Study into Levelized Cost of Energy

of variants for wind farm site boundaries of Hollandse Kust (west), Ten Noorden van de Waddeneilanden and IJmuiden Ver

BLIX PONDERA consult Energy Solutions High Voltage Engineering & Consultancy KCI

From:	BLIX Consultancy BV & partners
Reference:	WOZ 2180096 – Lot 1
To:	Netherlands Enterprise Agency

Authors:	BLIX Consultancy: Ir. B. de Sonneville, Drs. E. Weekamp
	Pondera: Drs. P. Rooijmans, Drs. H. Hussin, Drs. E. Holtslag
Review committee:	BLIX Consultancy: Ir. A.B. van der Hem
	Wind Werk: Dr. E.J. van Zuijlen

Version:	Final – V3.0
Date:	14 November 2018

Table of contents

MANAGEMENT SUMMARY

1.1 Introduction and approach

The Ministry of Economic Affairs and Climate recently published the Roadmap for offshore wind energy 2030, calling for the deployment of an additional 7,000 MW of offshore wind energy capacity by 2030 in several new zones: Hollandse Kust (west) (HKW), Ten Noorden van de Waddeneilanden (TNW) and IJmuiden Ver (IJV).

The Netherlands Enterprise Agency awarded BLIX Consultancy & partners a study to investigate the Levelized Cost of Energy (LCoE) of different variants for the wind farm site boundaries. The results are described in the current report.

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 in each zone and the areas with most favourable conditions.

1.2 Overview of considered variants

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

Table A: Overview of the evaluated layout variants.

Variant	Description	Wind farm capacity	Wind farm density
HKW reference	Reference layout using the full wind farm area	2 x 756 MW	6.2 MW/km^2
HKW variant 1	Excluding helicopter safety zone in the north	2 x 756 MW	6.5 MW/km^2
HKW variant 2	Excluding helicopter safety zone in the south	2 x 756 MW	6.7 MW/km^2
HKW variant 3	Excluding both helicopter safety zones	2 x 756 MW	7.0 MW/km^2
HKW variant 4	Three instead of two wind farm sites	3 x 756 MW	9.2 MW/km^2
HKW variant 5	Three instead of two wind farm sites, without pre-described site boundaries and locations of substations	3 x 756 MW	9.2 MW/km^2
HKW variant 6	Sensitivity analysis for HKW reference, using a larger wind turbine spacing in the main wind direction and a smaller spacing perpendicular to the main wind direction	2 x 756 MW	6.2 MW/km^2
HKW variant 7	Same as variant 4, but where area on north is excluded, leaving space for another wind farm that could potentially be developed later	2 x 756 MW	8.7 MW/km^2
HKW variant 8	Same as variant 4, but where area on south is excluded, leaving space for another wind farm that could potentially be developed later	2 x 756 MW	10.2 MW/km^2
TNW reference	Using the full wind farm area, except area between existing wind farm Gemini	1 x 756 MW	8.1 MW/km^2
TNW variant 1	Reduction to 84 % of the reference area	1 x 756 MW	9.6 MW/km^2
TNW variant 2	Reduction to 77 % of the reference area	1 x 756 MW	10.5 MW/km^2
TNW variant 3	Reduction to 65 % of the reference area	1 x 756 MW	12.5 MW/km^2

TNW variant 4	Reduction to 40 % of the reference area	1 x 756 MW	20.5 MW/km²
IJV variant 4a	Ferry route north; use northern and southern zone	4 GW	7.6 MW/km²
IJV variant 4b	Ferry route south; use northern and southern zone	4 GW	9.0 MW/km²
IJV variant 5a	Ferry route north; use only southern zone	4 GW	11.3 MW/km²
IJV variant 5b	Ferry route south; use only southern zone	4 GW	12.9 MW/km²

1.3 Results

The resulting differences in overall LCoE per variant are shown in Figure A and Figure B[1]:

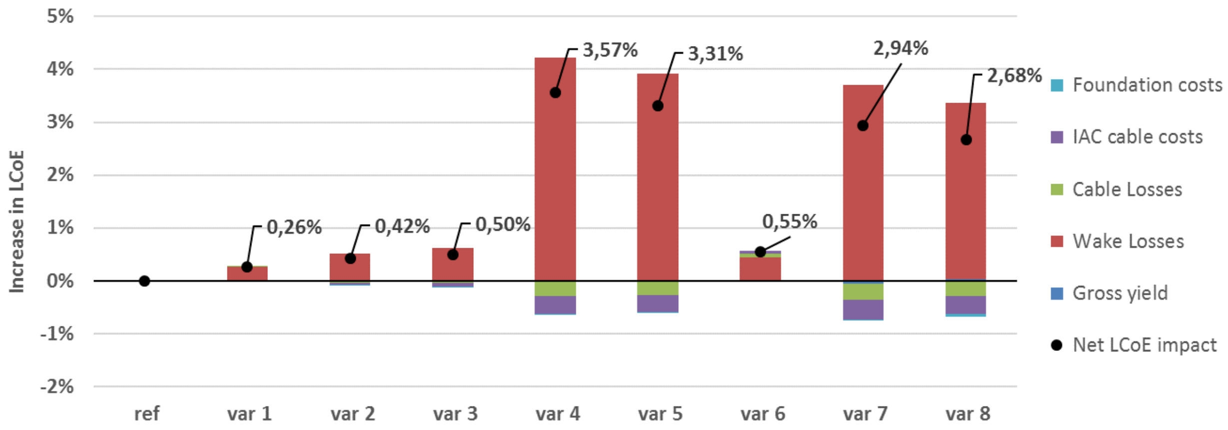


Figure A: Resulting LCoE difference of eight variants of Hollandse Kust (west) layouts compared to reference layout of Hollandse Kust (west). Differences between the variants are described in Table A.

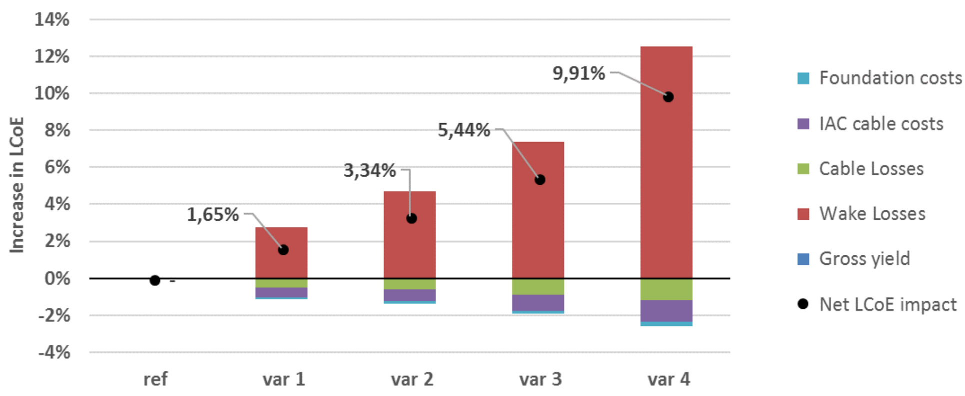


Figure B: Resulting LCoE difference of four variants of Ten Noorden van de Waddeneilanden layouts compared to reference layout of Ten Noorden van de Waddeneilanden.

[1] LCoE is in general expressed in euro/MWh, in this study only the relative differences between the LCoE will be shown

The impact of the wakes at TNW (variant 1) on existing offshore wind farm Gemini are shown in Table B.

Table B: Gemini and TNW (inter park) wake effects

Wake effects [%]	Stand alone	TNW + Gemini	Difference (%-points)
TNW variant 1	8,5%	9,1%	0,6%
Gemini	13,4%	14,6%	1,2%

1.4 Conclusions

The following conclusions are drawn based on the outcome of the LCoE modelling:

Hollandse Kust (west)

- Excluding the helicopter safety zones has a negligible impact on the LCoE. The differences between the reference alternative and variants 1, 2 and 3 are lower than 1% and therefore considered smaller than the uncertainty of the applied approach. We note that the general trend is according to expectations (a smaller area leads to higher LCoE) which confirms the credibility of the approach.
- The LCoE is about 3.5% higher for three sites of 756 MW than for two sites of 756 MW.
- The LCoE is about 2.5 to 3% higher in case two sites of 756 MW are used and space is left for a future third site.

Ten Noorden van de Waddeneilanden

- The results of the sensitivity calculations (variants 2 – 4) show that a reduction of the available wind farm area will increase the LCoE.
- Variant 4 is not recommended from a technical viewpoint because it will force developers to use a too small distance between turbines (4D).
- The increase in wake effects on the existing Gemini wind farm as result of TNW variant 1 is assessed to be about 1%.

IJmuiden Ver

- Using only the area south of the ferry route will significantly increase wake effects, particularly in case of the southern ferry route (variant 5b).
- The available area associated with a ferry route more towards the south (variant 4b) causes a higher wind farm density (with more wake effects) in the area south of the ferry route than the ferry route more towards the north (variant 4a).

2 INTRODUCTION

2.1 Background

The Ministry of Economic Affairs and Climate recently published the Roadmap for offshore wind energy 2030, calling for the deployment of an additional 7,000 MW of offshore wind energy capacity by 2030. Combined with the 4,500 MW of the Roadmap 2023, this capacity will bring the Netherlands' total offshore wind capacity up to 11,500 MW.

The Roadmap 2030 comprises the following wind farm zones (see Table 1 and Figure 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 - 2026

The Netherlands Enterprise Agency, the Ministry of Economic Affairs and Climate, Rijkswaterstaat and TenneT (defined in the remainder of this document as the Working Group) are currently in discussions with stakeholders to determine the final wind farm site boundaries of these zones.

The Netherlands Enterprise Agency awarded BLIX Consultancy & partners a study to investigate the Levelized Cost of Energy (LCoE) for different variants of the wind farm site boundaries. The results are described in the current report.

Note that this report describes 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).

2.2 Study objective

The study objective was to assess the Levelized Cost of Energy of various wind farm site boundary alternatives for future wind farm zones Hollandse Kust (west), Ten Noorden van de Waddeneilanden and IJmuiden Ver to support decisions on the final boundaries of these wind farm zones.

The sub objectives were as follows:

1. Define variants and provide indicative wind farm layouts for each variant;
2. Perform yield calculations for each variant;
3. Perform cost modelling to obtain the LCoE for each variant;
4. Compare the results and summarize conclusions.

2.3 Structure of report

Chapter 2 describes the approach and the project team. The starting points and assumptions are described in Chapter 3. In Chapter 4, the variants and layouts are presented. Chapter 5 contains an analysis of the yield, foundation cost and LCoE per turbine. Finally, the overall LCoE associated with each variant is described in Chapter 6, followed by a discussion in Chapter 7 and conclusions in Chapter 8.

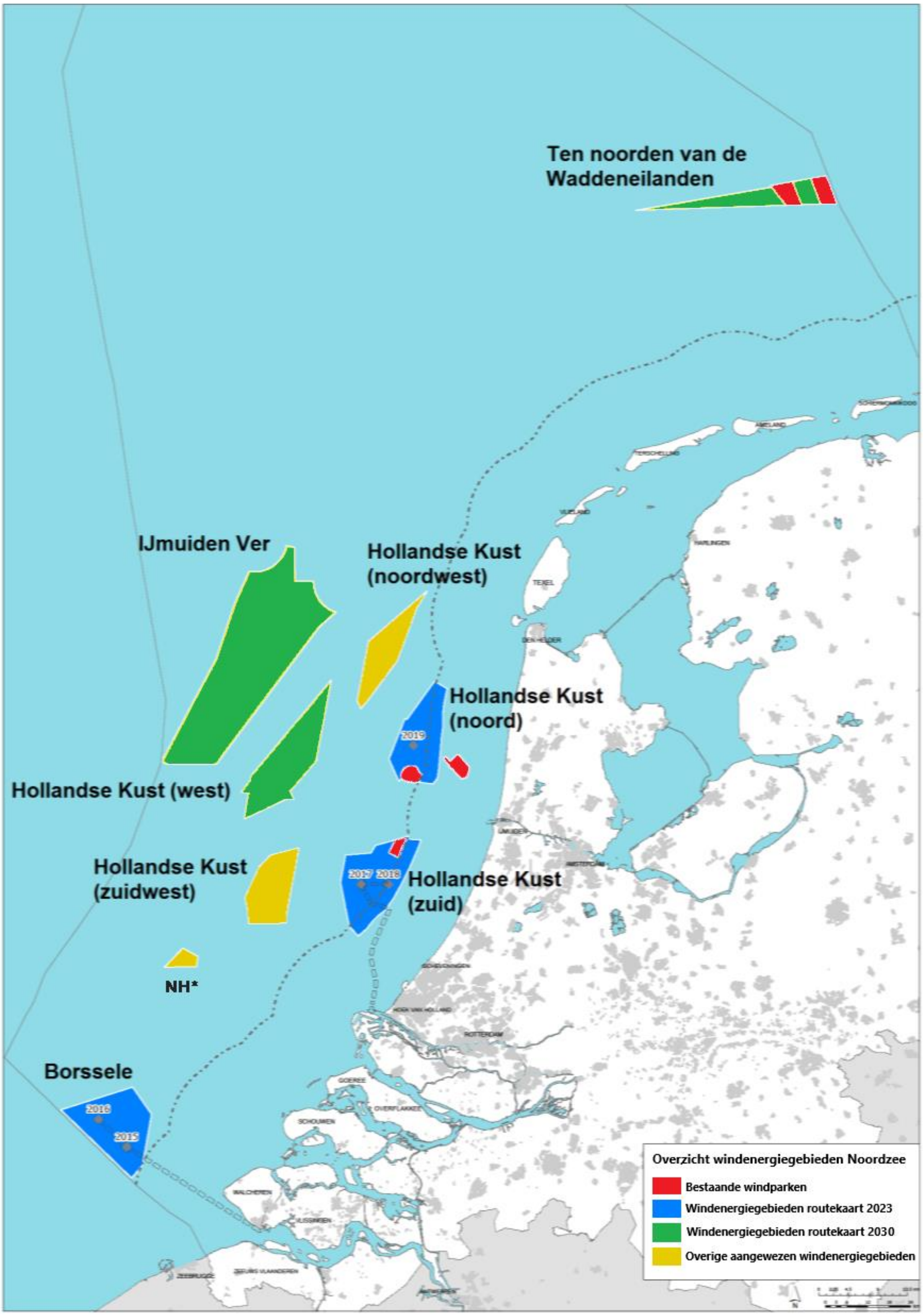


Figure 1: Overview of wind farm zones of Roadmap 2023 and Roadmap 2030.

3 APPROACH

3.1 Team & partners

The approach for the project was to incorporate state-of-the-art knowledge and up-to-date assumptions on price levels to provide a realistic picture and division of costs, since the prices for offshore wind farms have experienced such a rapid decrease in the past years in the Netherlands. BLIX Consultancy worked together with the following project partners to fulfil this approach:

Their roles are described below:

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

Furthermore, an external reviewer was appointed to review the assumptions and the results of the study, besides the regular ISO-certified BLIX quality assurance process. The external reviewer was Dr. Ernst van Zuijlen, a renowned independent offshore wind farm expert.

3.2 Study approach

The study was based on the following approach:

1. Define variants per wind farm zone

   Most of the variants were provided by the Working Group, some were proposed by our project team. For Hollandse Kust (west) the variants consisted of excluding tolerance areas for helicopter safety zones for existing oil & gas platforms and using the site for a capacity of 3 x 756 MW instead of 2 x 756 MW (see Figure 10). For Ten Noorden van de Waddeneilanden, the variants consisted of either using the full area or excluding the western part. Note that the area within existing offshore wind farm Gemini was assumed not to be used. In addition, a sensitivity calculation was performed to investigate the impact of a further stepwise reduction of the wind farm area on the LCoE (see Figure 11). For IJmuiden Ver, alternatives were defined based on two alternative ferry routes.

2. Provide baseline wind farm layouts for each variant

   Next, indicative wind farm and cable layouts were provided for each wind farm zone, based on a schematised approach with a regular turbine spacing. Then, 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 set up the BLIX financial model for this project. 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 latest market prices insight of BLIX in recent North Sea tenders.

4. Calculate the LCoE of each variant

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

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 a 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 most recent price levels and assumptions for wind farm design. BLIX has been involved in tender preparations for developers and wind farms all over the world, including in the North Sea. These insights have been used 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.
5. No cost modelling was performed for IJmuiden Ver.

4.3 Main parameters that vary between variants

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. These are described below in Table 2.

Table 2: Main parameters that vary 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 that was used in the wind resource assessments for offshore wind farm areas Borssele and Hollandse Kust (zuid) has been followed. 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) and IJmuiden Ver wind farm area, while the FINO1 met mast data was used for the Ten Noorden van de Waddeneilanden (TNW) wind farm area. These wind measurements were found to be the most representative, complete and closest to the wind farm areas. The datasets were quality controlled, filtered for errors and anomalies, processed and delimited to complete years: 4 years for IJmuiden and 14 years for FINO1.
- The WindPRO measure-correlation-prediction method (MCP) was used in the long-term scaling of the IJmuiden and FINO1 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 were found to be 2.0 % higher than the long-term EMD ConWx-mesoscale wind speeds. The FINO1 met mast average wind speed measurement values were found to be 2.1 % lower than the long-term EMD ConWx-mesoscale wind speeds. 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 areas, 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 areas. This method helped to determine the representative wind speeds at the project sites.

Table 3 summarizes the most important parameters and values found in the wind resource assessment of the wind farm areas. Figures 2 and 3 graphically summarize the wind climate (Weibull distributions and wind roses) at HKW and TNW wind farm areas, respectively.

Table 3 Wind parameters for Hollandse Kust (west) and Ten Noorden van de Waddeneilanden.

