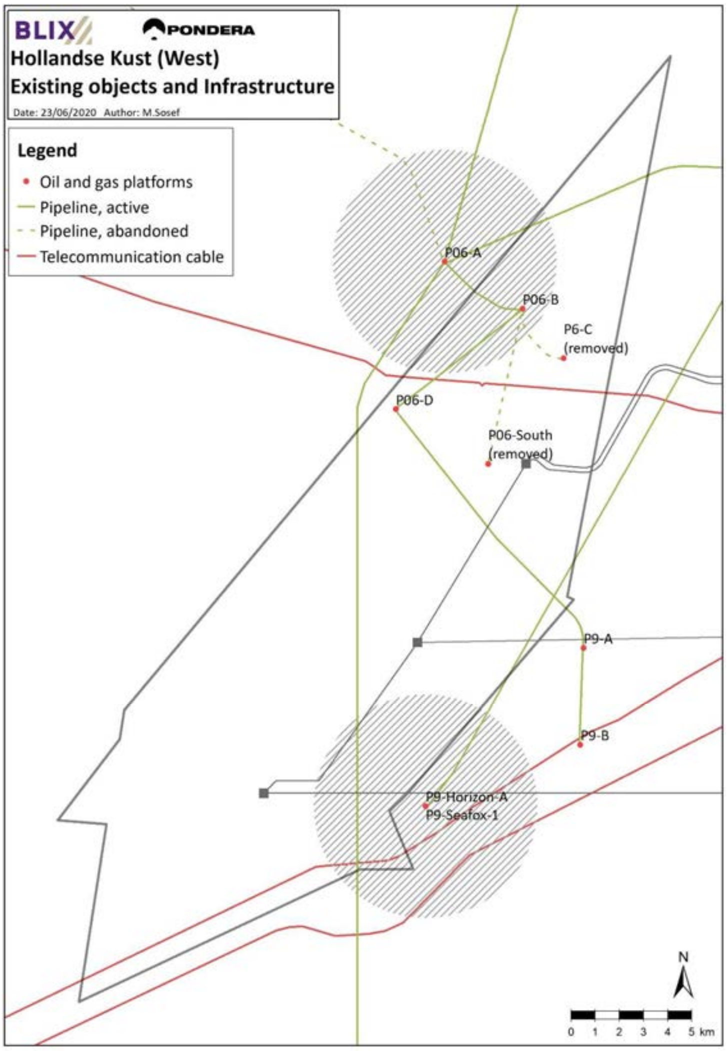


Figure 4 Obstructions and infrastructure around Hollandse Kust (west)

4.5 Wind farm layouts and yield calculations

The wind farm layouts of the variants are defined using the following guidelines:

- The layout basis of every wind farm site (Dutch: 'kavel') is a rectangular grid of wind turbines that are positioned along the longest site boundaries. A minimum wind turbine spacing of five times the rotor diameter is applied, which avoids the largest turbulence effects;
- When a site is divided in several sub-areas, for example by a maintenance zone across the site, separate grids are defined if this enhances wind turbine placement possibilities and if this reduces the overall wind farm density of the site;
- Wind turbines are placed along the wind farm zone boundaries as much as possible. This is done to minimize wake losses;
- One site contains 63 wind turbines of 12MW each, adding up to a 756MW capacity. As the maximum capacity of TenneT platforms is 700MW, there is 56MW of surplus capacity. This principle, called 'overplanting', leads to higher energy yields at lower wind speeds but leads to power curtailment at higher wind speeds. Overplanting is common in offshore wind farms.

The layouts comply with applicable wind farm site rules and regulations; i.a. wind turbine positions comply with maintenance distances from existing pipelines and telecommunication cables (500m), nor do turbine blades exceed the boundaries of the wind farm zone. The technical assumptions for the wind farm layout and yield determination are summarised in Table 8:

Table 8: Technical assumptions for wind farm layouts and yield

Parameter	Assumption	Reference
Turbine capacity	12MW	Based on experience and brief market consultation
Rotor diameter	200m rotor diameter	Based on currently available information
Hub height	130m	Based on 30m clearance
Power curve	Confidential	Based on available prototype
Capacity per wind farm site	756MW	Based on the standard 700MW TenneT platform. 56MW overplanting is assumed as reference in consultation with the Working group.
Infield cables	66kV, 6 WTG/string	Based on assessment of Energy Solutions (assuming 630A switchgear in turbines)
Construction & maintenance harbours	Rotterdam (HKW)	Based on currently available information
Wake losses	NO Jensen 2005 model, using offshore Wake Decay Constant (WDC) 0.03	Industry standard for basic AEP calculations, with WDC following EMD recommendations and practical experience from nearby projects
Cable losses	Use of an increased losses formula when more turbines feed power over an inter-array cable. Formula is confidential	Provided by Energy Solutions

After determination of the layouts for each variant, the inter array cabling has been defined for each site, which contains one offshore substation. A maximum of six 12MW wind turbines are placed on one string.

With turbine positions and cabling determined, the gross annual energy yield for each turbine will be calculated using WindPRO and WasP. The calculations include the present, albeit small, wind speed gradients across the wind farm zone. Each wind turbine is assigned to the closest wind climate node to calculate its gross annual energy yield.

The net annual energy yield is calculated by subtracting loss factors from the gross annual energy yield. The following loss factors are considered:

Wake losses

The dominant loss factor is the wake effect, and is described as the aggregated influence on the energy production of the wind farm, which results from the changes in wind speed caused by the impact of the turbines on each other. The existing offshore wind farms Windpark Egmond aan Zee (OWEZ), Prinses Amalia wind farm and Luchterduinen windfarm were modelled, in order to include their wake effects in the calculations. The actual built wind turbine types and hub heights were used.

Infield cable losses
Electrical losses in power cables occur due to heat build-up in the cables, increasing the cable resistance. The infield cables have been drawn for every variant. The electrical losses are calculated based on the infield cable length. Export cable losses are excluded from this analysis.

Wind turbine non-availability
This production loss concerns the periods of a wind turbine that is not in operation due to maintenance, malfunctions and repositioning of the wind turbine nacelle. The losses for offshore wind turbines are assumed to be 5%.

Other losses
Other environment-related losses are included in the energy production calculation, such as blade degradation losses due to contamination, shutdown events due to lightning or hail or wind speed hysteresis (fluctuations of wind speeds around cut-off wind speed).

4.6 Financial model

The LCoE calculations have been conducted with the financial model of BLIX. This model has been developed throughout the years, used for many projects, and has been validated several times for projects BLIX worked on. The LCoE model uses the same assumptions as used for the 2018 LCoE study so that the results of both studies can be compared with each other.

The model inputs are based on the latest projects BLIX participated in at that time (2018), such as the Dutch offshore wind tenders (Borssele I&II, III&IV and Hollandse Kust (zuid) I&II), German offshore tenders (latest 2017) and UK offshore tenders (latest 2018). Due to the in-depth & diverse market insights that BLIX has gained in offshore wind projects, this model and its inputs are particularly well equipped for conducting LCoE comparison studies.

For this study it is assumed that the wind-farm is financed on a balance sheet basis (an alternative approach would be to assume project finance[3]). This approach gives the cleanest approach of the LCoE of the offshore wind farms.

4.6.1 Levelized cost of energy

The definition of Levelized Cost of Energy from Wikipedia is:

The levelized cost of energy (LCoE) is the net present value of the unit-cost of energy over the lifetime of a generating asset. It is often taken as a proxy for the average price that the generating asset must receive in a market to break even over its lifetime.

The LCoE is therefore represented by the following formula (simple form):

$$LCoE = \frac{Sum\ of\ costs\ of\ windfarm\ over\ lifetime\ (in\ euro)}{Total\ \ produced\ electricity\ (MWh)}$$

[3] A project finance approach for calculating a LCoE for offshore wind would also include financing costs, as project finance uses bank loans to finance a large part of the project CAPEX. The LCoE of a project finance wind-farm will therefore also include these costs. As in this study we would like to mainly focus on the wind-farm costs/CAPEX, we have decided to take a balance sheet financing approach. This approach is very much in line in how several large developers finance their wind project.

When including the discounting of cashflows, the detailed formula looks as follows:

$$LCoE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Production_t}{(1+r)^t}}$$

Where[4];
n = total number of years
t = year
r = required return/WACC
CAPEX = Capital Expenditure (Investments)
OPEX = Operational Expenditure (Operational costs)

The inputs of Table 9 feed into the wind farm cost part of this formula and are discounted based on the required return over the lifetime of the wind farm. The LCoE per variant is calculated by dividing the discounted costs by the yield per variant. After calculating the LCoE per variant, the LCoE of the different variants will be compared and analysed.

The yield and costs are calculated on a per turbine basis. The main varying parameters are the yield (through wake losses), the foundation costs (through water depth differences), cable length & cable losses and number of cable crossings. OPEX costs and turbine prices do have a large impact on the absolute level of LCoE but are not expected to differ (significantly) between the variants. This is because these costs will not be affected by changing the layout (these costs are primarily driven by the type of turbine, and these are the same for every variant).

4.6.2 Assumptions

The main cost assumptions are shortly explained in Table 9. As mentioned in previous chapters, most of these items will not impact the relative LCoE analysis. Therefore, most attention is paid to the items that do impact the relative LCoE (see Table 3).

[4] The LCoE will (in most literature cases) furthermore be corrected for tax costs therefore making the LCoE a post-tax LCoE (not taken along in the above formula)

Table 9: Costs assumptions for financial model

Parameter	Assumption	Reference
Capital Expenditure (CAPEX)		
Cost of turbine	Confidential	Based on BLIX price database
Foundation method	Monopiles	Expected to be economically favourable in the considered water depths
Steel prices	Based on latest market prices (2018)	Based on BLIX price database
Foundation weight	Use of formula that is based on relation water depth and wave conditions. Formula is confidential	Based on BLIX price database
Foundation costs	Includes supply & installation of foundations. Costs are confidential	Based on BLIX price database
Inter Array Cable costs	Based on aluminium inter array cables. Costs are confidential	Based on BLIX price database
Cost for cable crossings	Based on number of crossings per site. Costs are confidential	Based on BLIX price database
Other CAPEX	Various items (e.g. port facilities & construction management). Costs are confidential	Based on BLIX price database
CAPEX Contingency level	Based on market conform levels (2018).	Based on BLIX price database
Insurances during construction	Delay Start-Up, Construction All-Risk, Third Party Liability. Rates are confidential.	Based on BLIX price database
Development expenditure (DEVEX)	Confidential	Based on BLIX price database
Operational Expenditure (OPEX)		
Management costs	Based on small operational team	Based on BLIX price database
WTG maintenance	Use of Service Maintenance Agreement (SMA) with turbine supplier. Costs are confidential	Based on BLIX price database
Insurances during operations	Operational All-Risk, Business Interruption, Third Party Liability. Rates are confidential	Based on BLIX price database
Balance of Plant maintenance	Based on maintenance service provider costs. Costs are confidential	Based on BLIX price database
OPEX contingency level	Based on market conform levels (2018)	Based on BLIX price database
Other Assumptions		
Financing	Project is financed on balance sheet	Deemed most representative
Required return on investment	Based on market conform levels (2018)	Based on experience
Revenues	Not required for LCoE calculations	
Indexation levels	2% a year	Based on BLIX price database
Depreciation period	20 years	Based on BLIX price database

4.7 Grid connection

The location(s) of the TenneT substations of the northernmost two sites (VI and VII) were provided by RVO in close collaboration with TenneT. The location of the substation of the southernmost site (VI (alternative)) was determined by the project team, based on a number of main principles of TenneT for determining the location of the substation. Most important about the location is that the substation of site VI (alternative) is placed as centrally as possible in the wind farm (in north-south and east-west direction), a little closer to the coast (in east-west direction), away from obstacles and in a location with good soil conditions.

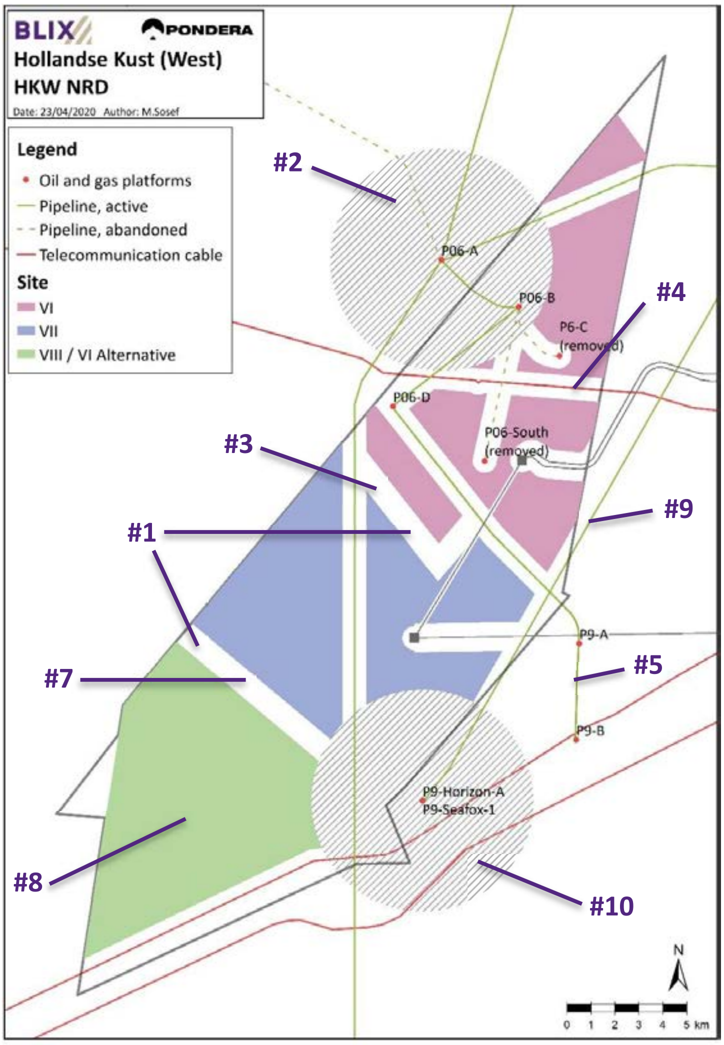
5 WIND FARM LAYOUTS

5.1 Introduction

Indicative wind farm- and infield cable lay-outs were designed to determine the relative LCoE differences between the wind farm zones and sites. This level of detail allows the determination of yields and costs on a turbine level, instead of crude assumptions based on e.g. a reduction in available area (and/or density) of wind turbines. This level of detail is required to obtain results that distinguish detailed differences between the sites and allows us to draw substantiated conclusions.

5.2 Reference variant NRD

Figure 5 shows the wind farm layout as based upon the definitive Memorandum Scope and Level of Detail (Dutch: 'Notitie Reikwijdte en Detailniveau' or 'NRD')[5]. This layout is used as reference variant of this study.



[5] https://www.rvo.nl/sites/default/files/2019/11/DEF%20Vaststellen%20NRD%20Kavelbesluiten%20VI%20en%20VII%20HKW%20voor%20de%20website.pdf

Figure 5: Base assumptions in reference variant NRD

The base assumptions for the site boundary options of variant NRD are as follows:

- #1. A safety zone of 1000m in between sites VI and VI and in between sites VII and VI alternative;
- #2. Wind turbines can not be placed in Helicopter traffic zone P06-A;
- #3. Shipping passage between site VI and VII doesn't fully coincide with the wind farm safety zone of site VI and VII;
- #4. Maintenance zone around the telecom cable of 500m on both sides;
- #5. Maintenance zones of 500m on both sides around pipelines connected to gas platforms P06-A, P06-B, P6-C, P06-D, P06-South, P9-A and P9-B;
- #6. The net area of site VI, VII and VI (alternative) is based upon the NRD and shows no equal distribution of the area of the sites;
- #7. Orientation site boundaries of site VII and VI (alternative) is based upon the NRD;
- #8. The NRD reference variant takes into account the realisation of windfarms in sites VI and VII. A realised windfarm in site VI (alternative) is not taken into account;
- #9. Maintenance zones of 500m are applied on both sides of all pipelines connected to P9-Horizon;
- #10. Wind turbines are not placed inside the Helicopter traffic zones (HTZ) of P9-Horizon-A;
- #11. Maintenance zone of 500m on both sides around the telecom cable to the south of site VI alternative.

These numbers correspond with the numbers mentioned in Figure 5, #6 is not presented in this figure.

5.3 Variant definition

The variants A, B, C, D, E were defined to investigate the effects of changes in the assumptions #1 to #6 of paragraph 5.2 on the energy yield and LCoE of the wind farm layouts according to Table 10. Each variant includes one modification compared to the previous variant, see also Table 12.

Table 10: Description of the variants NRD and A through E

Variant	Assumption
NRD	Reference case – as described in paragraph 5.2
A	Based on NRD with modified shipping passage width to 1500m [#1]
B	Based on variant A without helicopter traffic zone around platform P06-A [#2]
C	Based on variant B where the shipping passage between site VI and VII fully coincides with the wind farm site safety zones [#3]
D	Based on B with exclusion of maintenance zones around the telecom cable [#4], and of the maintenance zones around pipelines connected to P06-A [#5]
E	Based on D with equal distribution of the net area of site VI, VII and VI (alternative) [#6]

The basic principle in the E.I.A is that a northern (VI) and a southern option (VI (alternative)) for site VI is investigated. In order to give both variants equal opportunities, this LCoE study aimed for an equal LCoE for both alternatives in variant E.

Based on intermediate results and new insights by the Working Group a new reference variant F was defined and new variants G, H were added, see Table 11.

Variant F is based on modified site boundaries based upon the results of variants A through E; the shipping passage width is set to 1050m [#1], the maintenance zones around pipelines connected to gas rigs P06-A, P06-B, P6-C, P06-D, P06-South, P9-A and P9-B is set to 2x150m instead of 2x500m [#5] and the orientation of the boundary of the sites VII and VI (alternative) is exactly East-West oriented [#7]. Variant G investigates the effect of assuming a wind farm at site VI (alternative) [#8]. Variant H is an optimised version of variant G in which the LCoE is the same for every site, this was done via an iterative process by displacing the sites boundaries [#7].

Table 11: Description of the variants F through H

Variant	Assumption
F	Based on variant C with modified shipping passage width to 1050m [#1], 2x150m maintenance zones around pipelines connected to P06-A [#5] and east to west orientation of shipping passage between site VII and VI (alternative) [#7]
G	Based on variant F taking site VI (alternative) into account [#8]
H	Based on variant G with equal LCoE output of site VI, VII and VI (alternative) through displacement of shipping passage between site VI / VII and VII / VI (alternative) [#7]

Table 12 describes the different variants in more detail.

Table 12: Overview of all variants

#	Parameter	NRD	A	B	C	D	E	F	G	H
#1	Shipping passage width	1000m	1500m	1500m	1500m	1500m	1500m	1050m	1050m	1050m
#2	Wind turbines placed in Helicopter traffic zone P06-A	no	no	yes	yes	yes	yes	yes	yes	yes
#3	Shipping passage between site VI and VII coincides with the site boundaries	no	no	no	yes	no	yes	yes	yes	yes
#4	Maintenance zone around telecom cable of 2x500m	yes	yes	yes	yes	no	no	no	no	no
#5	Maintenance zones around pipelines connected to gas rigs P06-A, P06-B, P6-C, P06-D, P06-South, P9-A and P9-B	2x500m	2x500m	2x500m	2x500m	no	no	2x150m	2x150m	2x150m
#6	Equal distribution of the net area of site VI, VII and VI (alternative)	no	no	no	no	no	yes	no	no	no
#7	Orientation site boundaries (by shipping passage) of site VII and VI (alternative)	-39.9°	-39.9°	-39.9°	-39.9°	-39.9°	-39.9°	0°	0°	-4.6°
#8	Influence of wind farm at site VI (alternative) included	no	no	no	no	no	no	no	yes	yes

= changed parameter compared to previous variant

Figure 6 - Figure 14 illustrate the net usable area of variants NRD, A, B, C, D, E, F, G and H. Each variant includes one change compared to the previous variant as described in Table 12. The net areas of variant F and G are identical, as only the wind farm layout is modified in variant G (i.e. wind turbines added in site VI (alternative)).