Parameter	Hollandse Kust (west)	Ten Noorden van de Waddeneilanden	IJmuiden Ver
Met mast used for wind measurements	IJmuiden	FINO1	IJmuiden
Distance met mast to edge of wind farm area [km]	25	47	0
Met mast measurement time [years]	4	14	4
Mesoscale data used for long term correction (years)	EMD-ConWx Europe (25 years)	EMD-ConWx Europe (25 years)	EMD-ConWx Europe (25 years)
Scaling factor used for long term correction [%]	-2.0 %	+ 2.1 %	-2.0 %
Long-term average annual wind speed at wind farm area at 130 m height [m/s]	10.1	9.9	10.3

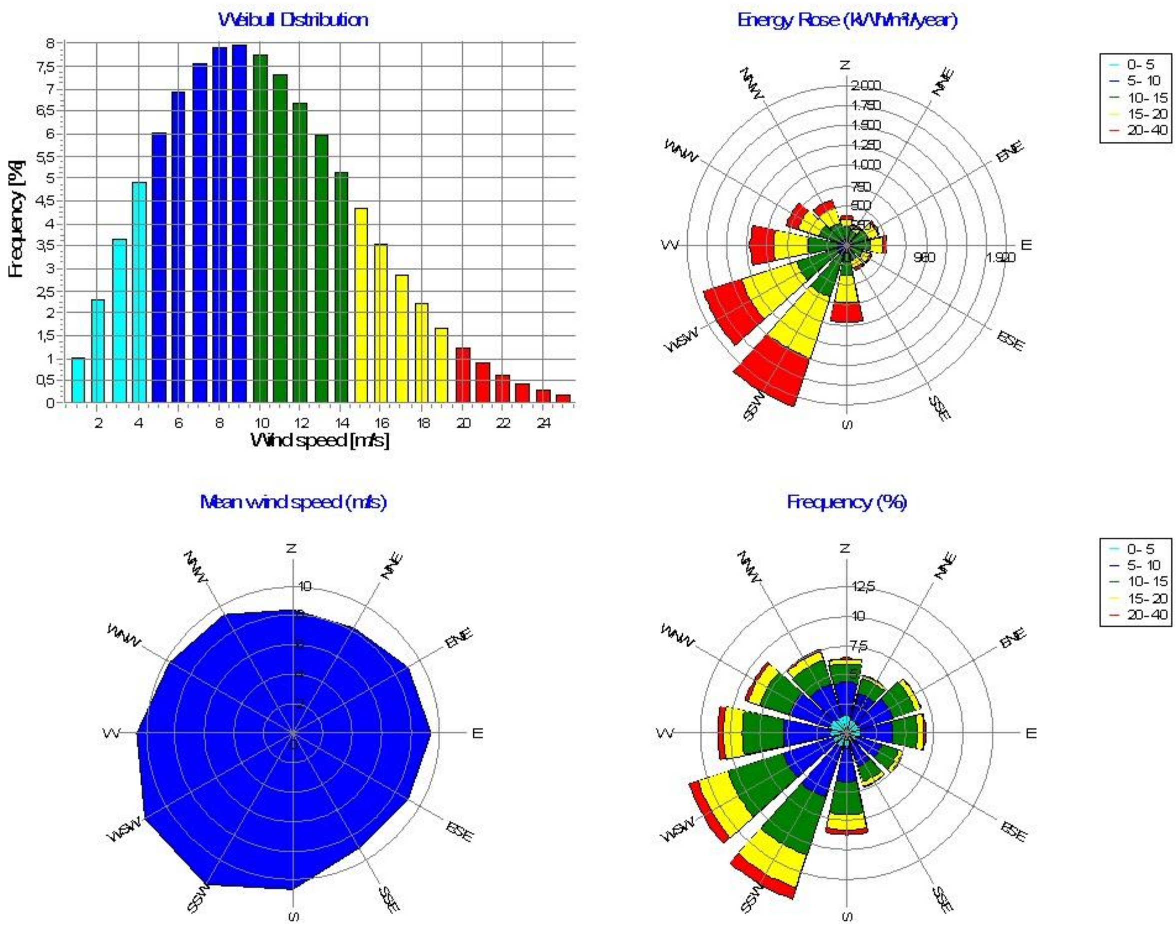


Figure 2 Wind climate summary at a central site data point in the HKW wind farm area at 130 m height.

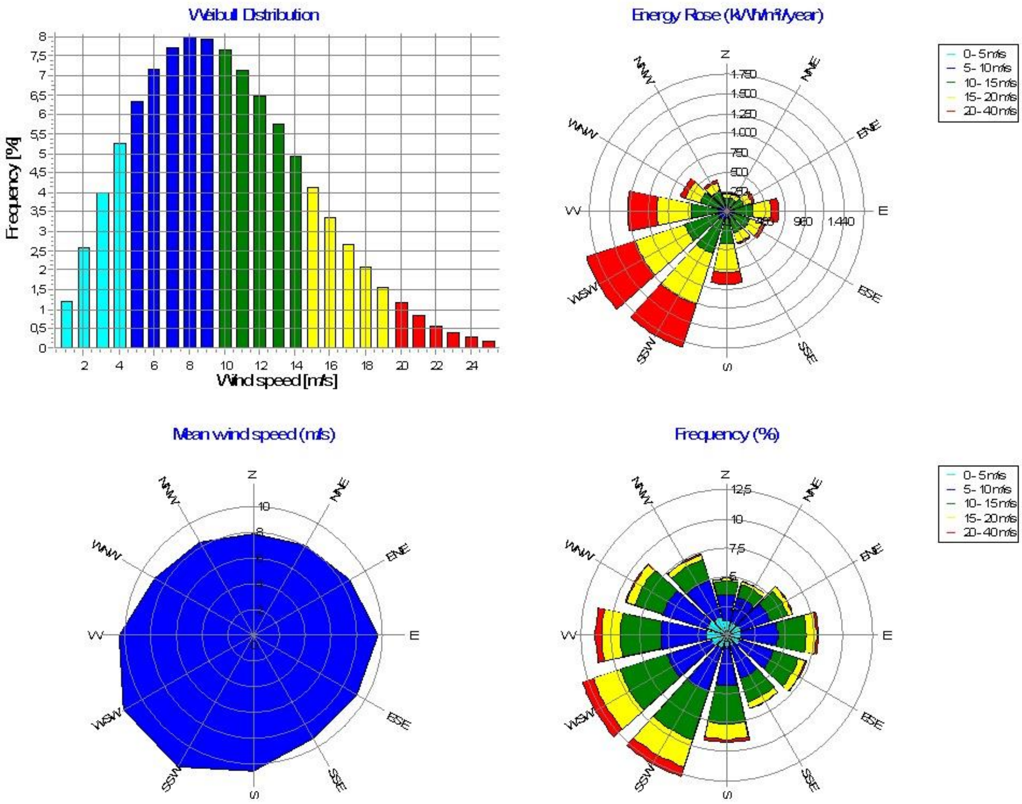


Figure 3 Wind climate summary at a central site data point in the TNW wind farm area at 130 m height.

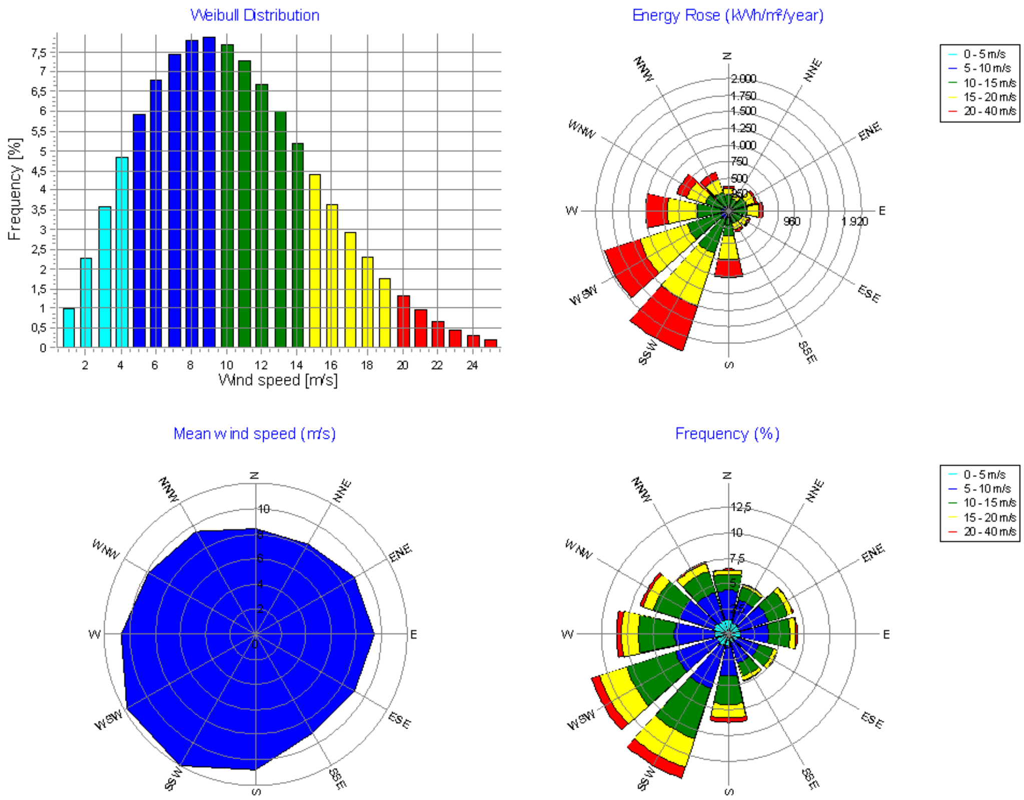


Figure 4 Wind climate summary at a central site data point in the IJV wind farm area at 130 m height.

From the calculation results, presented in Table 3, the calculated wind speed at HKW is found to be slightly higher than that of TNW. This may seem a bit counter-intuitive and also conflicts with other (e.g. mesoscale-data based) maps. However, it should be noted, that the difference in wind speed found between the sites is very small. The difference is in the order of magnitude of the corrections applied (2% on ~10 m/s). Furthermore, 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 datasets (LiDAR & mast), filtering & MCP and comparison & scaling to mesoscale data, an indicative uncertainty of 3-4% on the wind speed can be expected as a minimum. This means that the corrections done and the gradient found could actually also be reversed. In light of the goal of this current study however, which is to compare variants per wind farm zone (not compare between zones), the absolute wind speed is not crucial. Based on this evidence however, it is therefore also recommended, that on-site wind measurements are performed to reduce the uncertainty of the wind climate at these zones.

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 5 and Figure 6 show the bathymetry for the HKW and TNW wind farm zones.

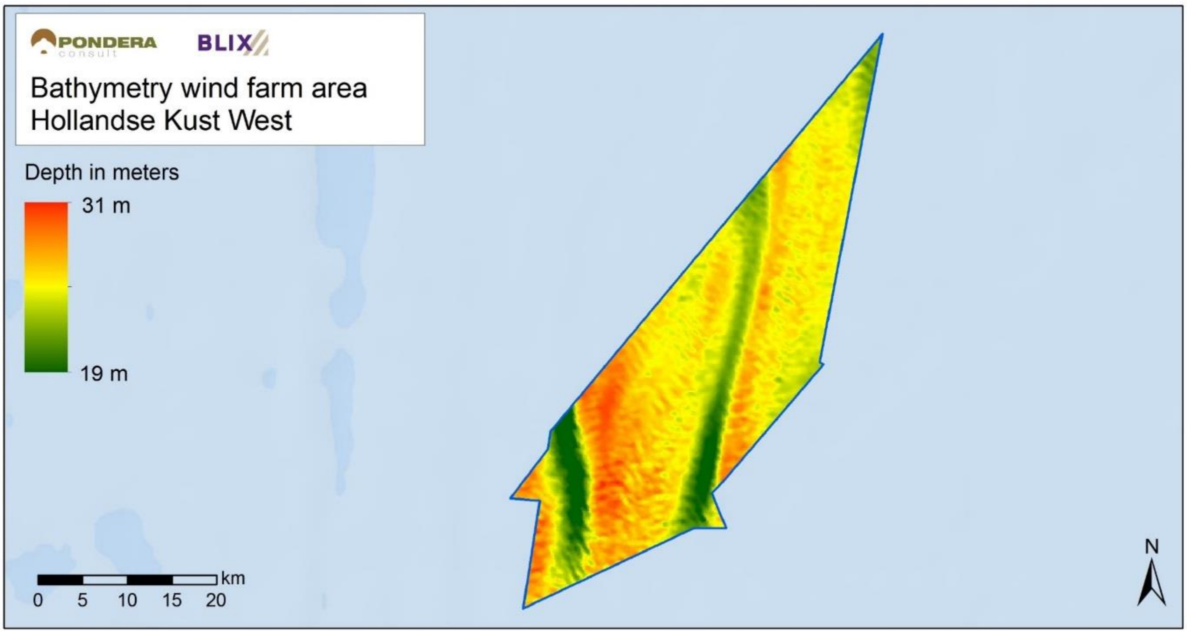


Figure 5 Bathymetry map Hollandse Kust (west).

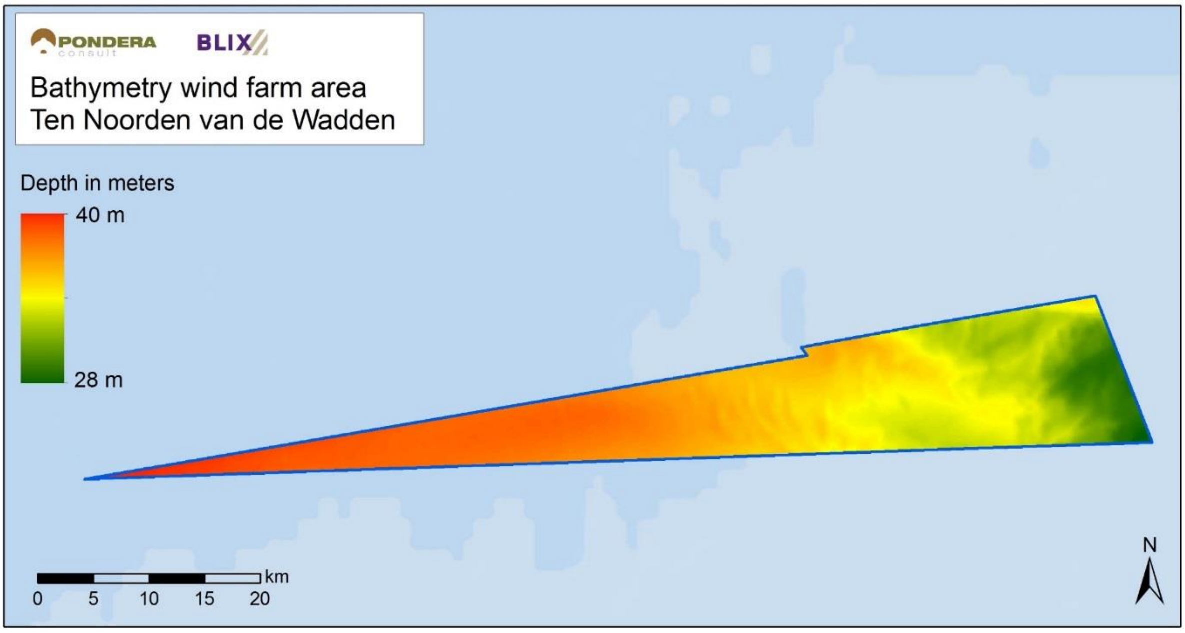


Figure 6 Bathymetry map Ten Noorden van de Waddeneilanden.

The HKW site shows two distinct sand banks running north-south across the wind farm zone with a small gradient in depth towards the northeast, where it becomes shallower. The TNW wind farm shows a water depth gradient from east to west, with water depth increasing towards the west. Water depths for HKW range from roughly 20 to 30 meters. For TNW it ranges between 30 and 40 meters.

For IJmuiden Ver, only yield calculations were performed. The bathymetry, wave and soil conditions do not affect yield. Therefore, these parameters were not considered for IJV.

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 areas, the design storm conditions were estimated based on the DHI metocean report for Hollandse Kust (noord). The assumed values are shown in Table 4.

Table 4: Design conditions with a 50-year return period.

Parameter	Hollandse Kust (west)	Ten Noorden van de Waddeneilanden
Significant wave height [m]	7.7	8.7
Peak wave period (s)	12.7	13.5

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

For HKW and TNW, 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 5).

Table 5: Assumed soil parameters.

Parameter	Hollandse Kust (west)	Ten Noorden van de Waddeneilanden
Assumed soil profile	uniform medium dense to dense sand	uniform medium dense to dense sand
Characteristic friction angle [degrees]	35	35
Submerged unit weight [kN/m^3]	9.5	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 Obstructions and stakeholders

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

The Ten Noorden van de Waddeneilanden zone is determined by the IMO shipping lane at the north of the wind farm zone and a military low flying area at the southern border. The eastern border is made up by the neighbouring Gemini offshore wind farms.

Both the Hollandse Kust (west) and Ten Noorden van de Waddeneilanden areas have numerous telecom cables and pipelines running along the site boundaries as well as through the wind farm zone itself. Figure 7, Figure 8 and Figure 9 show all relevant obstructions and stakeholders near and in the wind farm zones. Table 6 provides a description of the infrastructure per site.