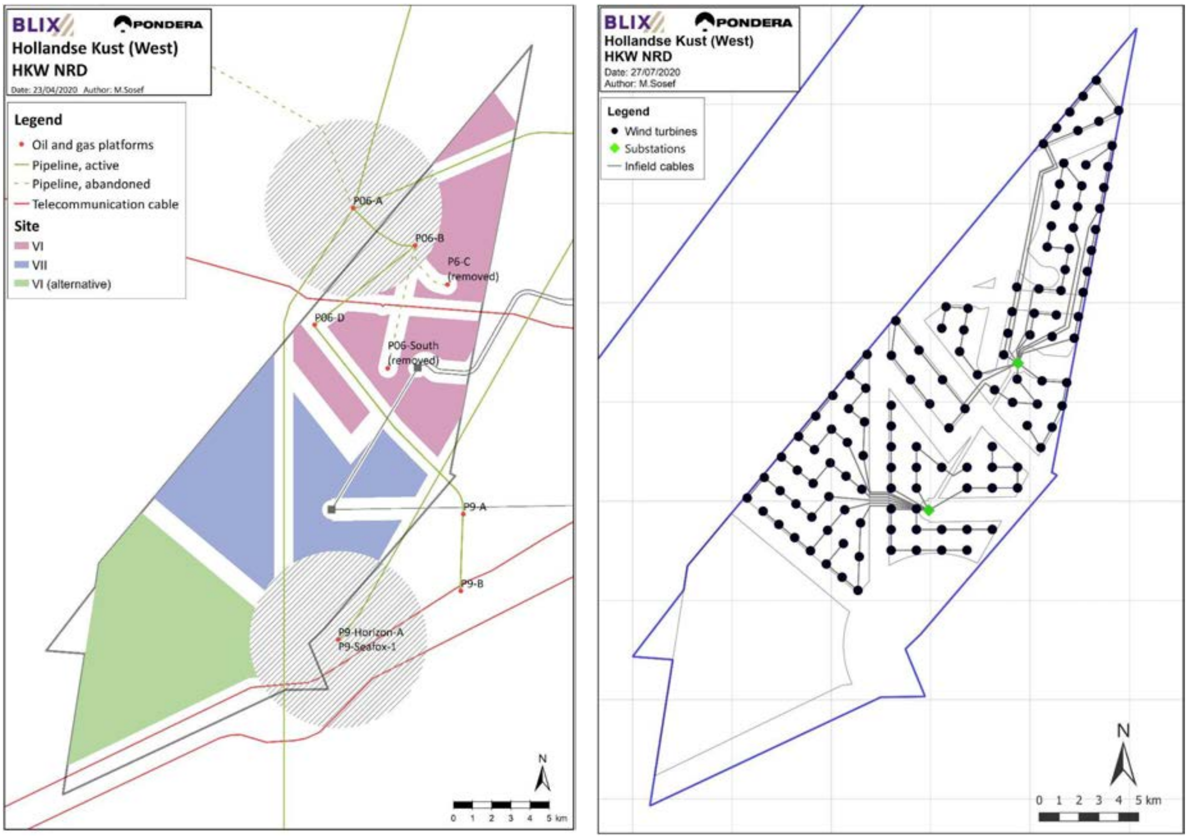


Figure 6: Variant NRD

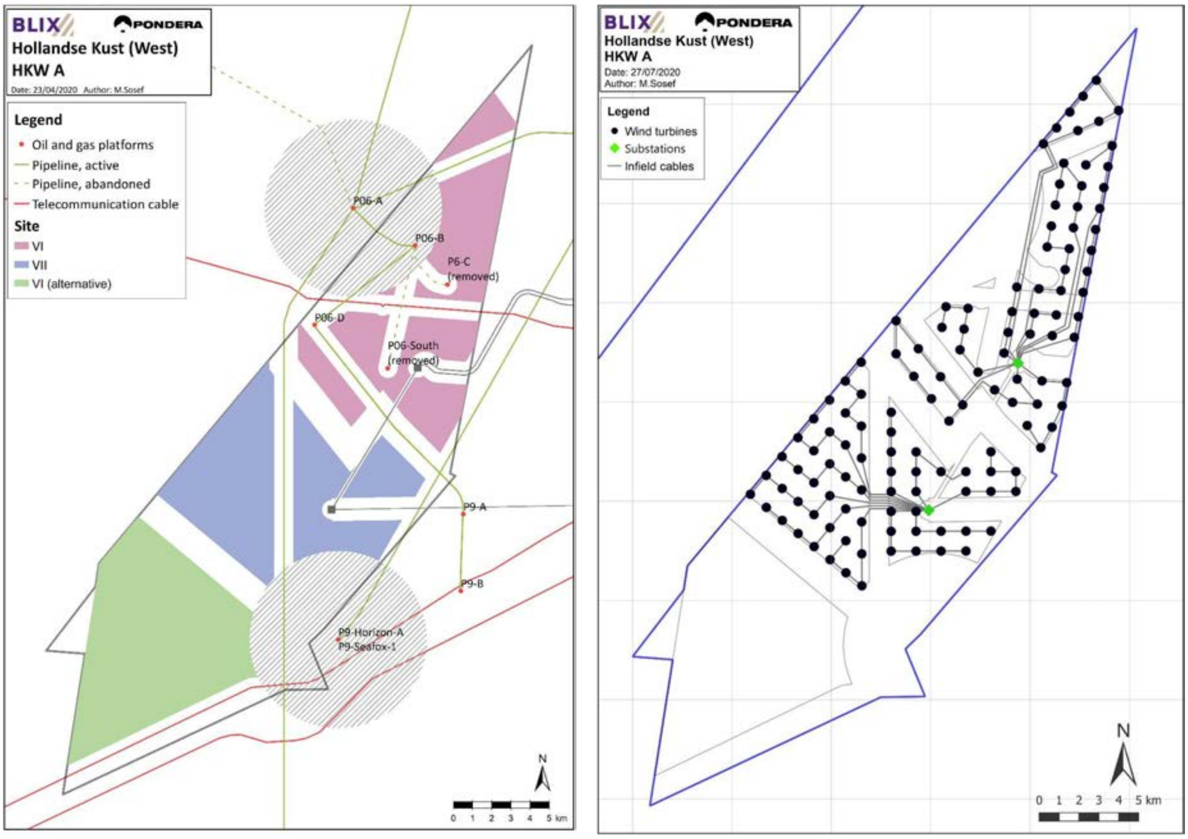


Figure 7: Variant A – Shipping passage 1500 m

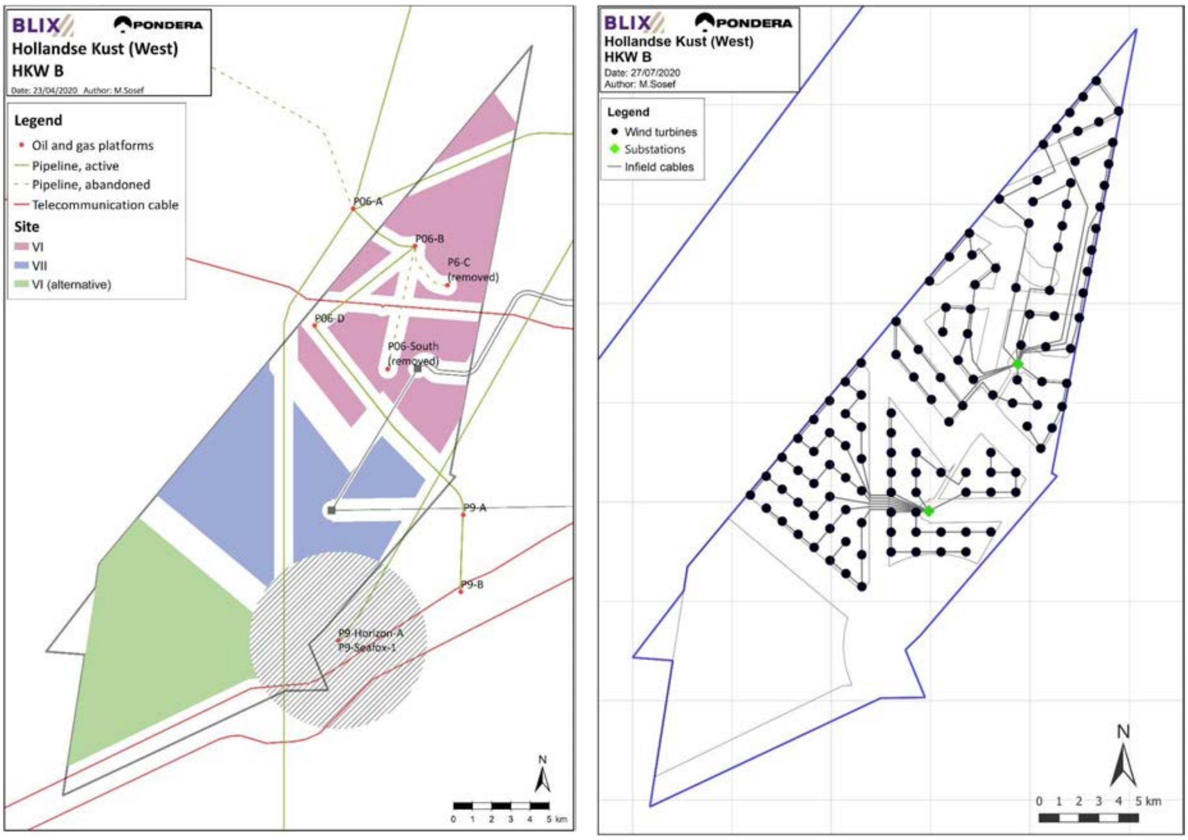


Figure 8: Variant B – HTZ P06-A excluded

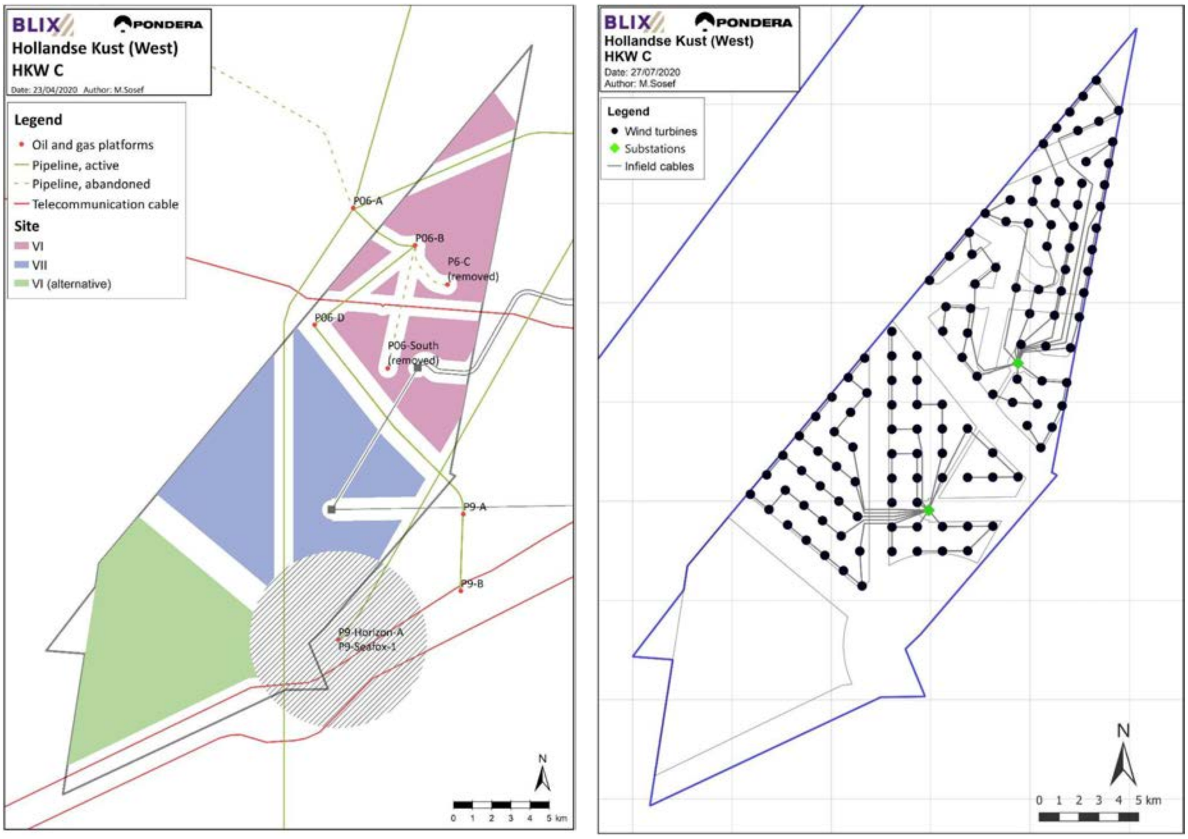


Figure 9: Variant C – Shipping passage as site boundary VI / VII

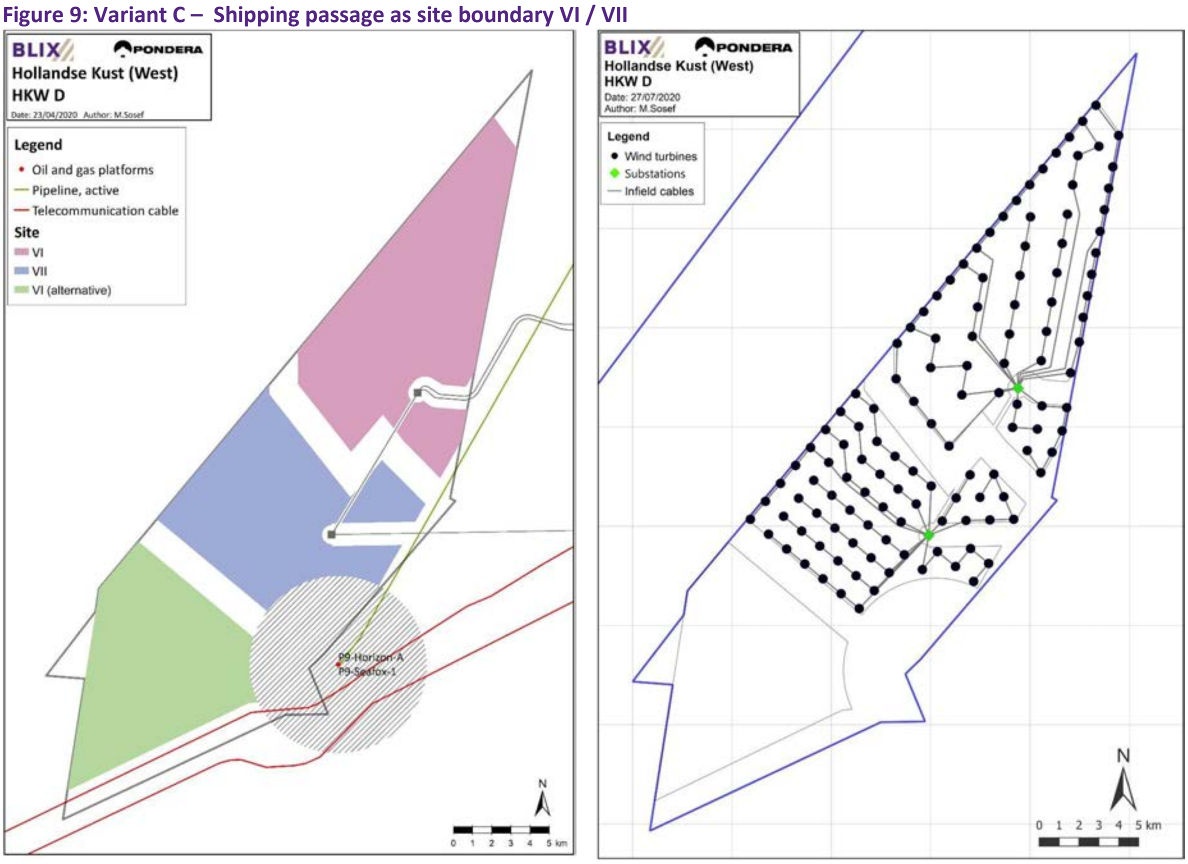


Figure 10: Variant D – maintenance zones excluded

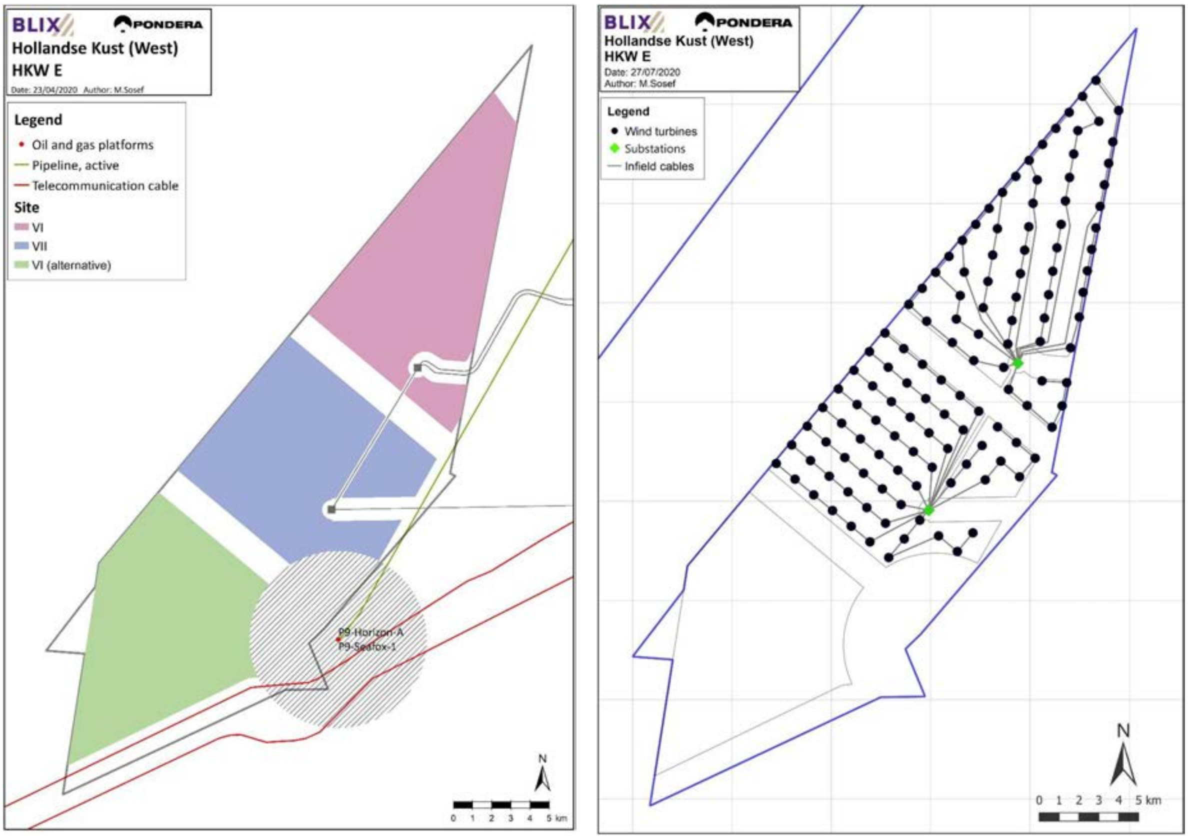


Figure 11: Variant E – Equally distributed areas

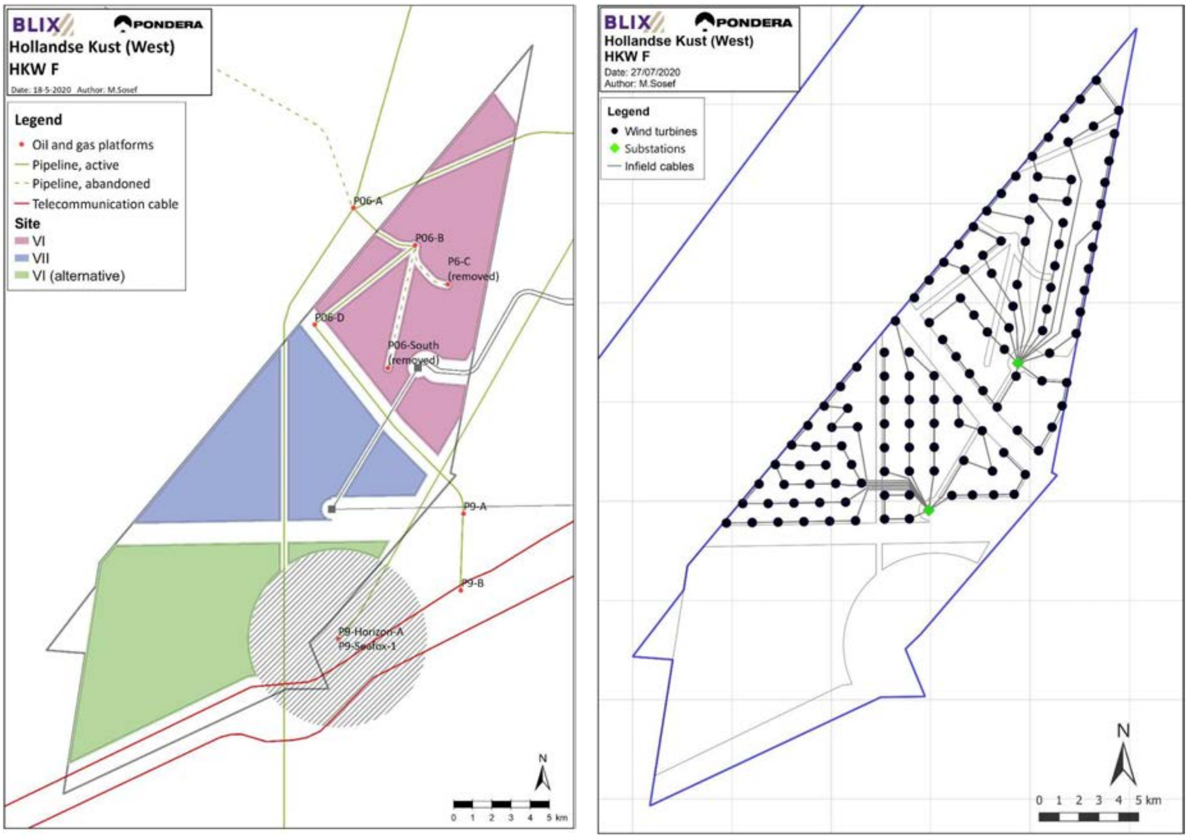


Figure 12: Variant F – shipping passage width to 1050m / 2x150m maintenance zones around pipelines and telecom cables / East-West orientation of shipping passage at site boundary VII - VI (alternative)