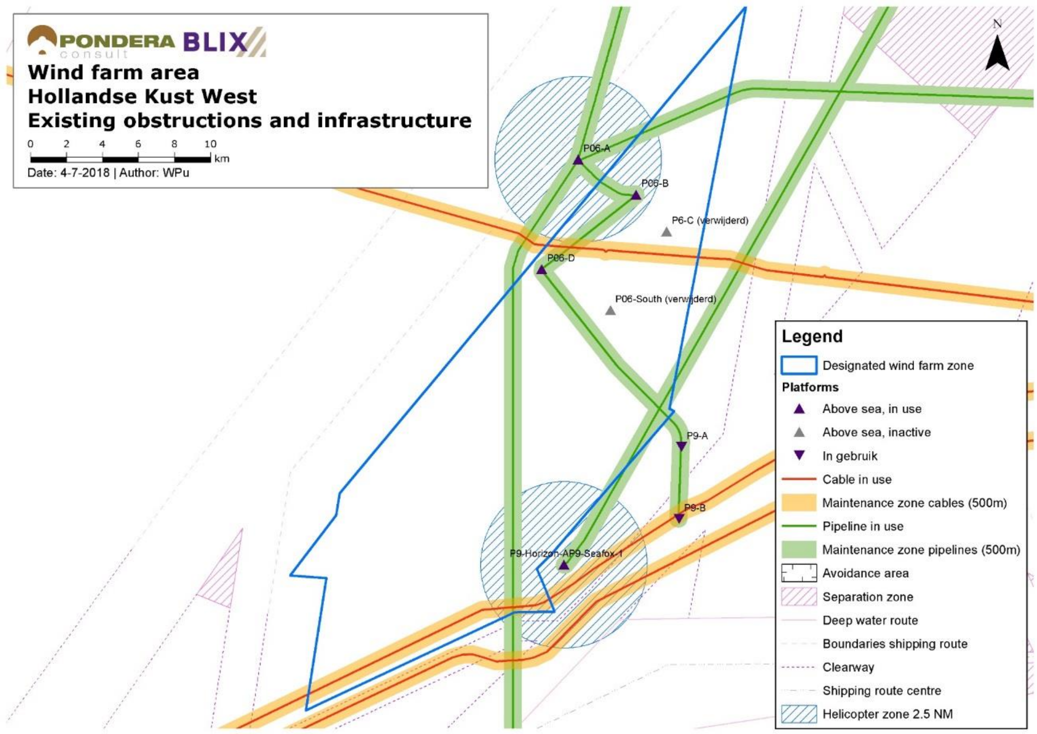


Figure 7 Obstructions and infrastructure around Hollandse Kust (west)

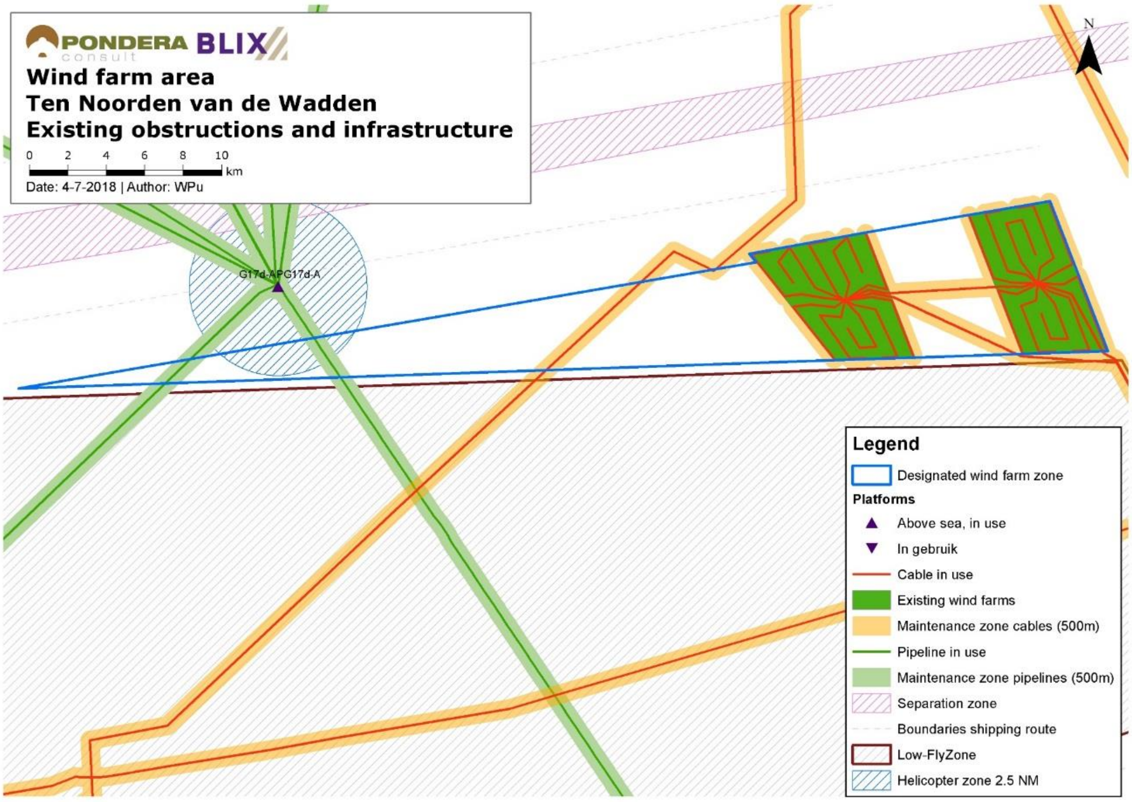


Figure 8 Obstructions and infrastructure around Ten Noorden van de Waddeneilanden.

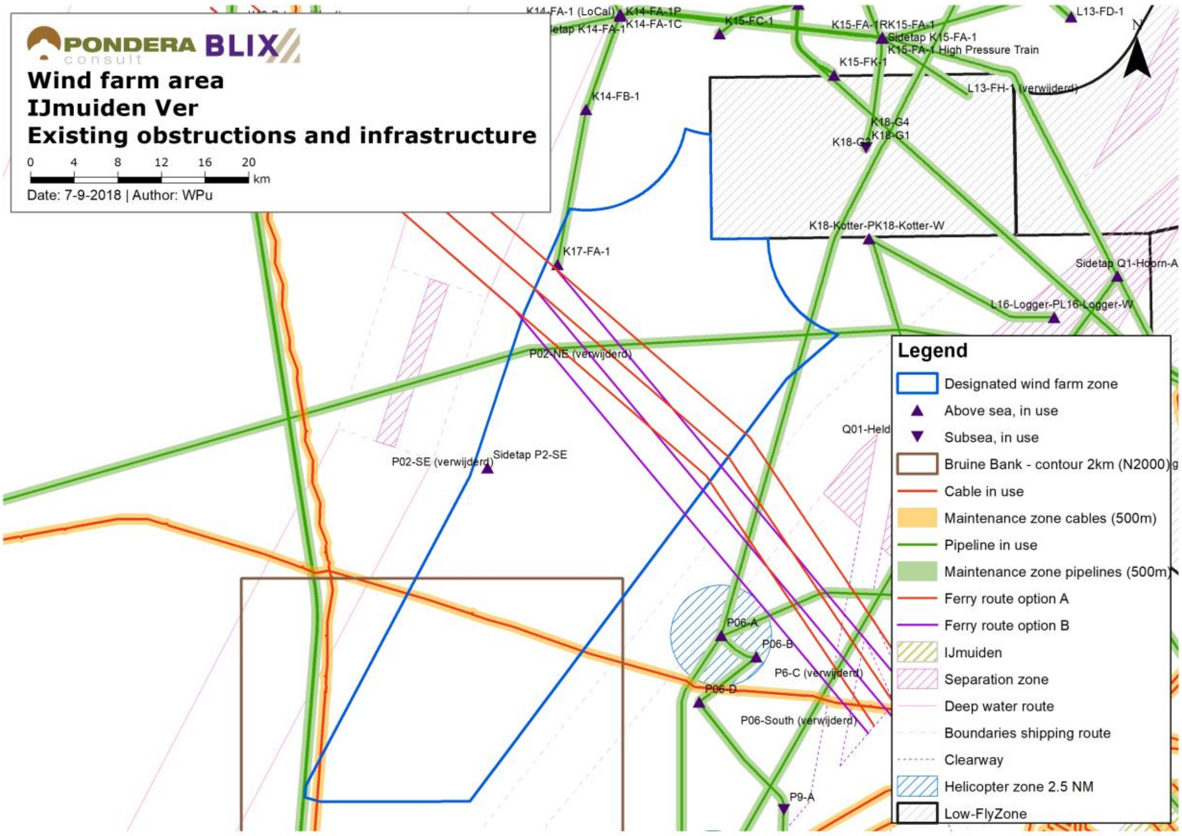


Figure 9 Obstructions and infrastructure around IJmuiden Ver.

Table 6: Overview of existing obstructions and infrastructure.

Item	Hollandse Kust (west)	Ten Noorden van de Waddeneilanden	IJmuiden Ver
Nature preservation areas	None	None	Bruine Bank (potentially Natura 2000)
Shipping lanes	On all sides of the wind farm zone	North of the wind farm zone	Ferry Route running through the wind farm zone
Helicopter zones	One north and one south of the wind farm zone	One north of the wind farm zone	One east of the wind farm zone
Existing oil & gas platforms	One north and one south of the wind farm zone	One north of the wind farm zone	Two inside the wind farm area
Existing wind farms	None present	Gemini offshore wind farms east of the wind farm zone	None present
Existing telecom cables	Two running through the wind farm area	One running through the wind farm area	Two running through the wind farm area
Existing pipelines	Numerous running through the wind farm area	Two running through the wind farm area	Numerous running through the wind farm area
Areas used by military	None	Large low flying area in south	None
Dredging licenses	None	None	None

Note that the shipping lane within HKW for the ferry towards the UK may be relocated to a more southern location in the future, based on information of Rijkswaterstaat.

4.5 Technical assumptions

4.5.1 Wind farm layouts and yield

The technical assumptions for wind farm layout and yield are described in Table 7 below:

Table 7: Technical assumptions for wind farm layouts and yield.

Parameter	Assumption	Reference
Turbine capacity	12 MW (HKW, TNW) 15 MW (IJV)	Based on experience and brief market consultation
Rotor diameter	200 m rotor diameter	Based on currently available information
Hub height	130 m	Based on 30 m clearance
Power curve	Confidential	Based on available prototype
Capacity per wind farm site	756 MW	Based on Borssele, overplanting is assumed as reference in consultation with the Working group
Infield cables	66 kV, 6 WTG/string	Based on assessment of Ensol (assuming 630A switchgear in turbines)

Construction & maintenance harbours	Rotterdam (HKW), Eemshaven (TNW)	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

4.5.2 Financial modelling

The LCoE model uses the latest market costs insights plus experts forecasts[2]. In below table the main cost assumptions will shortly be explained. As mentioned in previous chapters, most of these items will not impact the relative LCoE analysis. Therefore, most attention has been paid to the items that do impact the relative LCoE (see table 2).

Table 8: 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	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	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

[2] BLIX has supported development of several projects that will be constructed post 2020. Based on this knowledge, estimations/extrapolations have been made for wind-farms that will be constructed in the period around 2025 and later.

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	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	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

4.6 Grid connection

The location(s) of the TenneT substations were provided by RVO in close collaboration with TenneT. The main reasoning behind the substation locations is to have them in the centre of the different wind farm sites. Previous studies have shown that this results in the total lowest cost of energy (i.e. the additional export cable length costs do not outweigh the decreased costs for the infield cables).

Because the location of the substations does not differ between the different variants (see chapter 4 for more details) the costs for the substations and the export cable are not used in the LCoE calculations.

An important observation is that with the growing sizes of wind turbines the absolute values of the distance between wind turbines increase significantly. For the 12 MW wind turbine used in this study a distance of five times the rotor diameter equals 1 km. 1 km is roughly the size of the maintenance zone around the TenneT export cable. Export cable corridors inside the wind farm area therefore no longer create substantial loss of available area for wind turbines (i.e. the wind farm layout can to large extent adapt itself to whatever cable corridor is used without losing wind turbine positions). Of course, cable corridors limit the future developer somewhat in creating an optimal wind farm lay-out (i.e. when micro-siting the wind turbines).

5 WIND FARM LAYOUTS AND YIELD

5.1 Introduction

To determine the relative LCoE differences between the different variants indicative wind farm and infield cable lay-outs were designed. This allowed for the determination of the yield and costs on a turbine level instead of crude assumptions based on (for example) the reduced amount of area available for wind turbines. This level of detail was considered required to be able to distinguish the differences between variants and to draw firm conclusions.

5.2 Approach for wind farm layout and yield calculations

The wind farm lay outs used in this study are not fully optimised wind farm layouts. No micro-siting has been performed. No feedback loop with the cost model was applied in which relatively expensive wind turbine positions were relocated to cheaper locations.

The basis of the layouts was a rectangular grid of wind turbines that were positioned along the longest boundaries of the wind farm sites. Then the distance between the wind turbines was increased to such an extent that the total amount of remaining wind turbines inside the site boundaries added up to the maximum of 756 MW (63 x 12 MW).

The wind turbine layouts comply with applicable rules and regulations. For example, the layouts consider maintenance distances from existing pipelines and telecom cables (500 m buffer) and the blades of the wind turbines stay within the boundaries of the wind farm zone.

After the wind turbine positions were determined, the infield cable layouts were defined. As a baseline a maximum of six 12 MW wind turbines were placed on a string. In some cases, it was more efficient to put less wind turbines on a string due to siting constraints.

As a final step, for all created layouts yields were calculated using WindPRO/WAsP. In WindPRO multiple wind climate 'site data objects' across the wind farm zone were established to correctly represent the wind speed gradients across the site found from the mesoscale models. Each wind turbine makes use of the closest wind climate to calculate its energy yield.

For the TNW wind farm zone the wake effects of the Gemini offshore wind farms (east of the wind farm zone) have been considered by modelling the Gemini wind farms in the same way the TNW wind turbines were modelled. For the Gemini offshore wind farm the actual built turbine type and hub height were used.

5.2.1 Technical limits

The following chapters focus on the wind farm density and wake effects of the different layouts that are presented. The wake effects are modelled using WindPRO/WAsP, but no detailed turbulence calculations are performed in this study. With decreasing wind turbine distances an increase in turbulence is observed. What the exact limit of wind turbine distances is, depends on the wind farm layout and total amount of wind turbines. As a general rule of thumb a minimum distance of 4.5 to 5 times the rotor diameter is used in this study. Offshore wind farms with smaller wind turbine distances are likely to reach the turbulence limits and are therefore not included in this study.

5.3 Hollandse Kust (west)

The main research questions defined by the Working Group were for the Hollandse Kust (west) area were:

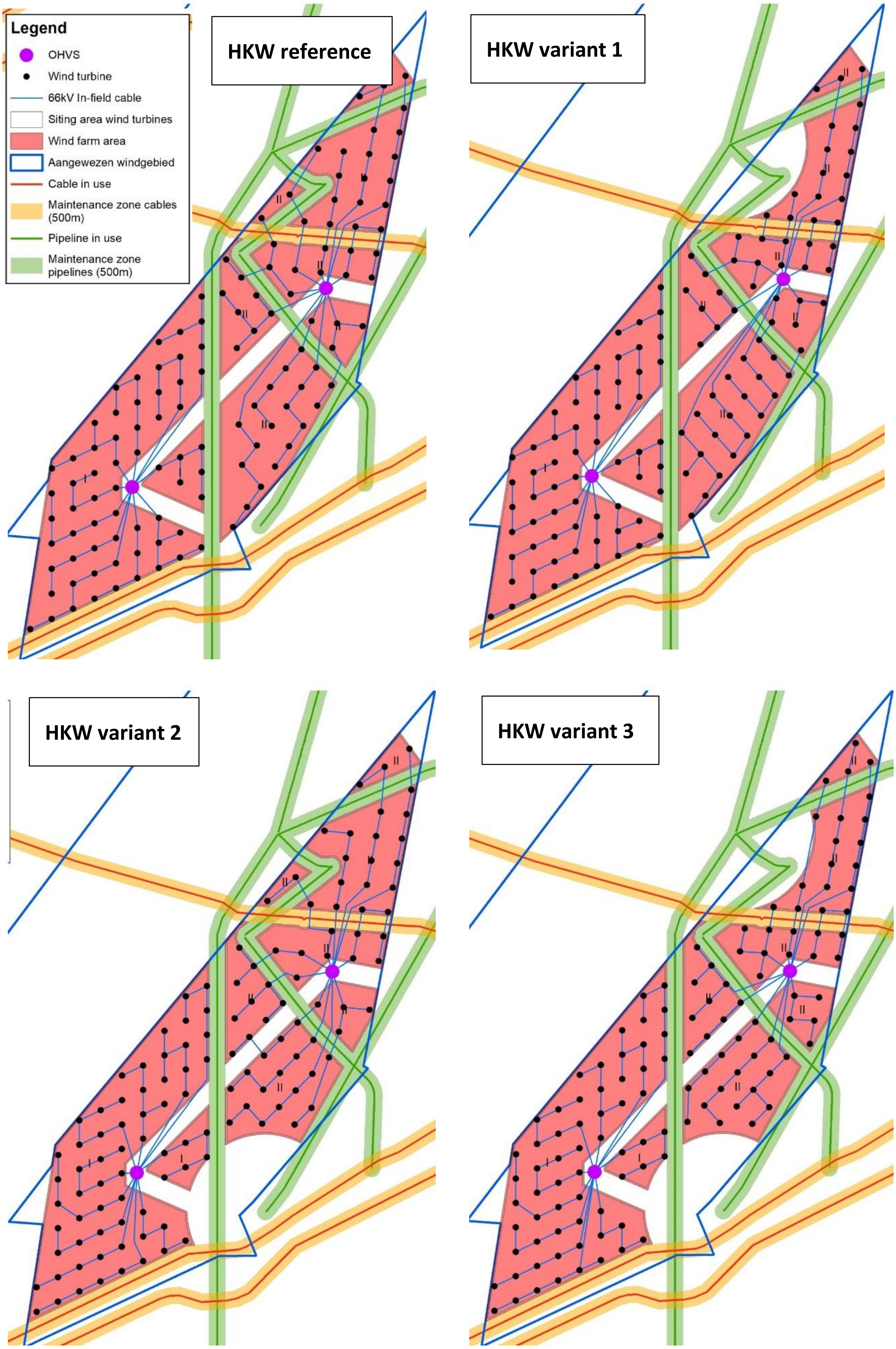
1) What is the effect of excluding the helicopter safety zones on the LCoE of the wind farm?
2) What is the effect of 3 sites of 756 MW instead of 2 sites of 756 MW on the LCoE of the wind farm?

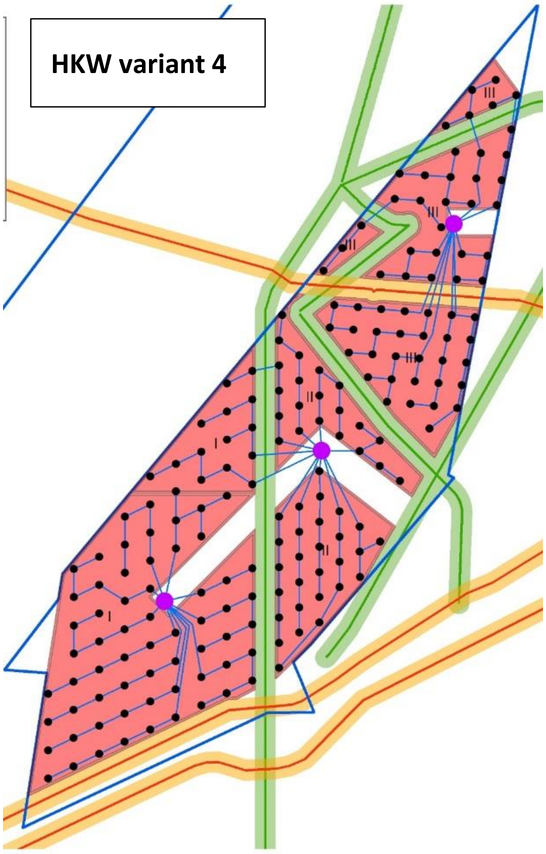
To answer these questions five variants were defined and investigated. At a later stage three variants were added. Variant 6 as a sensitivity run, variant 7 and 8 to further investigate the differences between developing 2 and 3 sites. The table below describes the different variants.