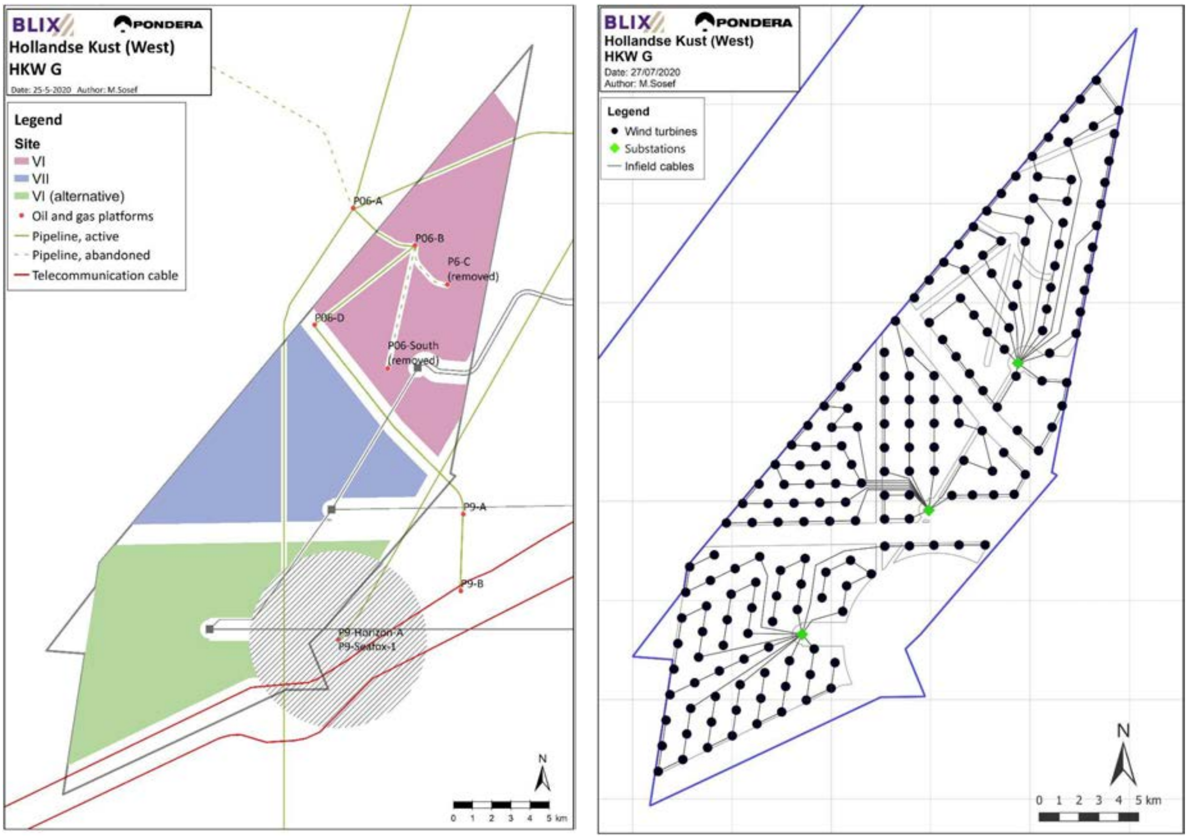


Figure 13: Variant G – Site VI (alternative) included

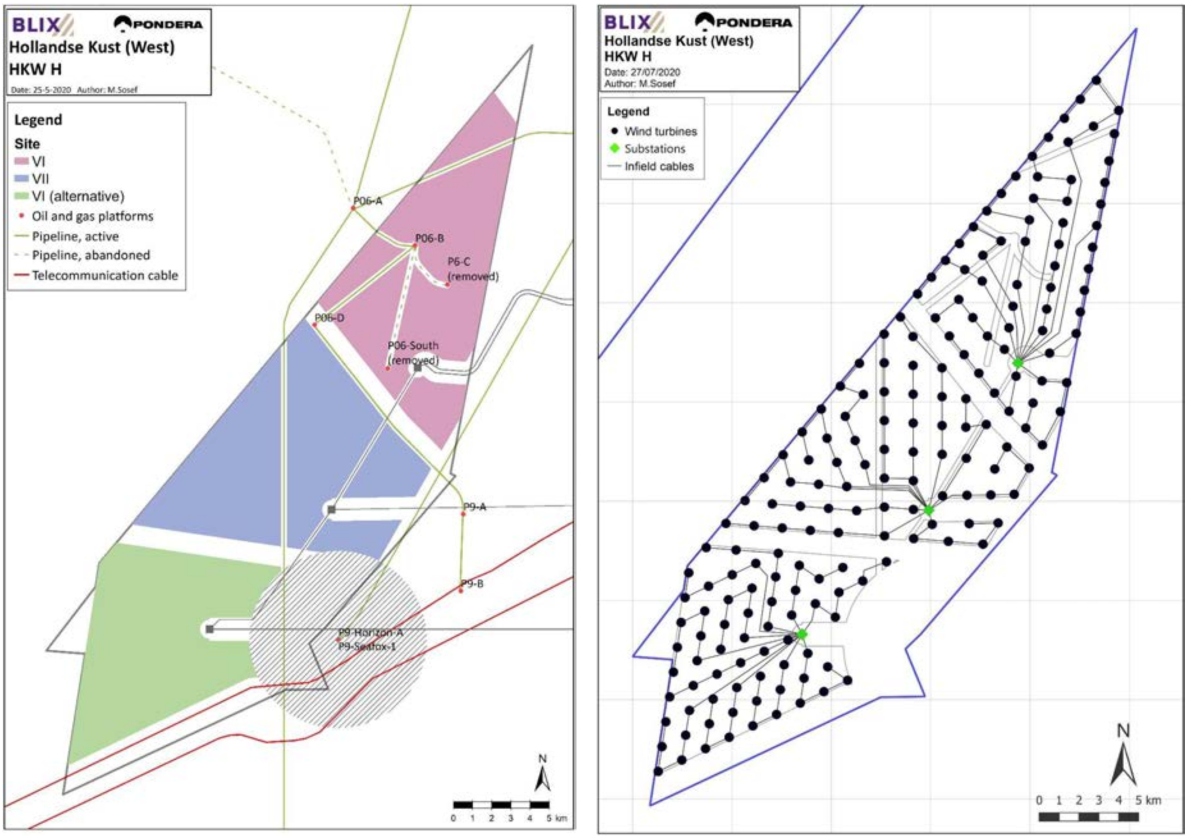


Figure 14: Variant H – Equal LCoE for all three sites

5.4 Sensitivity analyses

Two leading assumptions of the main study were changed, which are the layout determination and the wind turbine dimensions. Those modifications are described in following paragraphs. The sensitivity analyses were carried out using the same layout as variant H.

This paragraph describes the wind farm layouts. The yield and LCoE results are presented in chapter 6 and 7 respectively.

5.4.1 WindPro layout sensitivity analysis

The wind farm layouts of all variants are drawn based on the guidelines described in paragraph 4.5. In this sensitivity analysis a different approach is chosen to define a wind farm layout. This is done through an automatised layout design algorithm in WindPRO. The result is shown in Figure X. A regular grid is assumed with a fixed distance between wind turbines of 5 times the rotor diameter. No design parameters are set for grid orientation, which means that the grid is oriented north to south. Based on these settings, WindPRO’s design algorithm optimises the wind farm efficiency by eliminating wind turbines from the layout that suffer from the highest wake losses. This explains the gaps in the layout as shown in Figure 15.

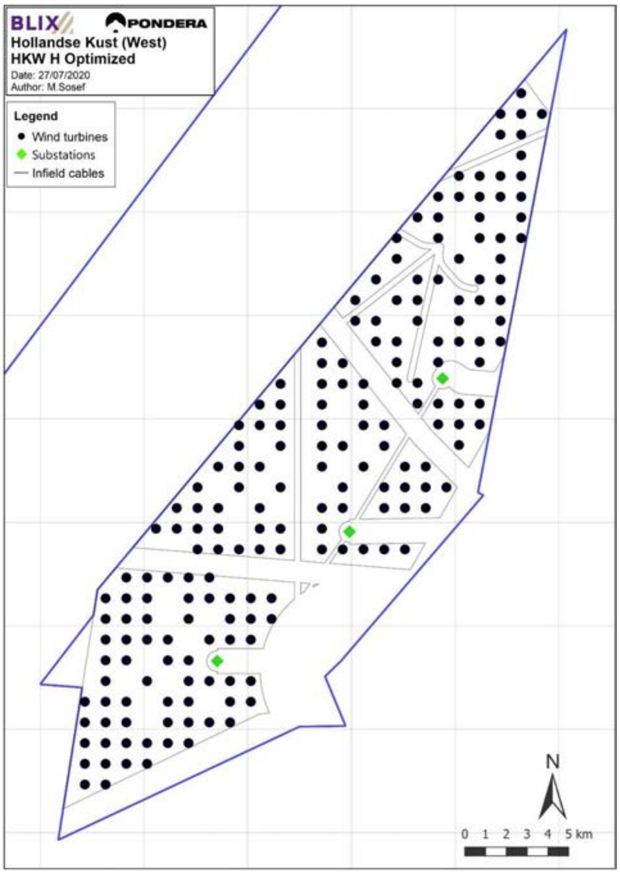


Figure 15: WindPro layout

5.4.2 15MW sensitivity analysis

All variants assume layouts with 12MW wind turbines with rotor diameters of 200m. A sensitivity analysis is conducted to find out if modifying the wind turbine size and nameplate capacity leads to different results. This effect is studied through a sensitivity analysis on variant H in which 15MW wind turbines are used for the wind turbine layout.

Table 13 shows the design parameters and technical assumptions used for a 15MW wind turbine in this study. The wind farm layout is shown in Figure 16.

The cost assumptions used in the LCoE model have also been adjusted to 15MW turbines.

Table 13: Comparison of technical assumptions for 12MW and 15MW wind farm layouts

Parameter	12MW WTG assumptions	15MW WTG assumptions	Reference for 15MW WTG assumptions
Turbine capacity	12MW	15MW	Based on experience and brief market consultation
Rotor diameter	200m rotor diameter	220m rotor diameter	Based on currently available information
Hub height	130m	140m	Based on 30m clearance
Power curve	Confidential	Confidential	Upscaled version based on available prototype.
Capacity per wind farm site	756MW	750MW	Based on Borssele WFZ. No overplanting is required.
Infield cables	6 kV, 6 WTG/string (assuming 630A switchgear in turbines)	66kV, 6 WTG/string (assuming 800A switchgear in turbines)	Based on assessment of Energy Solutions

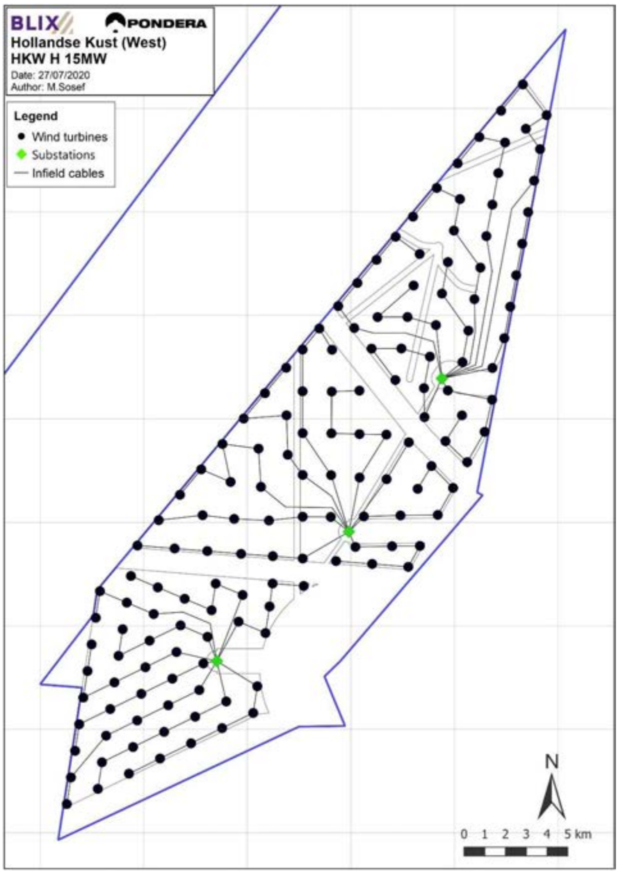


Figure 16: 15MW layout

6 YIELD ANALYSIS

6.1 Yield results per variant

Table 14 shows the main outcomes of the HKW wind farm layout and yield assessment. The following can be observed for variants NRD and A through E:

- The overall annual wind speed is the same for every variant. This is due to a very limited wind gradient across the site. The wind gradient therefore does not influence the relative LCoE between the variants.
- The gross annual yields are roughly the same for variants NRD and A through E (<0.05% difference). The differences in net annual yield are related to the differences in wake losses.
- The wake loss is generally closely related to the wind farm net density. Variant A has the highest wind farm net density and also the highest wake loss. This effect is observed in all variants with the exception of variant D, where the wind farm density decreases by 20% but the wake loss remains the same. This is caused by the fact that the maintenance zones (1000m width) are equal to or smaller than the current wind turbine spacing. The exclusion of maintenance zones in variant D leads to more placement options for the wind turbines, but not to a smaller distance between the wind turbine rows in the remaining area.
- However, there are also exceptions where a reduced density does not cause a proportional reduction of wakes. For example, in the case of 12MW wind turbines the minimum wind turbine spacing is a distance of five times the rotor diameter, which is 1km. 1km is roughly the size of the maintenance zone around the existing pipelines and the TenneT export cable. These maintenance zones in the wind farm zone therefore no longer create substantial loss of available area for wind turbines (i.e. in most cases the wind farm layout can adapt itself to these maintenance zones without creating additional rows). Of course, these maintenance zones limit the future developer somewhat in creating an optimal wind farm lay-out (i.e. when micro-siting the wind turbines) and can have an impact on the cable length and crossings and related cable costs and losses.
- All variants have comparable net annual yields, with the largest difference found between variant D and E (0.8%).
- There is no clear relationship between infield cable length and wind farm density: wind farm density varies between the variants while the infield cable length is fairly similar in all variants. A small effect is observed in variants D and E, where the infield cable lengths are reduced by 4.5 – 6.0% as a result of the exclusion of maintenance zones;
- Variants NRD, A, B and C have a similar number of cable crossings. The telecom cable and pipelines are excluded in variants D and E, resulting in zero crossings.

Table 14 also lists the main outcomes of variants F, G and H, which were added based on the previous variants. Since these variants are significantly different, their outcomes are observed separately:

- The wind farm density of variant F, G and H is significantly lower than variant NRD and A through C but higher than variant D and E. This is due to the reduced maintenance zone width to 150m, which is lower than variant NRD and A through C (500m) but higher than variant D and E (0m).
- The addition of site VI (alternative) is the only difference between variant F and G. This results in an increase in the overall wake loss by 0.8%-point of variant G compared to variant F, thereby reducing the overall wind farm efficiency.
- Compared to variant G, the equal distribution of sites in variant H based on LCoE also leads to a lower overall wind farm density and lower wake effects.

Table 14: Wind farm layout and yield characteristics of Hollandse Kust (west) variants

Variant	NRD	A	B	C	D	E	F	G	H
Number of turbines [-]	126	126	126	126	126	126	126	189	189
Minimal turbine spacing [x D]	5.1	5.0	5.0	5.2	5.2	5.3	5.1	5.1	5.2
Density [MW/km^2]	11.4	12.1	11.2	10.6	8.5	8.9	9.4	9.3	9.2
Mean wind speed at hub height [m/s]	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Gross annual yield [GWh/y]	8,153	8,154	8,154	8,151	8,153	8,152	8,153	12,230	12,231
Wake effects [%]	10.6	10.7	10.3	10.2	10.2	10.8	10.6	11.4	11.2
Net annual yield [GWh/y]	7,288	7,278	7,311	7,316	7,325	7,270	7,288	10,841	10,857
Net annual yield per WTG [GWh/y]	53.3	53.3	53.5	53.5	53.6	53.2	53.3	52.9	53.0
Total infield cable length (km)	221	218	225	229	211	208	222	330	324
Total crossings	20	20	20	19	0	0	16	18	17
Average foundation depth [m]	(26.8)	(26.8)	(26.7)	(26.7)	(26.7)	(26.6)	(26.8)	(26.8)	(26.7)

6.2 Sensitivity analysis

Table 15 shows the outcomes of variant H and the two variants used for the sensitivity analyses. There is little variation in the overall gross energy yield between all layouts.

The wake losses of the WindPRO layout are 1.1%-point higher than variant H, which shows that this layout slightly underperforms compared to variant H. In the 15MW layout, the sharply reduced wake effects in the 15MW layout (2.9 %-point reduction) result in a 3.2% higher net annual yield compared to variant H. The net annual yield for a 15MW wind turbine is 30% higher than the 12MW wind turbine type given the assumptions made in this analysis.

The impact of these sensitivity checks on the LCoE are described in paragraph 7.3.2.

Table 15: Wind farm layout and yield characteristics of Hollandse Kust (west) variant H and sensitivity analyses H – WindPRO layout and H – 15MW

Variant	H	H WindPRO layout	H 15MW
Number of turbines [-]	189	189	150
Gross annual yield [GWh/y]	12,231	12,231	12,219
Wake effects [%]	11.2	12.3	8.3
Net annual yield [GWh/y]	10,857	10,728	11,204

6.3 Relative yield per turbine

For a more in-depth understanding of the observed yield and wake losses for each variant, we investigated the relative yield per individual turbine. Figure 17 through Figure 25 present the relative yield for wind turbines in every variant, visualised with a colour range. A relative yield of 100% implies that there are no wake effects.

Figure 17: Variant NRD

Figure 18: Variant A

Figure 19: Variant B

Figure 20: Variant C

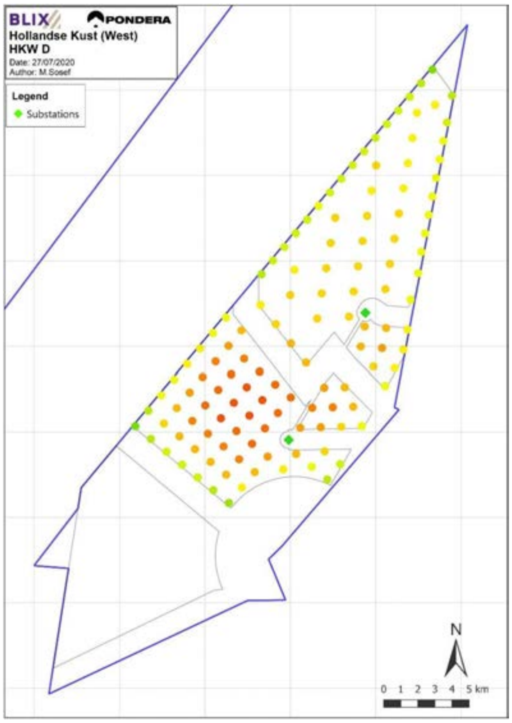


Figure 21: Variant D

Figure 22: Variant E

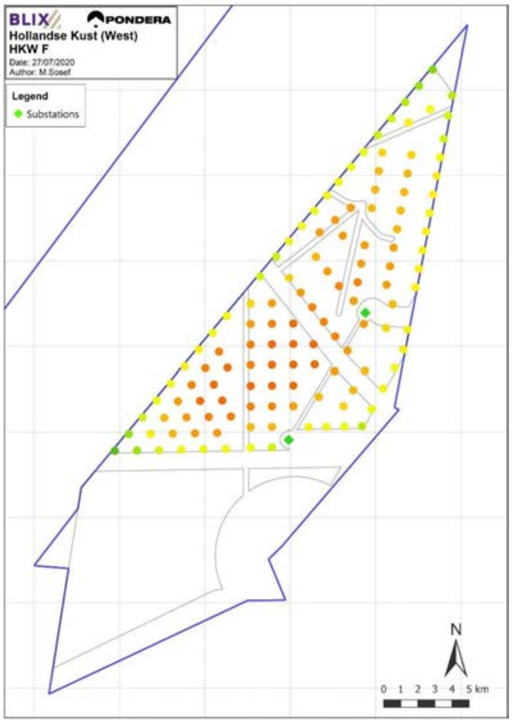


Figure 23: Variant F

Figure 24: Variant G

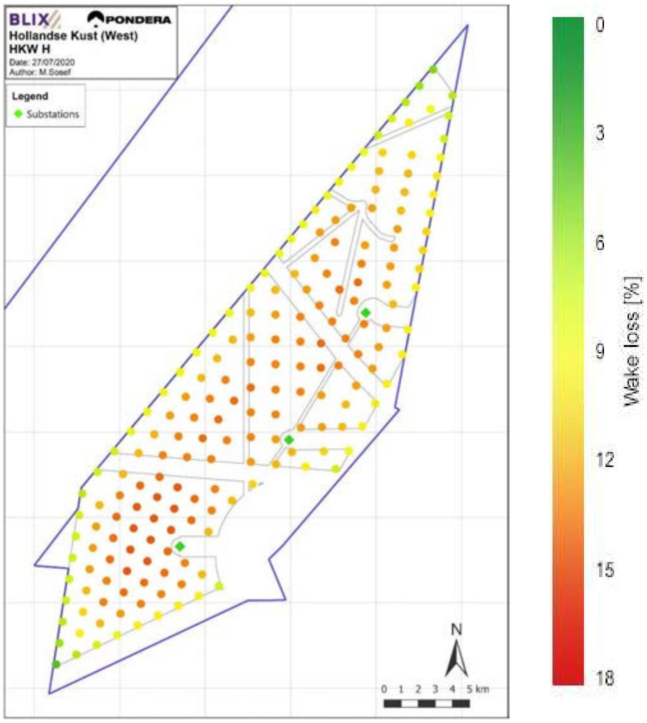


Figure 25: Variant H

The results show the following:

- The outer rows of wind turbines experience less wake effects, as these wind turbines do not suffer from wakes within at least 50% of all wind directions;
- Wind turbines in the centre of sites suffer from accumulated wake effects from all wind directions;
- The triangular and stretched shape of Site VI leads to a smaller number of wind turbine rows in the prevailing wind direction, which means that less wake accumulation occurs. Moreover, a larger number of wind turbines placed on the border that receive less wake effects.
- Site VI (alternative) has the most preferable location as it is situated in the prevailing wind direction (south-west) from the other sites. Site VII is enclosed between the two other sites, which leads to higher wake-effects in this site. This effect is mitigated by increasing the net area of the site, which allows for large turbine spacing;
- Maintenance zones and shipping passages reduce wake effects of the wind turbines closest to them. A larger distance between wind turbines interrupts the accumulation of wake effects.

7 COMPARISON OF LEVELIZED COST OF ENERGY

7.1 Relative LCoE impact

Table 16 and Figure 26 show the impact on LCoE of the different variants compared to the reference variant NRD. Several factors are assumed to remain the same between the variants, these are therefore not in the table below[6].

Table 16: LCoE impact of all variants compared to reference NRD. Note that all given percentages are relative

HKW variant	NRD	A	B	C	D	E	F	G	H
Capacity [MW]	*1,512*	1,512	1,512	1,512	1,512	1,512	1,512	2,218	2,218
ENERGY YIELD									
Wake Losses		1.23%	-2.49%	-3.39%	-4.21%	2.07%	0.02%	7.02%	5.86%
LCoE impact wake		**0.15%**	**-0.29%**	**-0.41%**	**-0.50%**	**0.25%**	0.00%	0.83%	0.70%
IAC cable length		-1.25%	1.86%	3.81%	-4.37%	-5.75%	0.55%	-0.13%	-2.05%
LCoE impact cable		**-0.02%**	**0.03%**	**0.06%**	**-0.06%**	**-0.08%**	**0.01%**	**-0.00%**	**-0.03%**
CAPEX									
IAC cable length		-1.25%	1.86%	3.81%	-4.37%	-5.75%	0.55%	-0.13%	-2.05%
Number of crossings		0%	0%	-5%	-100%	-100%	-20%	-40%	-43%
LCoE impact array cable		**-0.02%**	**0.03%**	**0.05%**	**-0.15%**	**-0.16%**	**-0.01%**	**-0.04%**	**-0.07%**
Average water depth		-0.06%	-0.31%	-0.44%	-0.48%	-0.83%	-0.06%	-0.55%	-0.45%
Foundation costs		-0.01%	-0.07%	-0.10%	-0.11%	-0.20%	-0.01%	-0.00%	-0.05%
LCoE impact		**-0.00%**	**-0.01%**	**-0.02%**	**-0.02%**	**-0.03%**	**-0.00%**	**-0.00%**	**-0.01%**
Net LCoE impact		**0.09%**	**-0.26%**	**-0.29%**	**-0.73%**	**-0.05%**	**-0.00%**	**0.81%**	**0.58%**

[6] Wind-farm availability, wind turbine costs, DEVEX, OPEX and more parameters are assumed to remain constant and are therefore excluded in Table 16.