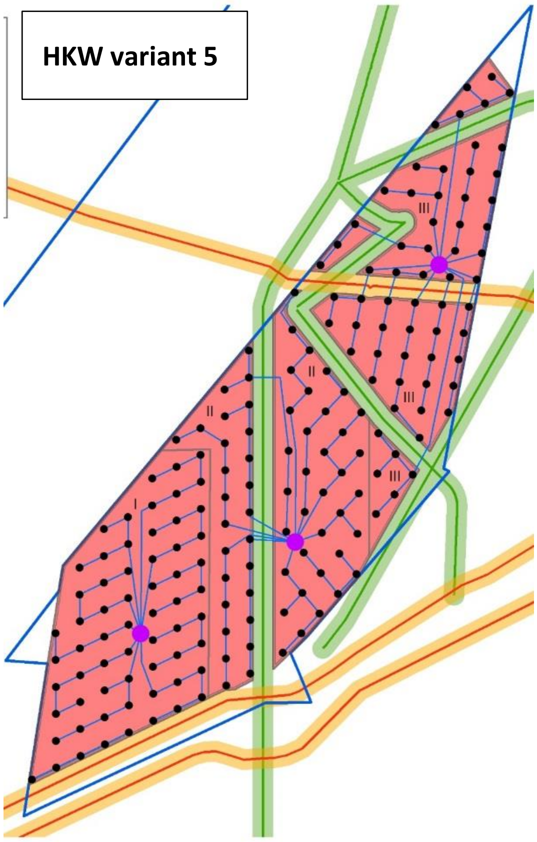
Table 9: Layout variants for Hollandse Kust (west).

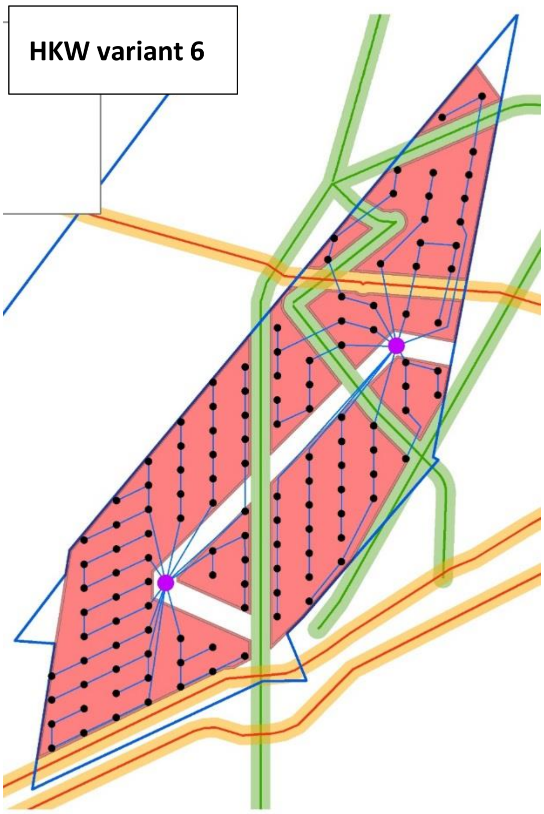
Variant	Description	Wind farm capacity	Wind farm density
HKW reference	Reference layout using the full wind farm area	2 x 756 MW	6.2 MW/km^2
HKW variant 1	Excluding helicopter safety zone in the north	2 x 756 MW	6.5 MW/km^2
HKW variant 2	Excluding helicopter safety zone in the south	2 x 756 MW	6.7 MW/km^2
HKW variant 3	Excluding both helicopter safety zones	2 x 756 MW	7.0 MW/km^2
HKW variant 4	Three instead of two wind farm sites	3 x 756 MW	9.2 MW/km^2
HKW variant 5	Three instead of two wind farm sites, without pre-described site boundaries and locations of substations	3 x 756 MW	9.2 MW/km^2
HKW variant 6	Sensitivity analysis on HKW reference, using a larger wind turbine spacing in the main wind direction and a shorter spacing perpendicular to the main wind direction	2 x 756 MW	6.2 MW/km^2
HKW variant 7	Same as variant 4, but where area on north is excluded, leaving space for another wind farm that could potentially be developed later	2 x 756 MW	8.7 MW/km^2
HKW variant 8	Same as variant 4, but where area on south is excluded, leaving space for another wind farm that could potentially be developed later	2 x 756 MW	10.2 MW/km^2

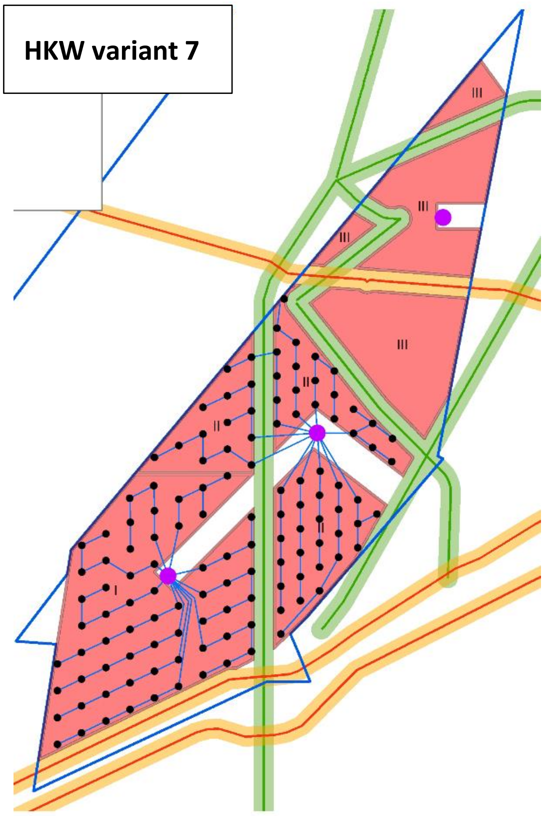
Figure 10 shows the different variants that were studied for Hollandse Kust (west).


Legend
OHVS
Wind turbine
66kV In-field cable
Siting area wind turbines
Wind farm area
Aangewezen windgebied
Cable in use
Maintenance zone cables (500m)
Pipeline in use
Maintenance zone pipelines (500m)
HKW reference
HKW variant 1
HKW variant 2
HKW variant 3


HKW variant 4


HKW variant 5


HKW variant 6


HKW variant 7

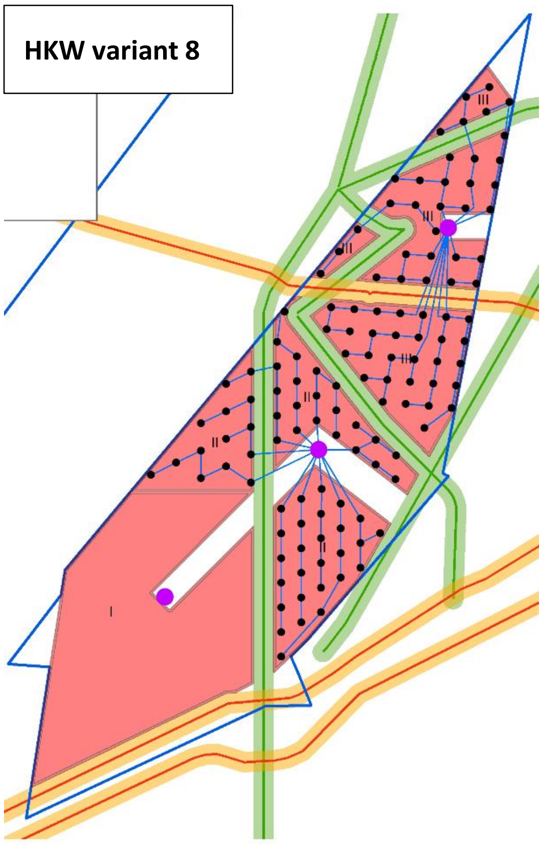


Figure 10: Overview of wind farm layouts for each of the variants for Hollandse Kust (west).

The difference between the HKW reference and variant 1, 2 and 3 are limited (slight rearrangement of turbines in line with the available area). The largest differences exist between the variants with a maximum of 2 x 756 MW (reference, 1, 2, 3 and 6) and the variants with a maximum of 3 x 756 MW installed capacity (variant 4 and 5) where the turbine density increases significantly.

Table 10 shows the main outcomes of the HKW wind farm layout and yield assessment. The results are as expected: with a slightly smaller available area we see a slight increase in wake effect (from 8.2% to a maximum of 8.7%). The increase in wake effect is higher when increasing the total amount of installed capacity (variant 4 and 5). An increase from 8.2% to maximum 11.9% is observed.

The total infield cable length increases with increasing number of wind turbines. However, the infield cable length per wind turbine decreases with increasing number of wind turbines. This is also influenced by the introduction of a third TenneT offshore station.

The results for variant 6 show that increasing the distance between wind turbines in line with the main wind direction does not necessarily result in higher yields. The increase in wake effects in all other directions (due to tighter spacing perpendicular to the main wind direction) is apparently larger than the decrease in wake effects in the main wind direction. This is because the initial distance of 7 times the rotor diameter (or wind farm density of 6.2 MW/km^2) is already quite large and additional benefits from further increasing this distance are relatively small.

The results for variant 7 and 8 show that the wake effects compared to variant 4 only decrease slightly (from 11.9% to 11.1% and 11.4% respectively). It shows that the average wake effect of the wind farm is mainly governed by the amount of wind turbines in the centre of the wind farm sites.

Table 10: Wind farm layout and yield characteristics of Hollandse Kust (west) variants.

Variant	ref	var 1	var 2	var 3	var 4	var 5	var 6	var 7	var 8
Number of turbines [-]	126	126	126	126	189	189	126	126	126
Minimal turbine spacing [x D]	7D	7D	7D	7D	6.5D	6.5D	6D	6.5D	6.5D
Density [MW/km²]	6.2	6.5	6.7	7.0	9.2	9.2	6.2	8.7	10.2
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]	8,132	8,132	8,133	8,133	12,198	12,198	8,133	8,133	8,133
Wake effects [%]	8.2	8.4	8.6	8.7	11.9	11.6	8.6	11.4	11.1
Net annual yield [GWh/y]	6,879	6,860	6,847	6,841	9,932	9,959	6,845	6,659	6,677
Net annual yield per WTG [GWh/y]	54.6	54.4	54.3	54.3	52.6	52.7	54.3	52.9	53.0
Total infield cable length (km)	239	240	234	233	295	298	250	194	195
Total crossings	18	15	15	14	11	14	15	3	11
Average foundation depth [m]	26.7	26.7	26.7	26.7	26.6	26.7	26.7	26.6	26.5

5.4 Ten Noorden van de Waddeneilanden

For Ten Noorden van de Waddeneilanden the two main research questions were:

1) What is the impact of excluding the western part of the wind farm zone on the LCoE?
2) How does a further reduction of the wind farm area impact the LCoE?

To answer these questions several variants were created. In the reference variant the entire wind farm zone is used, except the area in between Gemini. In variant 1, the westernmost part of the wind farm zone is not used. In variants 2 to 4, the wind farm area is further reduced in steps (see Table 11 and Figure 11). It is expected that the eastern part of the wind farm zone will have no or smaller shipping safety issues compared to the western part, therefore the reduction in available wind farm area was made in an eastern direction.

Table 11: Layout variants for Ten Noorden van de Waddeneilanden.

Variant	Description	Wind farm capacity	Wind farm density
TNW reference	Using the full wind farm area	1 x 756 MW	8.1 MW/km²
TNW variant 1	Reduction to 84 % of the reference area	1 x 756 MW	9.6 MW/km²
TNW variant 2	Reduction to 77 % of the reference area	1 x 756 MW	10.5 MW/km²
TNW variant 3	Reduction to 65 % of the reference area	1 x 756 MW	12.5 MW/km²
TNW variant 4	Reduction to 40 % of the reference area	1 x 756 MW	20.5 MW/km²

Table 12 shows that reducing the wind farm zone size has an impact on the wake effects (increase) as well as the infield cable length (decrease). How these two effects interact will be shown in the next chapters.

Note that TNW variant 4 is not recommended, because the distance between the turbines is less than recommended from technical viewpoint (4.0-4.5 D) to avoid damage due to excessive turbulence.

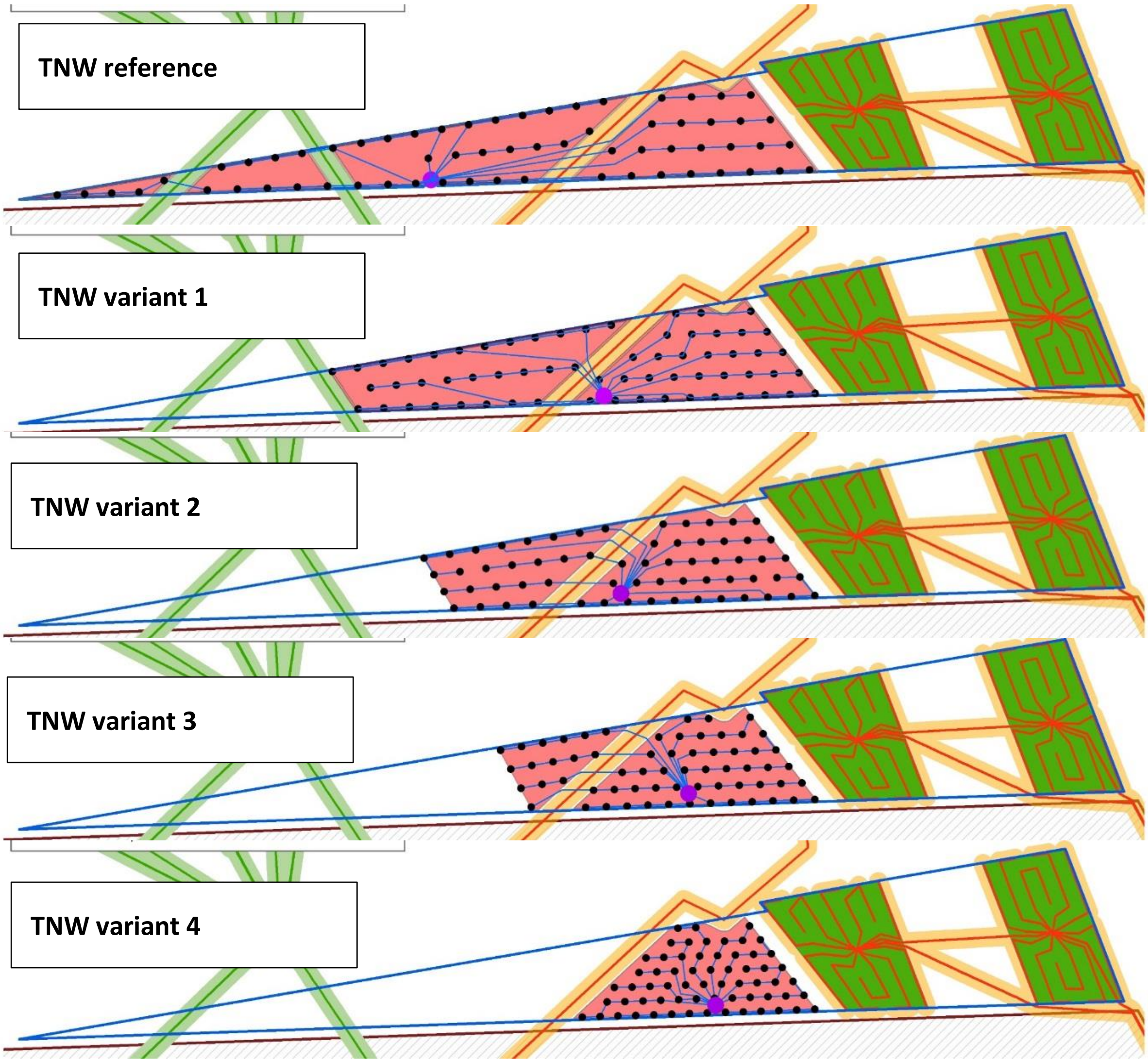


Figure 11: Overview of wind farm layouts for Ten Noorden van de Waddeneilanden.

Table 12: Wind farm layout and yield characteristics of Ten Noorden van de Waddeneilanden variants.

Variant	reference	variant 1	variant 2	variant 3	variant 4
Number of turbines [-]	63	63	63	63	63
Minimum turbine spacing [x D]	6.9D	5.9D	5.0D	4.8D	4.1D
Density [MW/km^2]	8.1	9.6	10.5	12.5	20.5
Mean wind speed at hub height [m/s]	9.9	9.9	9.9	9.9	9.9
Gross annual yield [GWh/y]	3.942	3.942	3.942	3.941	3.941
Wake effects [%]	6.6	9.1	10.8	13.1	17.2
Net annual yield [GWh/y]	3.377	3.302	3.244	3.169	3.054
Total infield cable length (km)	151	113	104	85	63
Total crossings	9	5	5	4	0
Average foundation depth [m]	36.6	36.1	36.0	35.7	35.2

5.4.1 Gemini wake effects

The results above take into account the inter-park wake effects from offshore wind farm Gemini on the different TNW variants. To give some more insight in the effects of TNW on Gemini and vice versa the table below shows the additional wake effects from Gemini on TNW (variant 1) and from TNW on Gemini. Please note that the wake effects of the Gemini wind farm are modelled in the same as the wake effects for TNW are (i.e. no measured wake-effect data is available from the Gemini wind farm).

Table 13: Gemini and TNW (inter park) wake effects

Wake effects [%]	Stand alone	TNW + Gemini	Difference (%-points)
TNW variant 1	8,5%	9,1%	0,6%
Gemini	13,4%	14,6%	1,2%

5.5 IJmuiden Ver

For the IJmuiden Ver wind farm area (IJV) four very preliminary lay-outs were created and only the wake effects were determined (no LCoE analysis). The layouts provide a first insight into the effects of using different parts of the available area. The total capacity that was modelled in the IJV wind farm area was set at 4GW and two different ferry route scenarios were defined. Using the ferry route scenarios, four wind farm variants were composed. Two using only the area below the ferry route and two dividing the wind turbines north (1/3) and south (2/3) of the ferry route (see Table 14).

Table 14 shows the four different scenarios. Please note that for the IJV wind farm layouts a generic 15 MW wind turbine was used instead of the generic 12 MW wind turbine that was used for HKW and TNW.

Table 14: Layout variants for IJmuiden Ver.

Variant	Description	Wind farm capacity	Wind farm density
IJV variant 4a	Ferry route north; use northern and southern zone	4GW	7.6 MW/km^2
IJV variant 4b	Ferry route south; use northern and southern zone	4GW	9.0 MW/km^2
IJV variant 5a	Ferry route north; use only southern zone	4GW	11.3 MW/km^2
IJV variant 5b	Ferry route south; use only southern zone	4GW	12.9 MW/km^2

Table 15 and Figure 12 show the power density and preliminary yield and wake effect results for the four variants. The wake effects of the different variants roughly range from 10 to 15%. It should be noted however that there is limited knowledge and experience with modelling very large-scale offshore wind farms using prototype large size wind turbines. Therefore, these values should be considered indicative.