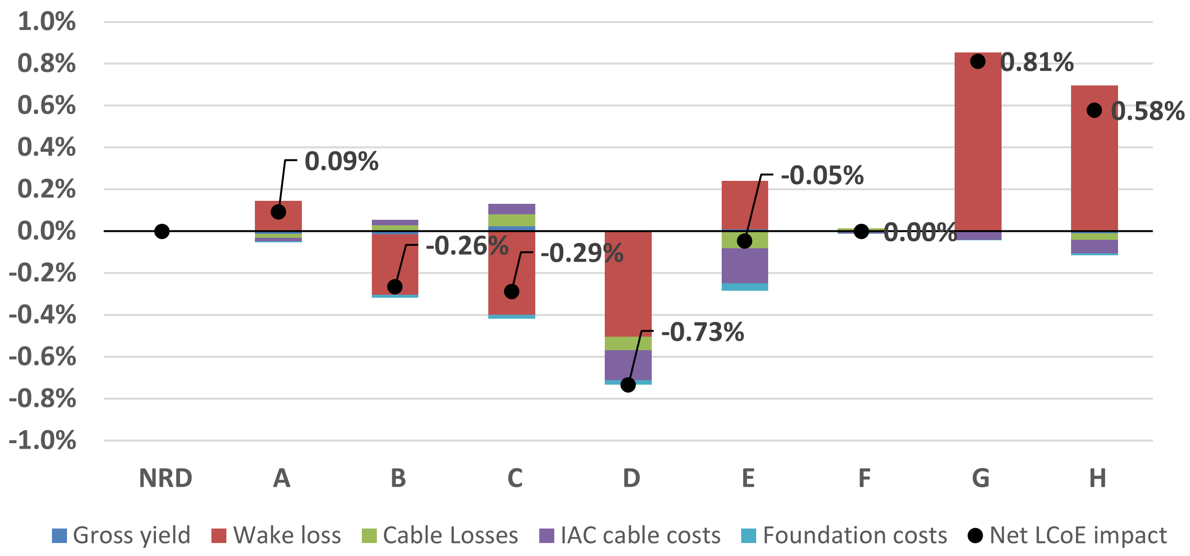


Figure 26: Resulting LCoE difference of eight variants of Hollandse Kust (west) layouts compared to reference layout NRD

The following can be observed for the variants compared to the reference NRD:

- The net LCoE impact compared to the reference NRD varies from a substantial decrease of -0.73% for variant D to a significant increase in LCoE of +0.81% for variant G.
- The wake effects cause the greatest impact on the LCoE differences of the variants A through H from the reference NRD (-0.5% to +0.2%), the impact of the cable losses and cable costs is limited (-0.16% to +0.06%) since the total array cable length differences are limited and the impact of the foundation costs is negligible (-0.03% to 0.00%) because in each variant the turbines are spread more or less equally over the site.

7.2 Impact of changes in site boundaries of variant A, B, C, D, E

Table 17 presents the impact on LCoE of the layout changes incorporated in the variants A, B, C, D and E.

Table 17: LCoE impact of different layout options. Note that all given percentages are relative

HKW variant	A	B	C	D	E
Description	*shipping passage width 1500m*	*HTZ P06-A excluded*	*shipping passage coincides with site boundary VI / VII*	*excl. maintenance zones pipelines and telecom cable*	*equally distributed areas*
Capacity [MW]	1,512	1,512	1,512	1,512	1,512
YIELD					
Gross yield	0.01%	0.00%	-0.04%	0.03%	-0.01%
LCoE impact gross yield	**-0.01%**	**-0.00%**	**0.04%**	**-0.03%**	**0.01%**
Wake Losses	1.23%	-3.67%	-0.93%	-0.85%	6.56%
LCoE impact wake losses	**0.15%**	**-0.43%**	**-0.11%**	**-0.13%**	**0.74%**

IAC cable length	-1.25%	3.15%	1.91%	-7.87%	-1.44%
LCoE impact cable losses	**0.02%**	**0.05%**	**0.03%**	**-0.12%**	**-0.02%**
CAPEX					
IAC cable length	-1.25%	3.15%	1.91%	-7.87%	-1.44%
Number of crossings	0%	0%	-5%	-100%	0%
LCoE impact array cable costs	**-0.02%**	**0.04%**	**0.02%**	**-0.19%**	**-0.2%**
Average water depth	-0.06%	-0.25%	-0.12%	-0.04%	-0.35%
Foundation costs	-0.01%	-0.06%	-0.03%	-0.01%	-0.08%
LCoE impact foundation costs	**-0.00%**	**-0.01%**	**-0.01%**	**-0.00%**	**-0.01%**
Net LCoE impact	**0.09%**	**-0.36%**	**-0.02%**	**-0.47%**	**0.69%**

The LCoE impact is graphically displayed as follows (see Figure 27);

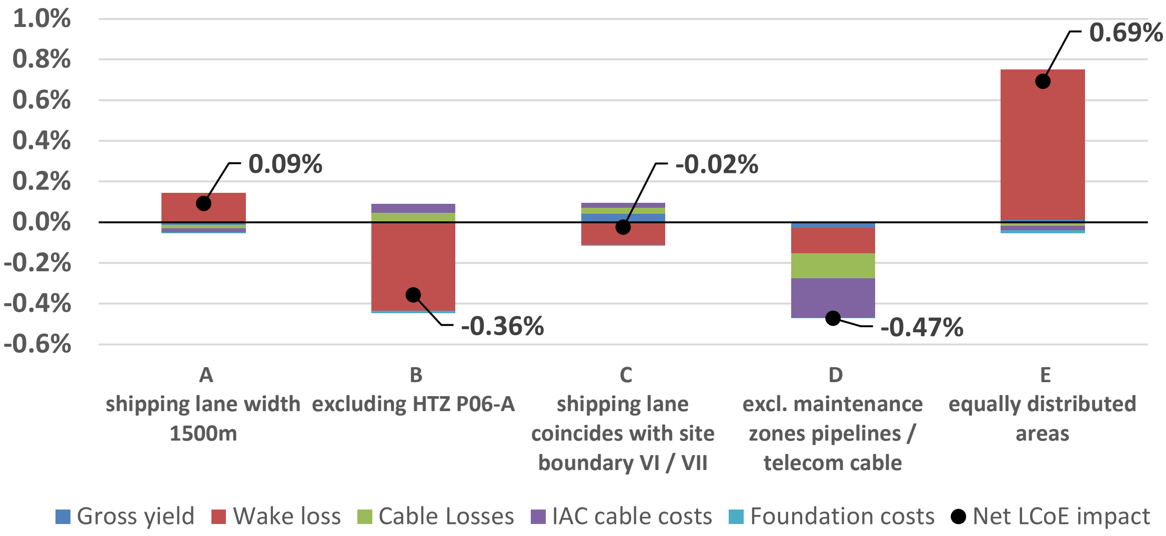


Figure 27: LCoE impact of changes in site boundaries of variants A through E.

The following can be observed for the layout options analyzed through variants A, B, C, D and E:

- Increasing the shipping passage width in variant A has a negligible effect on the cable losses, array cable costs and foundation costs and results in only a limited increase in LCoE by the increase in wake losses caused by the higher density (+0.09%).
- Excluding the helicopter traffic zone around P06-A causes a reduction in LCoE of -0.36%. The LCoE reduction is almost entirely explained by the reduction in wake loss of site VI. This is caused by the decreased wind farm density.
- In variant C the shipping passage between site VI and site VII coincides with the site boundaries and therefore the southwestern part of site VI is added to site VII. This has a negligible impact on the overall LCoE (~0.02%) since the decrease in average wake losses is compensated by an increase in cable losses and inter array cable costs.

- Excluding the maintenance zones of the telecom cable and the pipelines of variant D causes a significant reduction in the wind farm density (from 10.6 MW/km^2 to 8.5 MW/km^2), but the positive impact by reduced wake losses on the LCoE is limited since the distribution of the turbines is hardly affected. In contrast, the reduced cable losses cable costs due to the shorter overall cable length and fewer crossings have a larger impact on the LCoE difference, resulting in an overall reduction in LCoE of -0.45%.
- For variant E, the higher wake losses due to the higher wind farm densities of the equally distributed areas of the sites VI and VII increase the LCoE significantly (+0.7%). This is the result of reduced net areas for sites VI and VII due to the displacement of the site boundaries (by the shipping passages).

7.3 Impact of changes in site boundaries of variant F, G, H

Table 18 shows the impact on LCoE of the layout changes incorporated in the variants F, G and H.

Table 18: LCoE impact of different layout options. Note that all given percentages are relative

HKW variant	F	G	H
Description	*new reference*	*3 wind farm sites*	*equal LCoE for all 3 sites*
Capacity [MW]	1,512	2,218	2,218
YIELD			
Gross yield	-0.00%	0.01%	0.01%
LCoE impact gross yield	**0.00%**	**-0.01%**	**-0.01%**
Wake Losses	-0.02%	7.04%	-1.09%
LCoE impact wake losses	**-0.00%**	**0.86%**	**-0.15%**
IAC cable length	0.55%	-0.68%	-1.92%
LCoE impact cable losses	**0.01%**	**-0.01%**	**-0.03%**
CAPEX			
IAC cable length	0.55%	-0.68%	-1.92%
Number of crossings	-20%	-40%	-43%
LCoE impact array cable costs	**-0.01%**	**-0.03%**	**-0.03%**
Average water depth	-0.45%	0.58%	-0.32%
Foundation costs	-0.01%	0.01%	-0.05%
LCoE impact foundation costs	**-0.00%**	**0.00%**	**-0.01%**

Net LCoE impact	**0.00%**	**0.81%**	**-0.23%**

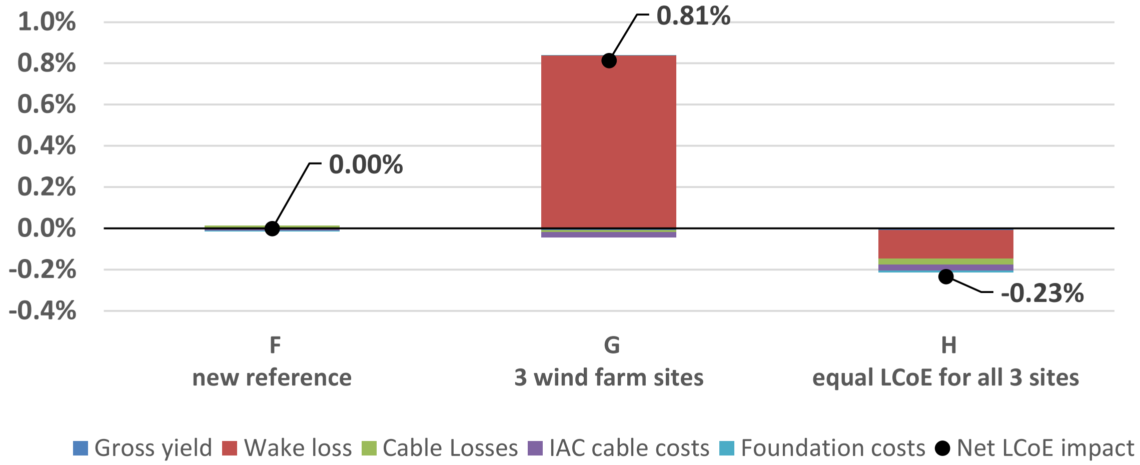


Figure 28: LCoE impact of changes in site boundaries of variants F through H.