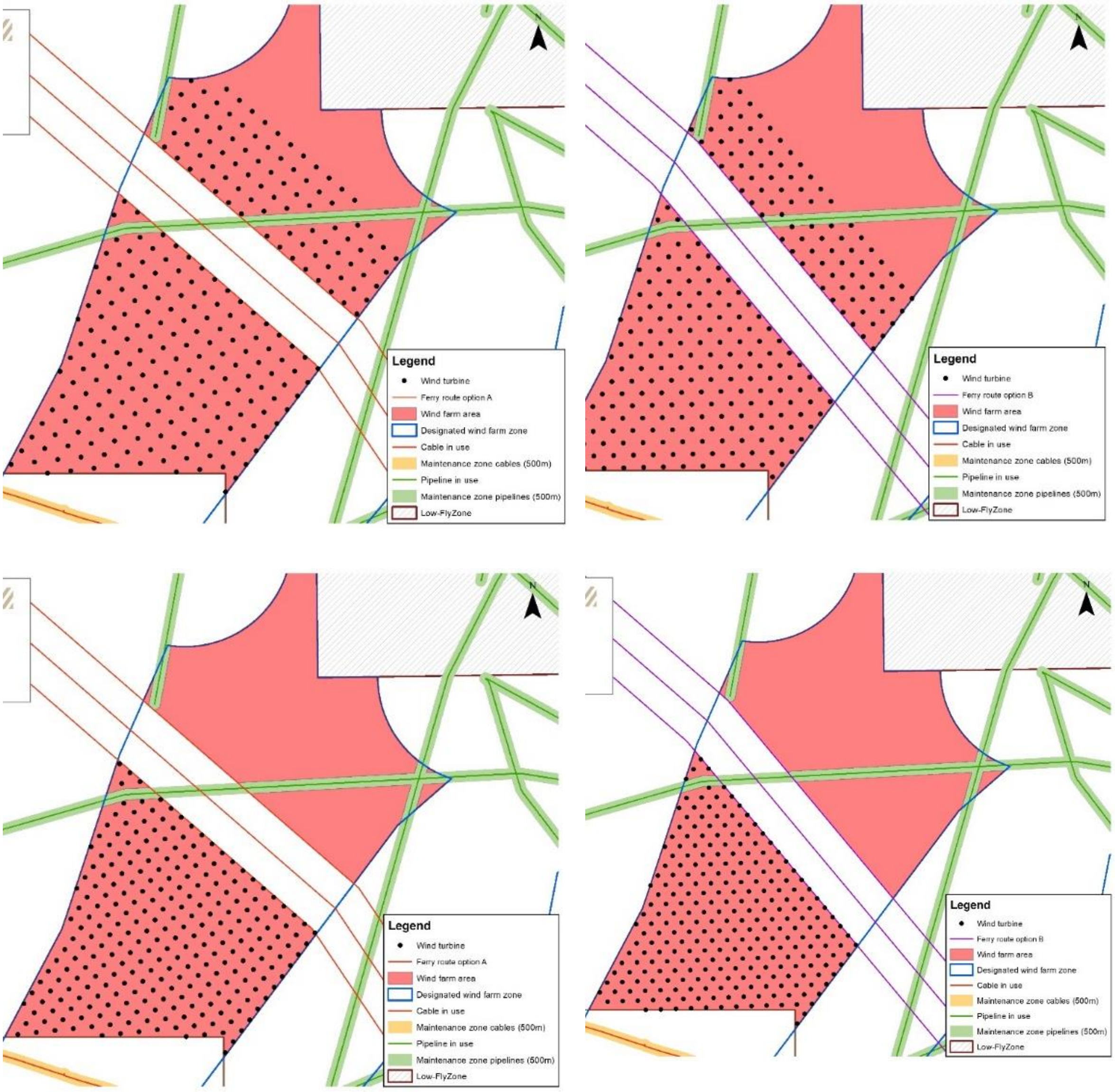


Figure 12: Overview of wind farm layouts for each of the variants for IJmuiden Ver.

Table 15: Wind farm layout and yield characteristics of IJmuiden Ver variants.

Variant	variant 4a	variant 4b	variant 5a	variant 5b
Number of turbines [-]	267	267	267	267
Minimum turbine spacing [x D]	6.6	6.2	5.3	5.0
Density [MW/km^2]	7.6	9.0	11.3	12.9
Mean wind speed at hub height [m/s]	10.3	10.3	10.3	10.3
Gross annual yield [GWh/y]	21,827	21,829	21,819	21,819
Wake effects [%]	9.7	10.3	13.8	14.6
Net annual yield [GWh/y]	18,456	18,306	17,603	17,422

6 YIELD AND COST ANALYSIS

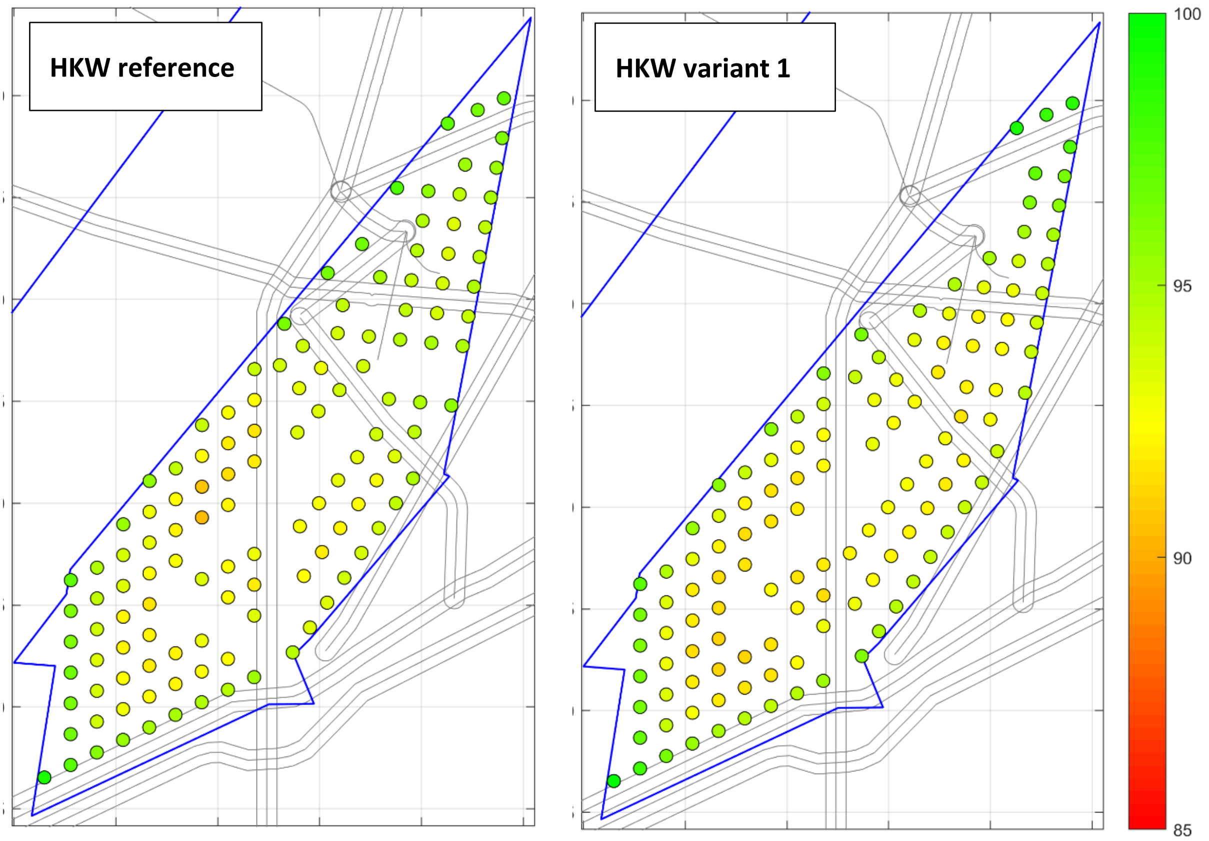
6.1 Relative yield per turbine

6.1.1 Differences between variants per site

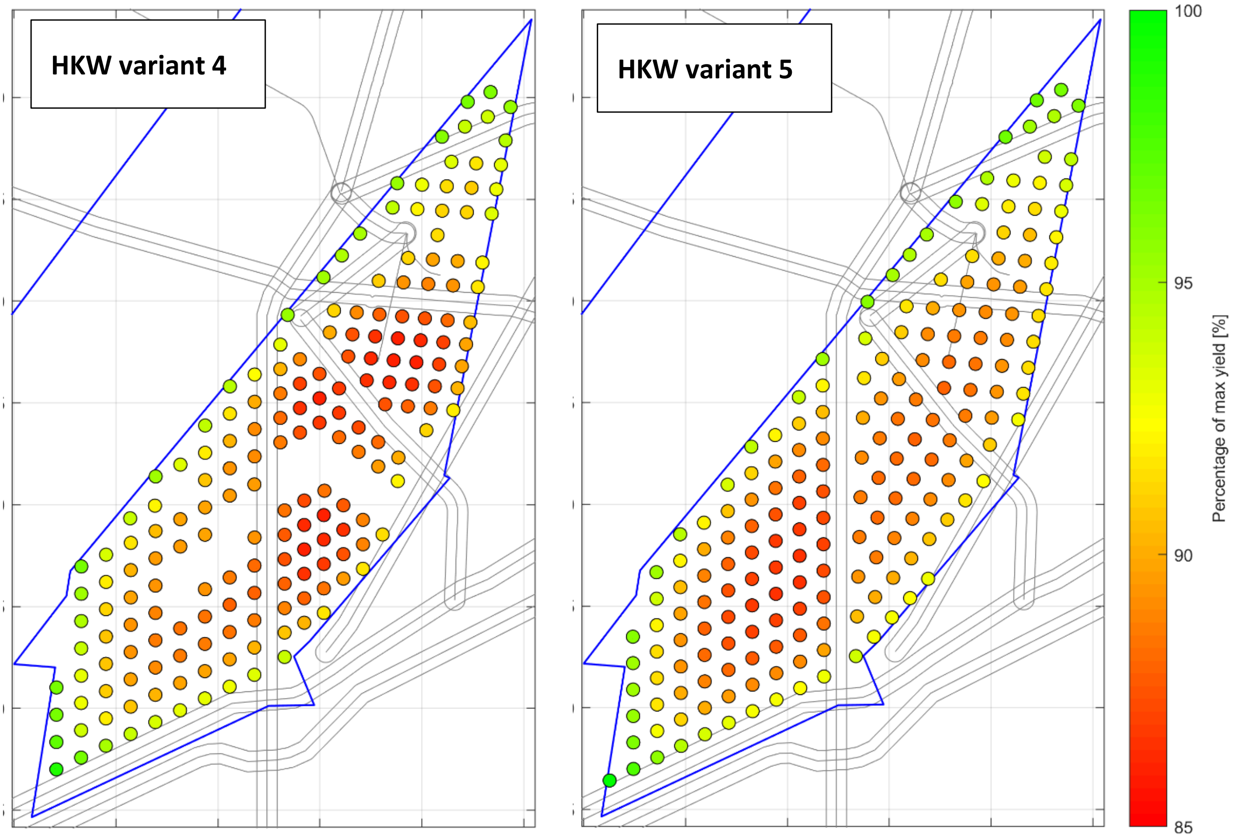
For a more in-depth understanding of the observed yield and wake losses for each variant, we investigated the relative yield per individual turbine. Figure 13 shows a series of plots in which the relative yield is visualised with colours. A relative yield of 100% implies that there are no wake effects.

The results show the following:

- The outer row of turbines generally experiences less wake effects, which is to be expected.
- Only small differences are observed between the reference layout, variant 1, 2 and 3. Excluding the helicopter zones leads to a slightly higher turbine density at other places with a slight increase of wake losses.
- A significant decrease of the relative yield (and increase of wake losses) can be seen in variant 4 and 5 due to the larger density of turbines. In variant 4, strong wakes are observed in 3 red zones. At variant 5, the wake effect is more evenly distributed across the area.
- Variant 6 shows quite comparable effects as the reference variant. This suggests that the wake reduction in the mean wind direction is compensated by the wake increase in the direction perpendicular to the mean wind direction.
- Differences between variant 7 and 8 are limited. Slightly more turbines are favourably located in variant 8, leading to slightly lower overall wake effects.




HKW variant 2
HKW variant 3
100
95
90
85
Percentage of max yield [%]


HKW variant 4
HKW variant 5
100
95
90
85
Percentage of max yield [%]

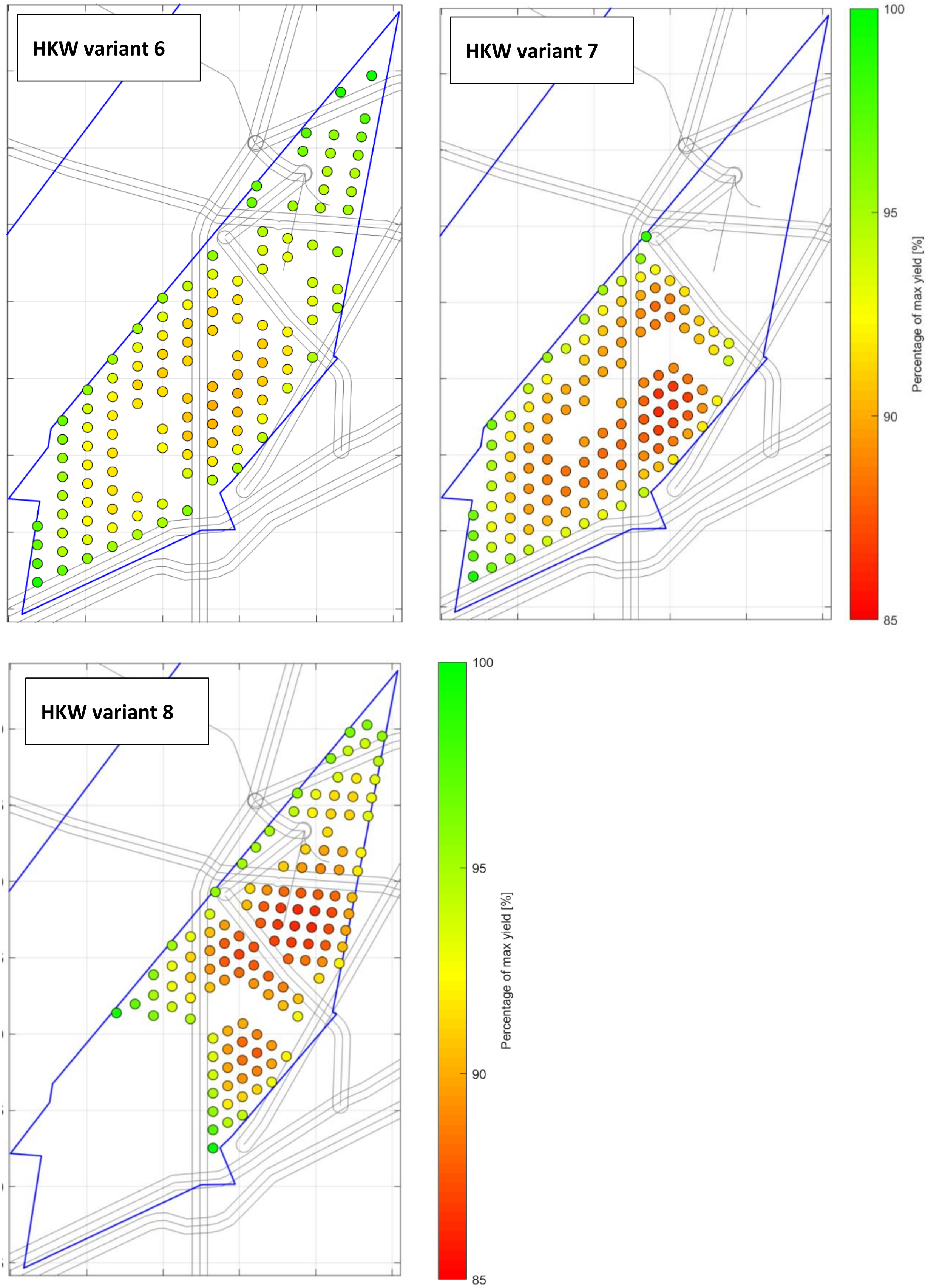


Figure 13: Relative yield for each of the variants for Hollandse Kust (west).

Figure 14 shows the relative yield for Ten Noorden van de Waddeneilanden. The results show a clear increase of wake effects as the wind farm area is reduced.

Figure 15 shows the relative yield for the IJmuiden Ver alternatives. It can be seen that the available area associated with a ferry route more towards the south (variant 4b) causes a larger wind farm density with larger wake effects in the area south of the ferry route than in case of a ferry route more towards the north (variant 4a). Using only the area south of the ferry route will significantly increase wake effects, particularly in case of the southern ferry route (variant 5b).

In general, the wake effects at IJmuiden Ver in a similar order of magnitude as Hollandse Kust (west) in case the part north of the ferry route is also used (~10%). Using only the southern area will lead to a large array of turbines (15 x 15) with considerably larger wake effects (in the order of 14-15%). As a rule of thumb, each 1% of additional wake effect causes an increase of about 0.6 €/MWh.

6.1.2 Differences between sites

If we compare the relative yield between HKW and TNW, both show a reducing yield with larger density. However, for a similar wind farm density (e.g. compare HKW variant 4/5 with TNW variant 1) we observe higher wake losses for HKW than for TNW. This is due to two effects:

- At TNW, the area is highly asymmetric. Many of the turbines placed on or very close to the wind farm site boundary. This causes the available area to be used more effectively than in case of a more symmetrical wind farm zone.
- The orientation of TNW with regard to wake effects is more favourable, because the long axis of HKW is parallel with the mean wind direction, while TNW is relatively perpendicular to the mean wind direction.

Hence, a given wind farm site density (or distance between turbines) can lead to different wake losses (and LCoE), depending on the asymmetry and orientation of a wind farm site in relation to the dominant wind direction.

The results of IJmuiden Ver show that large, more symmetrical arrays of turbines are unfavourable from the viewpoint of wake effects.

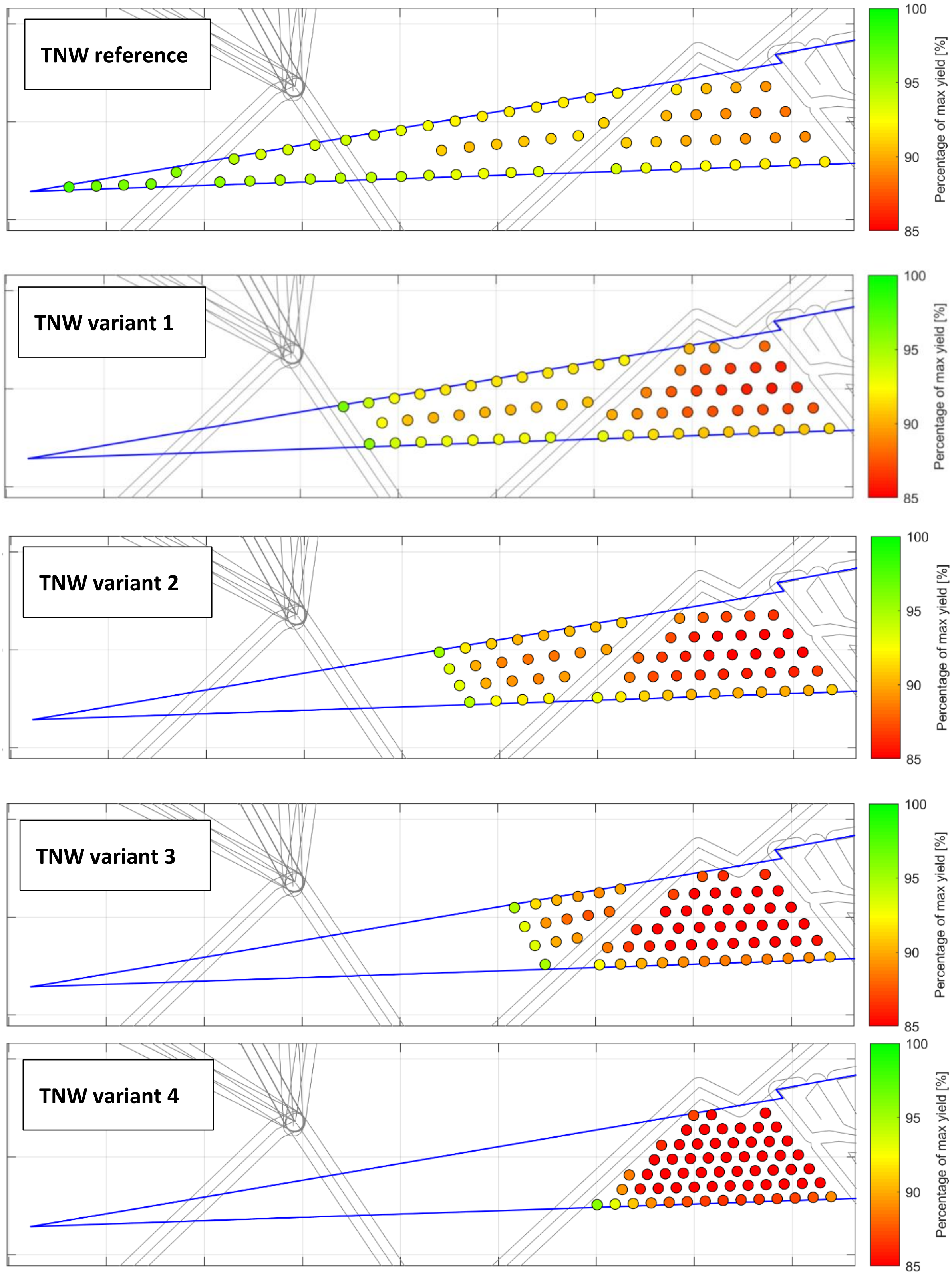


Figure 14: Relative yield for each of the variants for Ten Noorden van de Waddeneilanden.

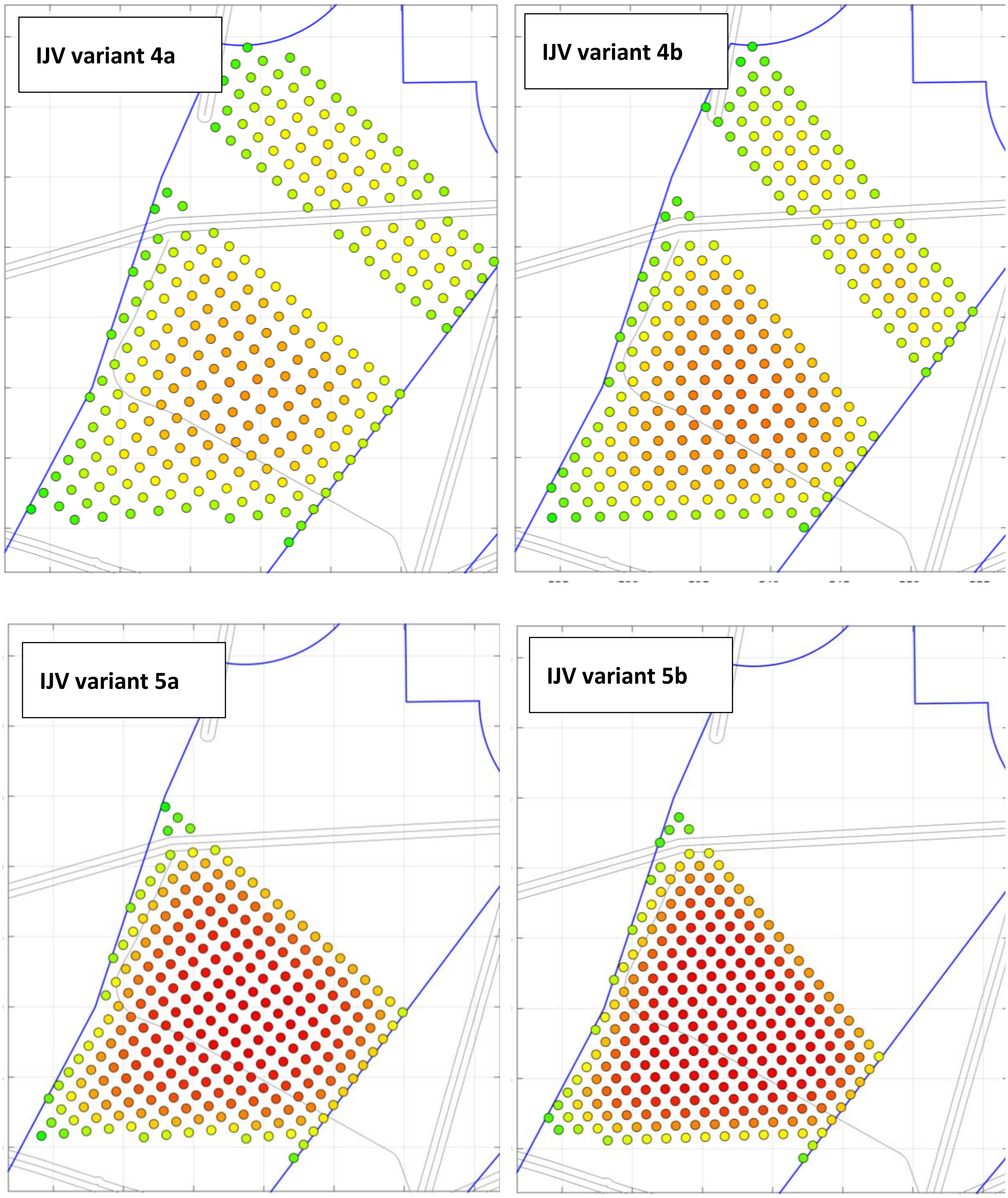


Figure 15: Relative yield for each of the variants for IJmuiden Ver.

6.2 Relative foundation cost

6.2.1 Differences between variants per site

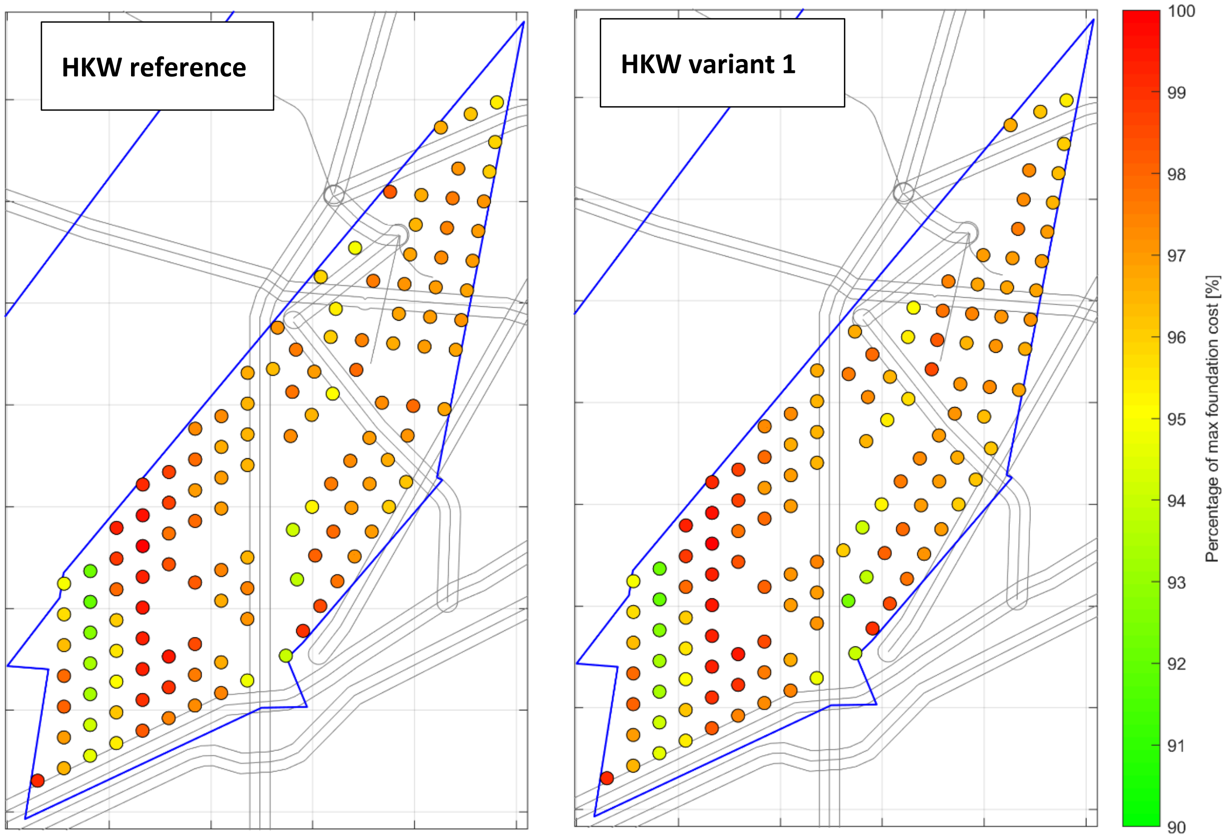
As a next step, the relative foundation cost per turbine is analysed with a similar approach. In all plots the figures are made relative to the turbine with the maximum cost of all HKW variants. A relative foundation cost of 100% refers to the most expensive foundation across all HKW variants.

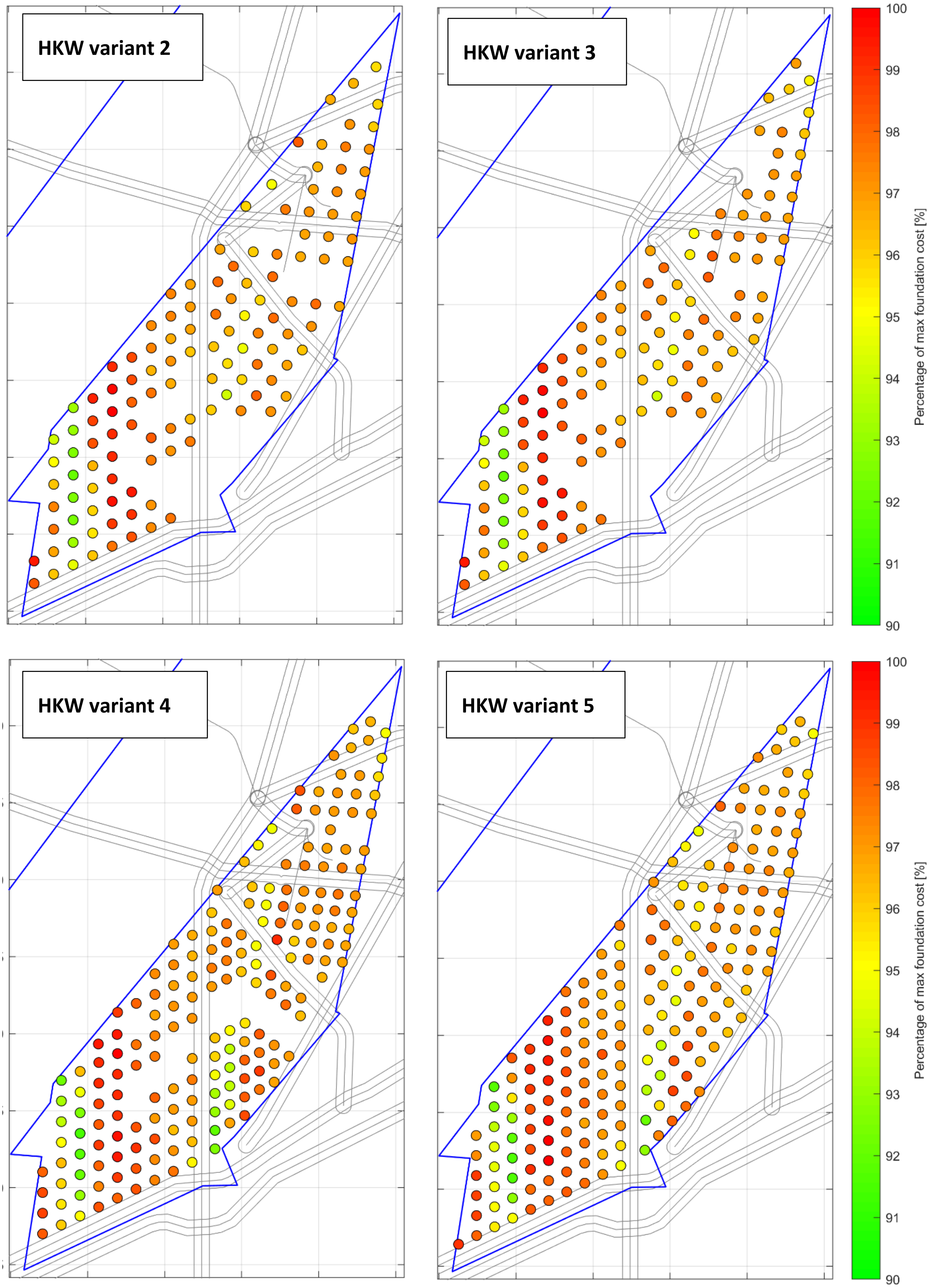
Figure 16 shows the relative foundation cost for the variants for Hollandse Kust (west). The results clearly show the impact of water depth variations. The foundation cost reduces on top of the shallow sand banks and increases in the deeper areas. The cost variations as result of bathymetrical features are most clearly distinguishable for variant 4 and 5, because these have the highest turbine density. The foundations are approximately 10% more expensive in the deepest areas, compared with the shallowest areas.

Figure 17 shows similar results for Ten Noorden van de Waddeneilanden. In both cases, the relative foundation costs reduce to the east because of the shallower water depth in the east. For variant 2, the western deeper part is not used, hence the relative foundations costs are lower than for variant 1. The foundations are about 5% more expensive in the deepest areas.

6.2.2 Differences between sites

If we compare TNW with HKW, the foundation cost variations are much larger at HKW (~10%) than at TNW (~5%), because the depth variations at HKW are larger.




HKW variant 2
HKW variant 3
HKW variant 4
HKW variant 5
100
99
98
97
96
95
94
93
92
91
90
Percentage of max foundation cost [%]

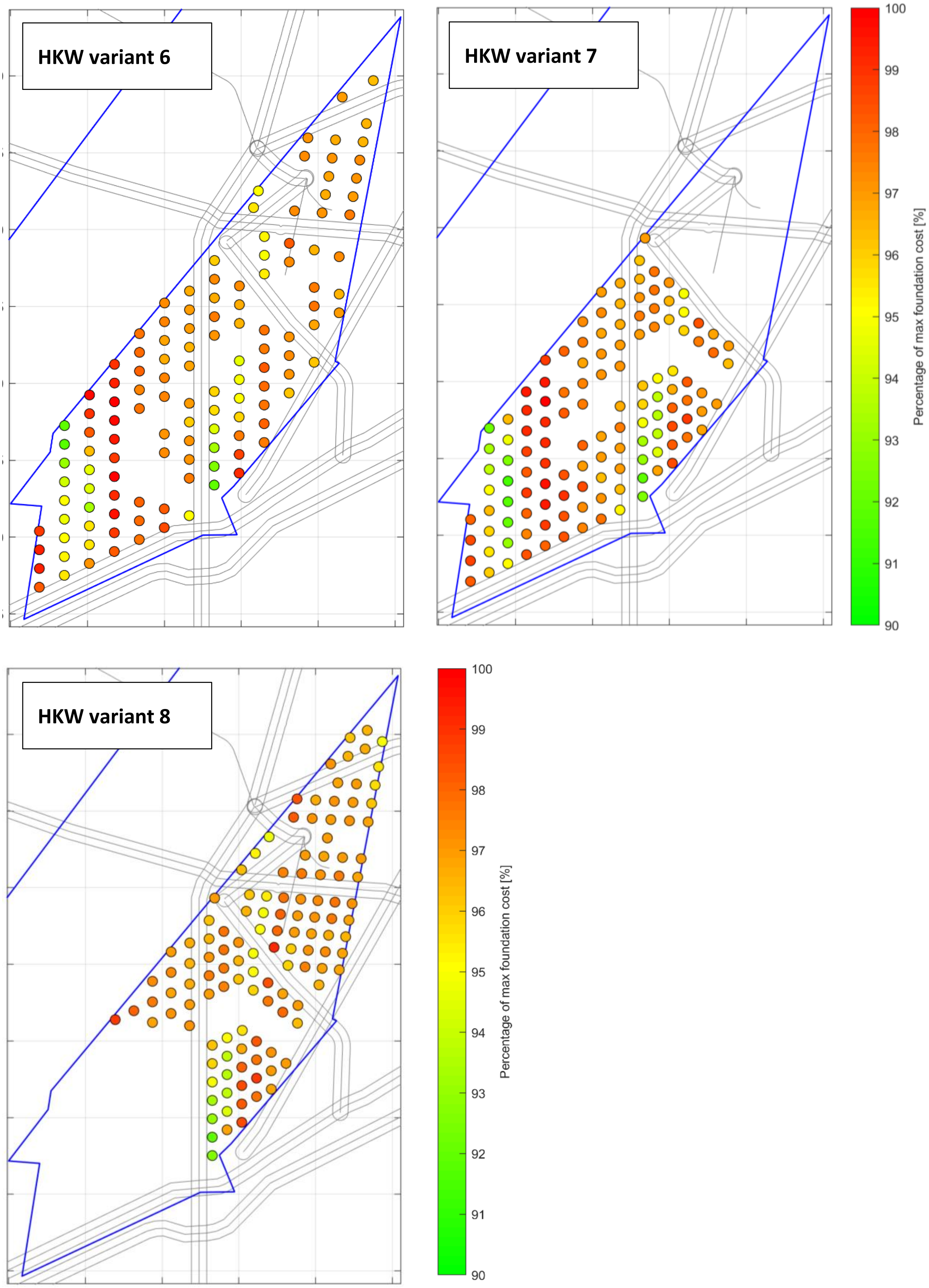


Figure 16: Relative foundation cost for each of the variants for Hollandse Kust (west).