The following can be observed for the variants F, G and H:

- Variant F has a comparable LCoE as the reference variant NRD since the shipping passage width (1050 m) is similar to the safety zone width from NRD (1000 m) and the positive effect of the narrowed maintenance zones for the pipelines connected to the P06-A platforms is offset by the slightly higher density of site VII caused by the different orientation of the boundaries of the sites VII and VI (alternative) by the shipping passage.
- For variant G, 189 wind turbines are installed instead of 126 wind turbines, which increases the overall wake losses and therefore the LCoE significantly with 0.81% compared to the same layout with two sites in use.
- As a result from the iteration process to obtain equal LCoE for all three sites (variant H) the average LCoE compared to the original layout of variant G was reduced by 0.23%.

7.3.1 Variant H - Equal LCoE for all three sites

The aim of variant H was to obtain equal LCoE for all three sites with a maximum deviation of +/- 0.5% from the mean LCoE of the three sites. The results are shown in Table 19 below.

Table 19: Deviations of the LCoE per site compared to the mean of the variants G and H

Variant	VI	VII	VI (alternative)
G	-1.15%	+1.89%	-0.74%
H	-0.43%	0.29%	0.14%

For variant G the deviation compared to the mean LCoE was significant with the lowest LCoE for site VI (-1.15% compared to the mean LCoE) and the highest LCoE for site VII (+1.89% compared to mean LCoE). Via an iterative process of displacing the shipping passages between the three sites the layout of variant H was achieved with almost equal LCoE for all three sites; -0.43% for site VI, 0.29% for site VII and 0.14% for site VI (alternative).

7.3.2 Sensitivity analysis results

Two sensitivity analyses, the WindPro layout sensitivity and the 15MW layout sensitivity, were performed to check the robustness of the results of two leading assumptions in this study, i.e. the layout determination guidelines and the wind turbine dimensions. Table 20 below shows that the deviations per site of the variants H and the sensitivity analyses are all within the margin of +/-0.5% from the mean LCoE. In other words, the results of variant H are robust for different wind farm layouts.

Table 20: Deviations of the LCoE per site compared to the mean of the variants G, H and the sensitivity analyses

Variant	VI	VII	VI (alternative)
G	-1.15%	+1.89%	-0.74%
H	-0.43%	0.29%	0.14%
WindPro layout sensitivity	-0.17%	0.26%	-0.08%
15MW layout sensitivity	-0.10%	0.20%	-0.09%

8 DISCUSSION

8.1 Limitations of current approach

The current study is based on a schematisation of reality. The layouts are created on a rectangular grid. The wind climate, yield and wake effects and cost functions are based on simplified relations. In reality, wind farm layouts will be further optimised, detailed site investigations will be performed and dedicated designs will be made.

The wind farm layouts used in this study are not fully optimised; micro-siting has not been performed, and results from the cost model have not been used for further layout optimizations (e.g. relatively expensive wind turbine positions have not been relocated to cheaper locations). The wake effects are modelled using WindPRO/WAsP, which use generalized wake models to calculate second, third and n-th order wake effects. Moreover, this approach does not entail detailed turbulence calculations. With decreasing wind turbine distances an increase in turbulence is usually observed. As a rule of thumb a minimum distance of 5 times the rotor diameter is applied to avoid the most significant turbulence effects.

Nevertheless, the present approach is deemed suitable for the purpose of this study, which is to compare relative differences between site alternatives.

8.2 Limitations of Levelized Cost of Energy

The current study is based on comparing the Levelized Cost of Energy for the given alternatives. The strong part of this parameter is that it allows for a fair comparison between the different alternatives. It includes (the net present value of) all costs that a developer takes into account to construct and operate a wind farm divided by the anticipated yield. The implicit assumption is that each MWh produced has an equivalent value. This is a valid assumption if a subsidy policy is in place to guarantee a minimum price for the generated electricity.

In practice the business case of an offshore wind farm is largely determined by the internal rate of return (IRR), which determines the attractiveness of an investment. The IRR depends on the anticipated income from power sales (and subsidy) minus all costs to construct and operate the wind farm. Power sales depend, besides the yield of the wind farm, on the electricity price of wind energy. This price fluctuates with time depending on market demand and supply. With the present European targets for renewable energy the number of offshore wind farms in the European North Sea is expected to grow significantly. On windy days in the future, depending on the demand and possible storage opportunities, oversupply of renewable energy may lead to lower electricity market prices. Because the supply of wind energy is less adjustable than other sources of energy, the price of a unit of wind energy will be lower than a unit of energy produced by a plant on demand. Within the present study, the “income side of power sales” is neglected. Possible deviations in the market value of a unit of energy yield are not taken along.

Figure 29 shows the power curve for the NRD reference layout without wake effects (purple line) and with wake effects (green line). The black line shows the wind speed distribution and the blue line shows the wake effect as a function of wind speed. The results show that wake effects are most dominant at lower wind speeds. Above about 13m/s wake effects have no influence on the power output (despite the wakes there remains sufficient wind energy for the turbines to achieve rated power). It is anticipated that future electricity prices will be higher during light wind speeds, i.e. within the regime where wake effects play a large role, due to less supply of wind energy. The present study results indicate that wakes have a dominant impact on costs of energy through a reduction of yield. We expect that if a unit of wind energy produced at a lower wind speed is given more value than energy produced in strong winds, the differences seen between the modelled scenarios would increase, because wakes have more influence in low wind speeds. This implies that, in absence of a subsidy policy with a guaranteed minimum price, the differences in income for a developer associated with each variant would be larger than the currently modelled difference in LCoE.

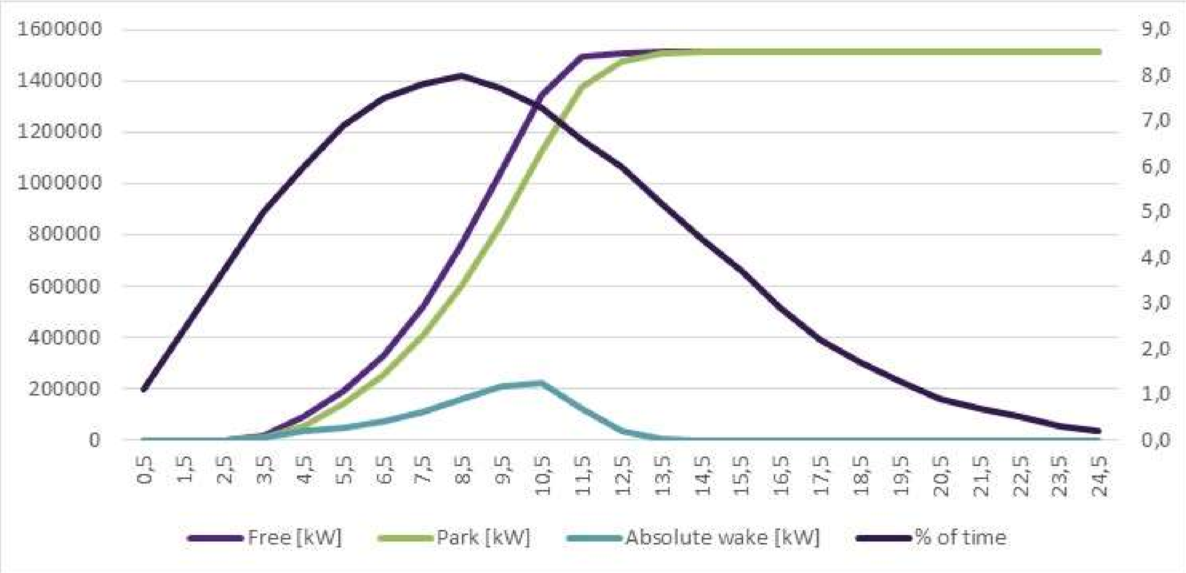


Figure 29 - Wind speed and wake effects HKW reference

9 CONCLUSIONS & RECOMMENDATIONS

Within the present study, the Levelized Cost of Energy (LCoE) of various wind farm site boundary alternatives for future wind farm zones was evaluated to support decisions on the final boundaries of these wind farm zones.

For each variant, indicative wind farm layouts were designed. Next, the wind climate at each of the zones was assessed and used as basis for yield calculations. Costs were modelled based on schematised relations for costs of foundations and cables. Finally, the LCoE was determined and results were analysed.

The following main conclusions are drawn based on the results of the LCoE study:

13. The results of this study are comparable to the 2018 study results. At that time, significant differences in LCoE were seen between the variants in which the total available surface of HKW was used for two or three wind farms, comparable to the current result of variant G.
14. Differences in the configuration of the site boundaries were analyzed resulting in limited to moderate differences in LCoE compared to the NRD reference, except when the areas of the three sites is equally distributed, which cause a significant increase in LCoE.
15. Wake losses are closely related to the wind farm density. However, the cause of the difference in density is very important here; an increase in density due to maintenance zones that fit within the turbine spacing have only a small effect on the wake losses, while increasing the density caused by shifting a site boundary has a large effect on the wake losses.
16. The wake effects have the greatest impact on the net LCoE differences, the impact of the other parameters is limited.
17. Broadening the shipping passage (variant A) has limited impact on the LCoE.
18. Excluding the HTZ around P06-A (variant B) has a moderate positive LCoE impact.
19. Adding the southwestern part of site VI to site VII with the shipping passage between site VI and site VII that coincides with the site boundaries of sites VI and VII (variant C) has a negligible LCoE impact.
20. Excluding the maintenance zones of the northern telecom cable and around pipelines connected to P06-A (variant D) cause a moderate decrease in LCoE.
21. Equally distributing the net areas of site VI, VII and VI (alternative) (variant E) and thereby reducing the net areas of site VI and VII compared to the reference increases the LCoE significantly.
22. Installing an additional 756MW of wind energy capacity (variant G) will increase the average LCoE of all three sites significantly by the substantial increase in wake losses.
23. For variant H, the site boundaries by the shipping passages are placed in such a way that the LCoE is similar for all three sites.
24. The sensitivity analyses show that the results of variant H with equal LCoE for all three sites are robust for variations in the wind farm layout.