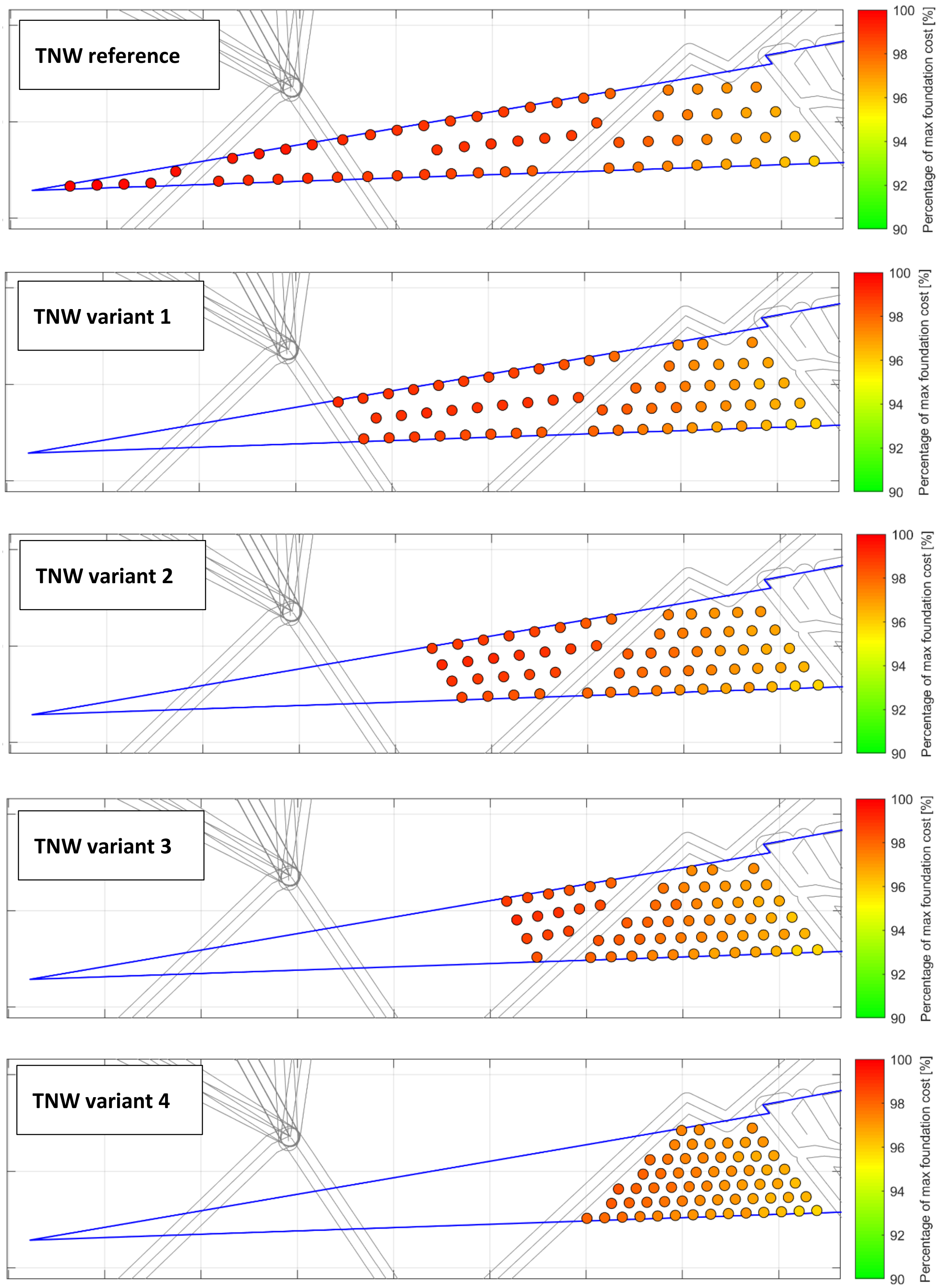


Figure 17: Relative foundation cost for each of the variants for Ten Noorden van de Waddeneilanden.

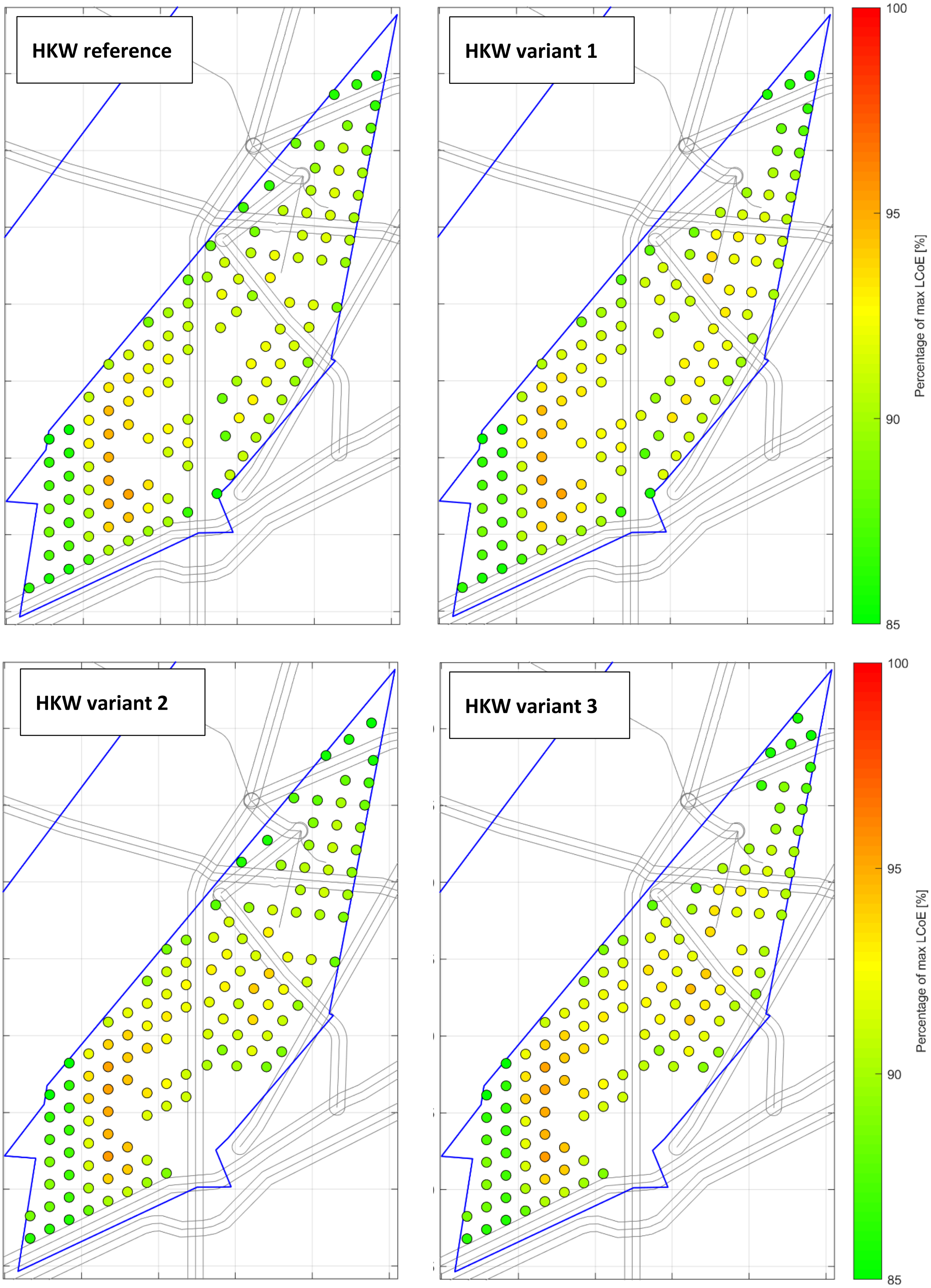
6.3 Levelized cost of energy per turbine

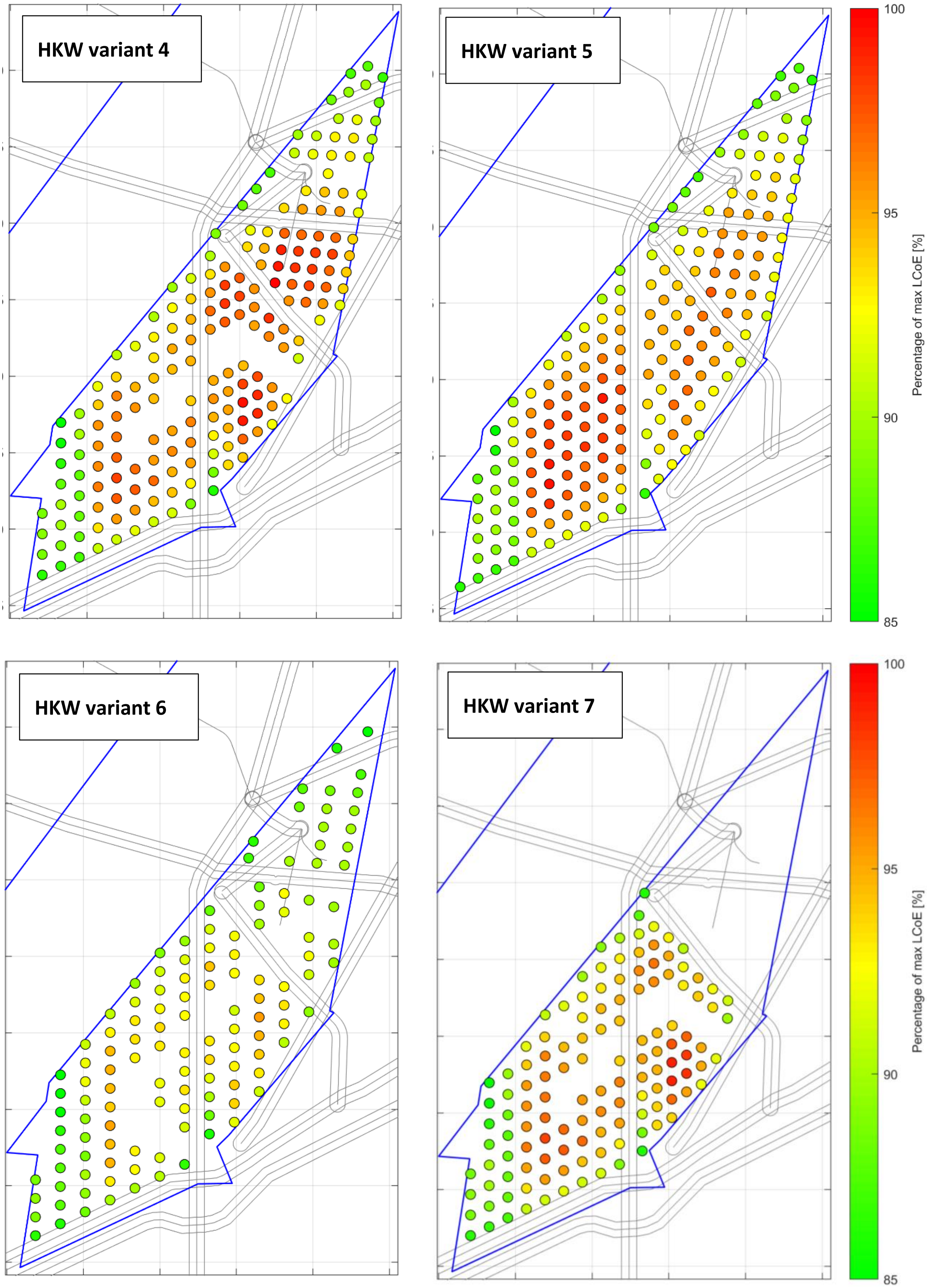
6.3.1 Differences between variants per site

In the last part of this analysis the Levelized Cost of Energy per turbine is investigated. The LCoE per turbine incorporates both the yield and the cost of each turbine foundation. The costs for cable length and cable crossings are evenly distributed over all turbines.

Figure 18 shows the relative LCoE per turbine for the variants of HKW. The following is observed:

- The cost per energy unit is lowest at the sides of the areas. This indicates that the effect of yield is dominant over foundation cost. However, the foundation cost variations also have a distinct influence.
- The first two rows of turbines (from left to right) have lowest LCoE. The first row primarily due to low wake effects, the second row due to the sand bank with shallow water (in combination with limited wakes).
- The fourth row of turbines (from left to right) have highest LCoE. This is because they experience a combination of deep water and a strong wake effect. The difference in LCoE amounts to 15%.
- Limited differences occur between the reference and the first three alternatives. The water depths are quite similar inside and around the helicopter zones, so the LCoE is mainly driven by the wake effects that are slightly higher if the helicopter zones are excluded, because of a general denser lay-out.
- Variant 4 and 5 show a stronger increase of LCoE within the wind farm zones, due to the higher density and stronger wakes. The largest LCoE occurs again in deep water in combination with significant wakes.
- Variant 6 shows comparable results as the reference alternatives. This indicates that 7D was already quite favourable in terms of LCoE. Increasing the distance further in the dominant wind direction hardly reduces the wakes.
- Variants 7 and 8 show that overall, using the northern area (variant 7) causes a slightly lower LCoE per turbine than using the southern area (variant 8), mainly due to the lower wake effects.


HKW reference
HKW variant 1
HKW variant 2
HKW variant 3
100
95
90
85
Percentage of max LCoE [%]


HKW variant 4
HKW variant 5
HKW variant 6
HKW variant 7
100
95
90
85
Percentage of max LCoE [%]
100
95
90
85
Percentage of max LCoE [%]

BLIX

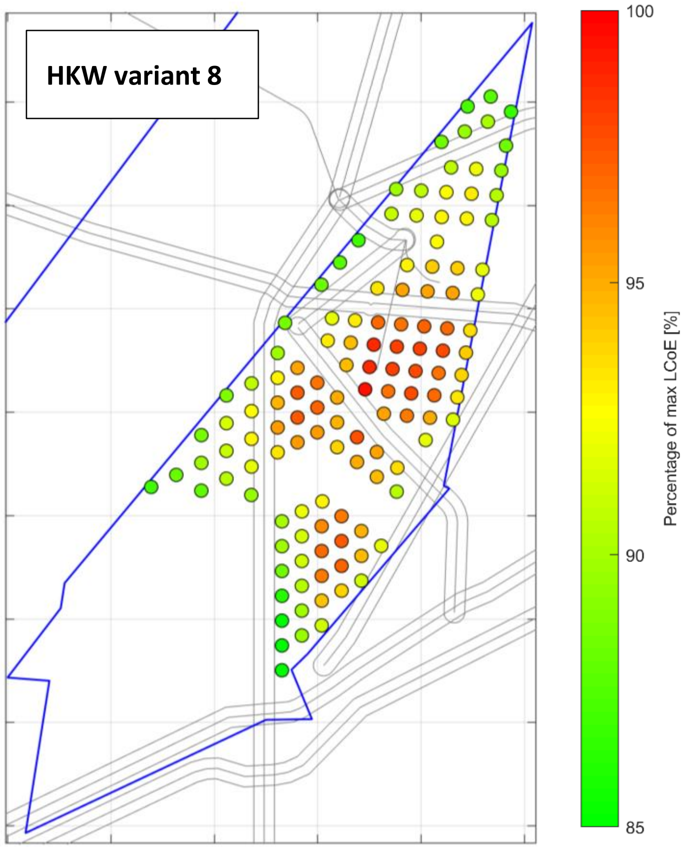


Figure 18: Relative LCoE for each of the variants for Hollandse Kust (west).

Figure 19 shows the relative LCoE per turbine for the variants of TNW. The results show the following:

- The cost per energy unit is lowest at the western side (only a few percent - hard to see in the plot). This implies that the additional yield exceeds the larger costs due to the larger water depth in this area.
- For variant 1 and 2, the larger turbine density leads to slightly larger wake effects and a slightly higher relative LCoE in the centre of the eastern side of the zone.
- For variant 3 and 4, a stronger increase of the wake effects can be observed, particularly for variant 4.

6.3.2 Differences between sites

If we compare TNW with HKW, the increase of wind farm density at TNW causes less increase of the LCoE compared to HKW, because of the more favourable shape and orientation of TNW than HKW. If TNW would have been oriented more along the SW-NE axis or be more symmetrical in both axes, then the increased density would have resulted in a steeper increase of the LCoE.

Costs at IJV were not considered.

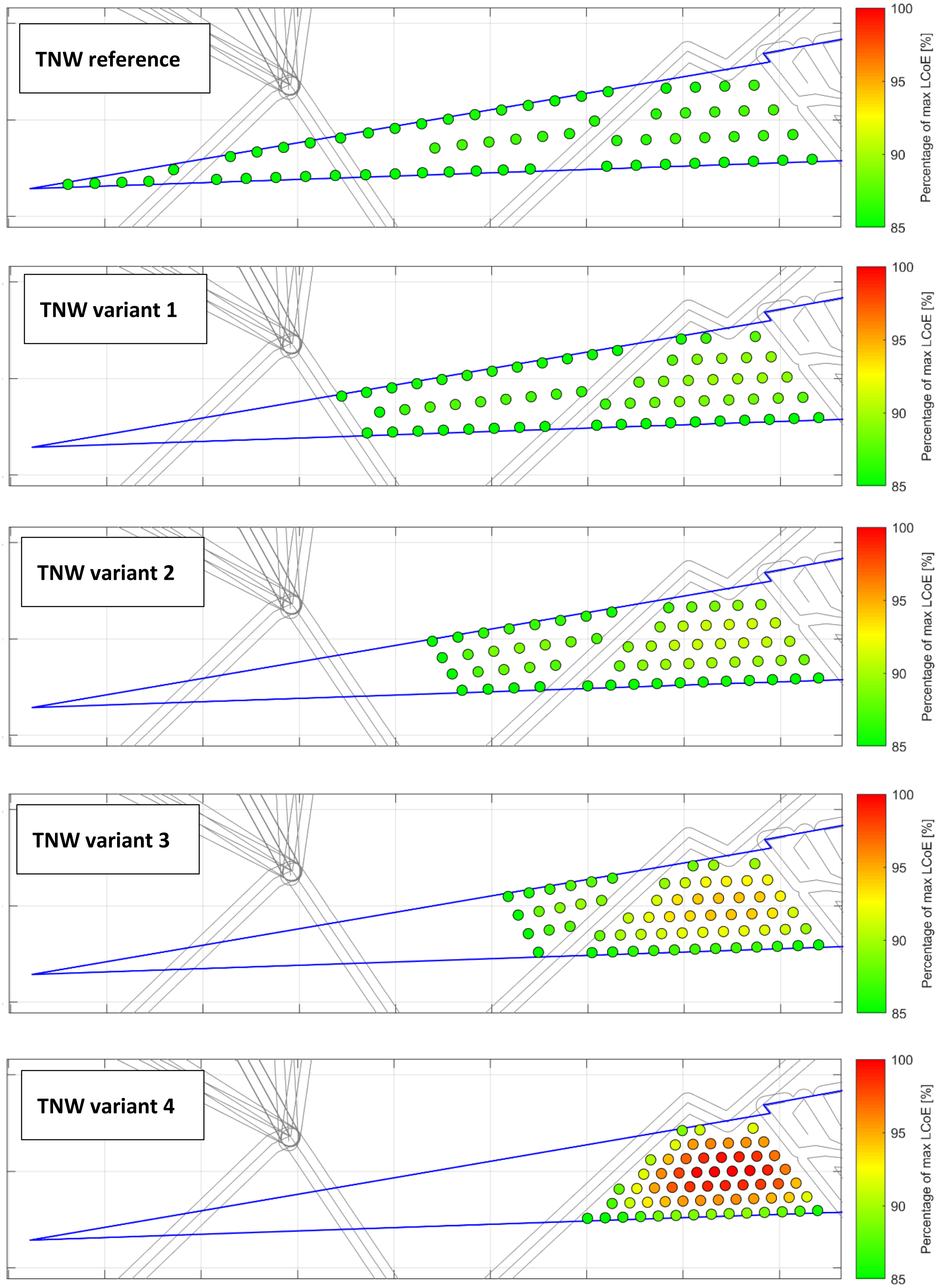


Figure 19: Relative LCoE for each of the variants for Ten Noorden van de Waddeneilanden.

7 COMPARISON OF LEVELIZED COST OF ENERGY

7.1 Financial model setup

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 model inputs are based on the latest projects BLIX participated in 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.

7.2 Levelized costs of energy

The definition of Levelized Costs 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):

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

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

[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.

[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)

r = required return/WACC
CAPEX = Capital Expenditure (Investments)
OPEX = Operational Expenditure (Operational costs)

The inputs of table 8 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 (see results of this in the following chapter).

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).

7.3 LCoE of Hollandse Kust (west)

Below table shows the impact on LCoE of the different variants compared to the reference variant. Several factors are assumed to remain the same between the variants, these are therefore not in below table[5].

7.4 Energy yield

From Table 16 it can be observed that wake losses differ significantly per variant. Wake losses increase particularly at the sites with higher turbine density. The effect of increasing wake losses with decreasing site area can clearly be seen from the results in Table 16. In the variant with highest wakes, the relative wake losses increase with around 45% compared to the reference variant. The energy yield loss due to wakes is around 8.2% in the reference variant, in variant 4 this is thus increased with 45% to 11.8%. This reflects a net energy loss of around 11.8 – 8.2 = 3.6%, which is a significant energy yield reduction. The impact on an overall LCoE level is therefore significant, the densest site (which has 63 x 3 = 189 turbines) has a LCoE of 3.56% higher than the reference variant (which has the lowest wind turbine density and only 126 turbines installed).

A denser site will, however, require less inter array cable length and have lower cable losses. This impact is however not as strong as the increased wake losses (difference between reference variant and site with lowest cable losses is -0.30% LCoE). Overall it can therefore be concluded that a denser site will reduce the energy yield per turbine. Of course, the total energy yield for the denser sites (with 50% more installed capacity) does increase strongly (total energy yield increases with around 45%) so from an efficient use of scarce space the higher density sites scores better.

As mentioned in table 2, there is very limited wind gradient across the site. The wind-gradient therefore does not influence the relative LCoE between the variants, hence the average wind-speeds are not included in below table.

[5] Wind-farm availability, wind turbine costs, DEVEX, OPEX and more parameters are assumed to remain constant and are therefore excluded in Table 13.

Table 16: LCoE of different variants for HKW. Note that all given percentages are relative to the reference variant.

Wind farm zone	*HKW reference*	HKW var 1	HKW Var 2	HKW var 3	HKW var 4	HKW var 5	HKW var 6	HKW var 7	HKW var 8
Site description	*Reference lay-out*	Exclude helicopter zone north	Exclude helicopter zone south	Exclude both helicopter zones	3 wind farm sites instead of two	Variant 4 but without prescribed exclusions	Reference lay-out with increased spacing in dominant direction	Var 4 whereas area on north is excluded	Var 4 whereas area on south is excluded
Capacity (MW)	*1,512*	1,512	1,512	1,512	2,268	2,268	1,512	1,512	1,512
ENERGY YIELD									
Wake Losses		2.98%	5.71%	6.81%	45.24%	42.10%	4.85%	39.85%	36.02%
LCoE impact wake losses		**0.27%**	**0.51%**	**0.61%**	**4.22%**	**3.91%**	**0.44%**	**3.70%**	**3.33%**
IAC cable length		0.33%	-2.09%	-2.72%	-17.89%	-16.88%	4.56%	-18.70%	-18.53%
LCOE impact cable losses		**0.01%**	**-0.03%**	**-0.04%**	**-0.28%**	**-0.27%**	**0.07%**	**-0.30%**	**-0.29%**
CAPEX									
IAC cable length		0.33%	-2.09%	-2.72%	-17.89%	-16.88%	4.56%	-18.70%	-18.53%
Number of crossings		-16.7%	-16.7%	-22.2%	-59.3%	-48.2%	-16.7%	-83.33%	-38.89%
LCoE impact array cable costs		**-0.01%**	**-0.05%**	**-0.06%**	**-0.35%**	**-0.32%**	**0.06%**	**-0.38%**	**-0.34%**
Average water depth		-0.16%	-0.14%	-0.18%	-0.48%	-0.24%	-0.25%	-0.46%	-1.03%
Foundation costs		-0.04%	-0.03%	-0.04%	-0.11%	-0.06%	-0.06%	-0.11%	-0.25%
LCoE impact foundation costs		**-0.01%**	**-0.01%**	**-0.01%**	**-0.02%**	**-0.01%**	**-0.01%**	**-0.02%**	**-0.05%**
Net LCoE impact		**0.26%**	**0.42%**	**0.50%**	**3.57%**	**3.31%**	**0.55%**	**2.94%**	**2.68%**

7.4.1 CAPEX

As a denser site requires fewer inter array cables, the investment costs of these will decrease. Fewer cable crossings for the different variants will furthermore have an investment reducing effect. On a LCoE basis, the maximum impact is -0.38% LCoE compared to the reference variant.

The different variants have different lay-outs and therefore also different water depths per turbine. When the water depth varies, it will impact the costs of the foundation (deeper water requires more steel for the turbine foundation). Although the water depth varies considerably across the site, the overall impacts are limited. The largest LCoE reduction compared to the reference is only -0.05%. This is because in each variant the turbines are spread more or less equally over the site. A larger impact would have been observed in case one of the variants would have included or excluded a deeper area.

7.4.2 Overall

Graphically the overall difference in LCoE can be displayed as follows (see Figure 20);

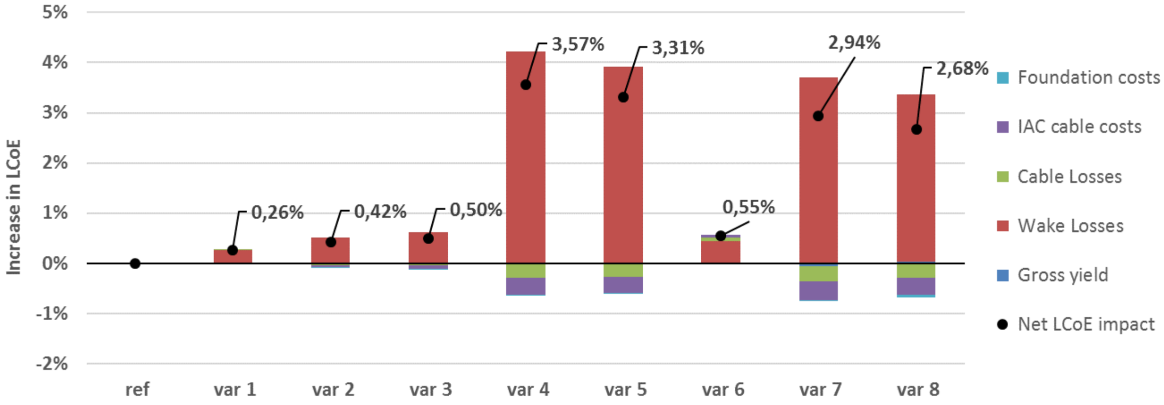


Figure 20 Resulting LCoE difference of six variants of Hollandse Kust (west) layouts compared to reference layout of Hollandse Kust (west).

The above differences between variants results in increasing LCoE compared to the reference variant. The increase in LCoE ranges from 0.26% to 3.57%. The difference between the reference lay-out and variant is mostly governed by increasing wake-losses. Particularly when 189 wind turbines are installed instead of 126 wind turbines the wake losses will increase significantly. Note that possible synergy in construction and O&M in case of three sites have not been taken along, because it is not yet known if the site would be tendered as a whole. When looking at variant 6, it can be observed that increasing the turbine spacing in the dominant wind direction does not decrease the LCoE (as the decreased spacing of the non-dominant wind direction has a larger impact than the increased spacing for the dominant wind direction). Leaving about a third of the area available for future wind farms (variant 7 and 8) causes an increase of the LCOE of about 2.5 to 3%.

7.5 LCoE of Ten Noorden van de Waddeneilanden

Table 17 shows the impact of variants compared to the reference. Several factors will remain the same between the variants, these are therefore not included[6].

7.5.1 Energy yield

The TNW table shows that decreasing the area for wind turbines will increase wake losses significantly, cable losses however show the opposite effects, these decrease strongly.

As mentioned in table 2, there is limited wind gradient across the site. The wind-gradient therefore does not influence the relative LCoE between the variants, hence the average wind-speeds are not included in below table.

[6] Wind-farm availability, wind turbine costs, DEVEX, OPEX and more parameters are expected to remain constant and are therefore excluded in Table 14.

Table 17: LCoE of different variants for TNW. Note that all given percentages are relative to the reference variant.

Wind farm zone	*TNW reference*	TNW variant 1	TNW variant 2	TNW variant 3	TNW variant 4
Site description	*Include whole area*	Exclude part of western side of area	Further reduce area from west	Further reduce area from west	Further reduce area from west
Installed capacity (MW)	*756*	756	756	756	756
ENERGY YIELD					
Wake Losses		38.40%	63.63%	98.47%	160.59%
LCoE impact wake losses		**2.78%**	**4.69%**	**7.36%**	**12.51%**
IAC cable length		-25.17%	-30.86%	-43.51%	-58.15%
LCoE impact cable losses		**-0.50%**	**-0.61%**	**-0.87%**	**-1.16%**
CAPEX					
IAC cable length		-25.17%	-30.86%	-43.51%	-58.15%
Number of crossings		-44.44%	-44.44%	-55.56%	-100.00%
LCoE impact IAC cable costs		**-0.52%**	**-0.63%**	**-0.88%**	**-1.20%**
Average water depth		-1.27%	-1.70%	-2.51%	-3.64%
Foundation costs		-0.38%	-0.51%	-0.75%	-1.09%
LCoE impact Foundation costs		**-0.09%**	**-0.11%**	**-0.17%**	**-0.25%**
Net LCoE impact		**1.65%**	**3.34%**	**5.44%**	**9.91%**

7.5.2 CAPEX

Due to decreased cable distances, the investment costs of the cables decrease significantly in more dense variants than the reference variant (in variant 4 for example no cable crossings are required anymore). Foundation costs show a small decrease for all variants compared to the reference variant (maximum of -0.25% on LCoE basis), as water depth decreases slightly when removing large parts of the western area (maximum reduction foundation costs as result of water depth of -1.09%).

7.5.3 Overall

The overall difference in LCoE is shown in Figure 21. Overall it can be concluded that the decreased spacing (and thus increased wake losses) has a larger impact on the LCoE than the decreased cable investment costs and cable losses. The net impact on LCoE for the most dense lay-out (+9.91%) is considered to be significant.

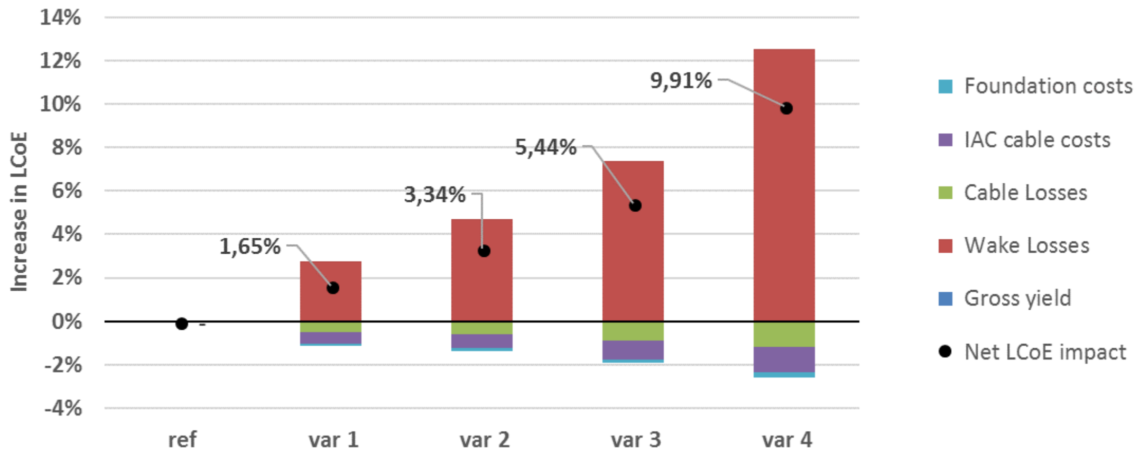


Figure 21 Resulting LCoE difference of four variants of Ten Noorden van de Waddeneilanden layouts compared to reference layout of Ten Noorden van de Waddeneilanden.

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.

Nevertheless, the present approach is deemed suitable for the purpose of this study, which is to compare relative differences between site alternatives. But given the uncertainties caused by these simplifications, we consider small differences (smaller than about 1%) to be insignificant (smaller than the uncertainty associated with the approach). The differences observed however confirm the general 'gut feeling' regarding effects of limitations and other assumptions and therefore contribute to the overall credibility of the approach.

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 22 shows the power curve for the HKW 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 13 m/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.

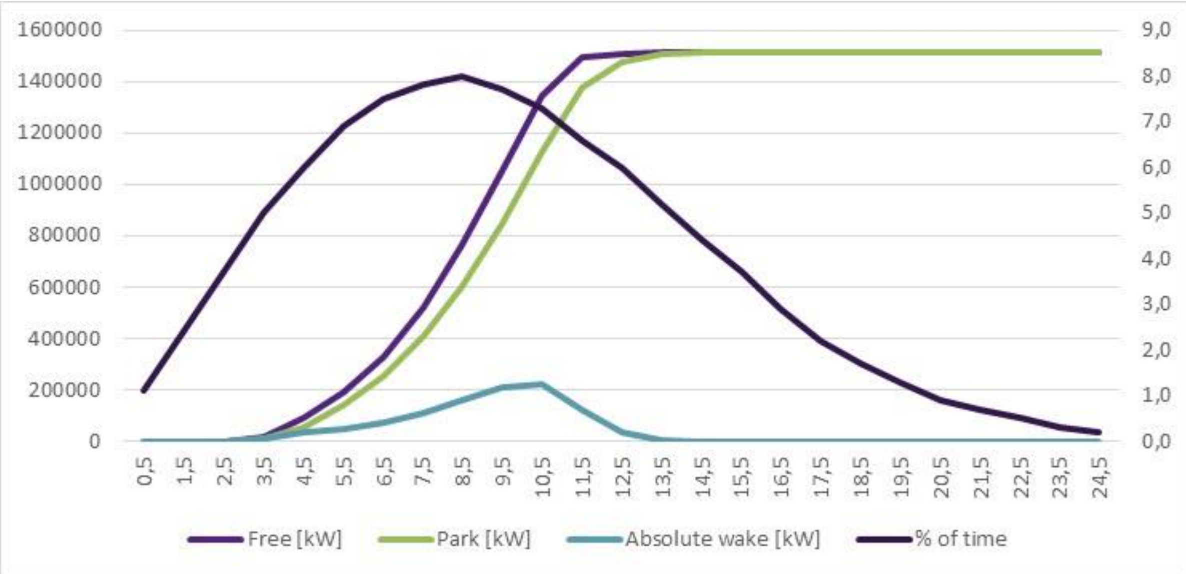


Figure 22 - Wind speed and wake effects HKW reference

9 CONCLUSIONS & RECOMMENDATIONS

9.1 Conclusions

Within the present study, the Levelized Cost of Energy 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 for each turbine individually and aggregated per variant. Note that for IJV only the yield was considered.

The following main conclusions are drawn based on the LCOE modelling:

<u>Hollandse Kust (west)</u>

- Based on the results we conclude that excluding the helicopter safety zones has a negligible impact on the LCoE. The difference between the reference alternative and variants 1, 2 and 3 are lower than 1% and therefore considered smaller than the uncertainty of the applied approach. We note that the general trend is according to expectations (a smaller area leads to higher LCoE) which confirms the credibility of the approach.
- The LCoE is about 3.5% higher for three sites of 756 MW than for two sites of 756 MW.
- The LCoE is about 2.5 to 3% higher in case 2 sites of 756 MW are used and space is left for a future third site.

<u>Ten Noorden van de Waddeneilanden</u>

- The results of the sensitivity calculation (variants 2 – 4) show that a reduction of the available wind farm area will increase the LCoE.
- Variant 4 is not recommended from a technical viewpoint because it will cause developers to use an unconservative distance between turbines (4 D).
- The increase in wake effects on the existing Gemini wind farm as result of TNW variant 1 is calculated to be about 1%.

<u>IJmuiden Ver</u>

- Using only the area south of the ferry route will significantly increase wake effects, particularly in case of the southern ferry route (variant 5b).
- The available area associated with a ferry route more towards the south (variant 4b) causes a higher wind farm density (with more wake effects) in the area south of the ferry route than the ferry route more towards the north (variant 4a).

9.2 Recommendations

We recommend to investigate the impact of a variable energy price on the income differences between variants for an unsubsidized wind park. A lower value of electricity produced under high wind speeds will amplify the differences in total value between alternatives and may therefore influence the decision-making process.