# Determination of the cost levels of wind farms (and their grid connections) in new offshore wind energy search areas

BLIX PONDERA Energy Solutions High Voltage Engineering & Consultancy

| | |
|---|---|
| **From:** | BLIX Consultancy BV & partners |
| **Reference:** | Determination of the cost levels of wind farms (and their grid connections) in new offshore wind energy search areas, WOZ2180096 |
| **To:** | Ministry of Economic Affairs and Climate Policy, Netherlands Enterprise Agency (RVO), Ministry of Infrastructure and Water Management and The Directorate-General for Public Works and Water Management |
| **Authors:** | BLIX Consultancy: I. Maassen van den Brink Msc, N. Olijve MSc<br>Pondera: W. Pustjens MSc |
| **Review committee:** | BLIX Consultancy: B. de Sonneville Msc<br>Pondera: S. Geujen MSc |
| **Version:** | Final |
| **Date:** | 15 December 2020 |

# Table of contents

# List of Figures

# List of Tables

# Abbreviations and Terms

List of abbreviations and terms with their definitions:

| **Abbreviation or term** | **Definition** |
|---|---|
| AEP | Annual Energy Production |
| Capex | Capital expenditure |
| Devex | Development expenditure |
| DOWA | Dutch Offshore Wind Atlas |
| GCS | Grid Connection System |
| HVAC | High Voltage Alternating Current |
| HVDC | High Voltage Direct Current |
| IA | Inter-Array |
| IRR | Internal Rate of Return |
| KNMI | Koninklijk Nederlands Meteorologisch Instituut |
| KNW Atlas | KNMI North Sea Wind Atlas |
| LCoE | Levelized Cost of Energy |
| Opex | Operational expenditure |
| Overall LCoE | Sum of the OWF LCoE and GCS LCoE |
| OVHS | Offshore High Voltage Station |
| OWF | Offshore Wind Farm |
| Search area | An area that is being explored for possible assignment as Wind Farm Zone |
| String | A group of wind turbines connected to a substation with the same cable |
| TSO | Transmission System Operator |
| WACC | Weighted Average Cost of Capital |
| WDC | Wake Decay Constant |
| WFS | Wind Farm Site, part of a Wind Farm Zone |
| WFZ | Wind Farm Zone, zone officially assigned for development of offshore wind energy |
| Working group | Netherlands Enterprise Agency, The Ministry of Economic Affairs and Climate Policy, Ministry of Infrastructure and Water Management and The Directorate-General for Public Works and Water Management |
| WTG | Wind Turbine Generator |

# 1 INTRODUCTION

## 1.1 Background

BLIX Consultancy & partners were asked by the Netherlands Enterprise Agency (RVO), The Ministry of Economic Affairs and Climate Policy, Ministry of Infrastructure and Water Management and The Directorate-General for Public Works and Water Management, referred to as “Working group”, to determine the cost levels of offshore wind farms and their grid connection systems in new offshore wind energy search areas by performing a Levelized Cost of Energy (“LCoE”) study.

The reference for this study is IJmuiden Ver as this wind farm zone (in Dutch: “windenergiegebied”) is the last of the currently allocated wind farm zones within the 2030 Roadmap that will be developed and because IJmuiden Ver will be connected with 2 GW High Voltage Direct Current (“HVDC”) grid connection systems, currently also assumed for wind farm zones in the new search areas.

The report consists of two parts, in which newly considered wind farm zones consisting of one or more wind farm sites (in Dutch: “kavels”) are defined and assessed for two different layouts (with varying size, location and orientation) of the search areas. A distinction is made between the LCoE of the offshore wind farm (“OWF”) and the grid connection system (“GCS”).

Part I contains the results from a first study into the OWF LCoE of the offshore wind energy search areas with the assumed wind farm zones and sites listed in Table 1 and shown in Figure 1, compared to the OWF LCoE of Wind Farm Zone IJmuiden Ver.

Table 1: Wind farm zones considered in Part I

| Wind Farm Zone | Abbreviation | Number of sites | Total capacity |
|---|---|---|---|
| **IJmuiden Ver** | IJV | 2 | 4 GW |
| **Zone 1** | | 4 | 8 GW |
| **Zone 2** | | 3 | 6 GW |
| **Zone 3** | | 1 | 2 GW |
| **Zone 5** | | 5 | 10 GW |
| **Zone 5 (mb)** | | 4 | 8 GW |
| **Zone 6** | | 6 | 12 GW |
| **Zone 7** | | 4 | 8 GW |
| **TOTAL** | | **29** | **58 GW** |

After and during this study the offshore wind energy search areas were altered in shape, orientation and size based on new insights from Part I of this study, other studies commissioned by the Working group and following discussions with stakeholders.

Part II contains the results from the follow-up LCoE study of the OWF, the GCS and the sum of both (“overall LCoE”) of the defined wind farm zones and sites of the adapted search areas, IJmuiden Ver (noord), Hollandse Kust (noordwest) and Hollandse Kust (zuidwest) compared to the reference zone IJmuiden Ver and Hollands Kust (west). Table 2 lists and Figure 2 shows the wind farm zones studied in Part II with their subdivision into sites. Figure 3 shows both the wind farm zones of Part I and Part II.

Table 2: Wind farm zones considered in Part II

| Wind Farm Zone | Abbreviation | Number of sites | Total capacity |
|---|---|---|---|
| <u>High Voltage Direct Current</u> | | | |
| **IJmuiden Ver (reference)** | IJV | 2 | 4 GW |
| **IJmuiden Ver (noord)** | IJVN | 1 | 2 GW |
| **Zone 1** | | 3 | 6 GW |

| | | | |
|---|---|---|---|
| **Zone 2*** | | **3** | **6 GW** |
| **Zone 3*** | | 1 | 2 GW |
| **Zone 4** | | 5 | 10 GW |
| **Zone 5** | | 2 | 4 GW |
| **Zone 5 clearway** | | 2 | 4 GW |
| **Zone 5 (mb)** | | 1 | 2 GW |
| **Zone 6** | | 5 | 10 GW |
| **Zone 7** | | 5 | 8 GW |
| **Zone 8** | | 1 | 2 GW |
| **High Voltage Alternating Current** | | | |
| **Hollandse Kust (west)** | HKW | 3 | 2.1 GW |
| **Hollandse Kust (noordwest)** | HKNW | 2 | 1.4 GW |
| **Hollandse Kust (zuidwest)** | HKZW | 2 | 1.4 GW |
| **TOTAL** | | **38** | **64.9 GW** |

*Size, location and orientation of this zone is not adapted after Part I analysis.

## 1.2 Study objective

The objective of this study is to assess the Levelized Cost of Energy (LCoE) of offshore wind farms and grid connection systems in the new search areas, IJVN, HKNW and HKZW in relation to IJmuiden Ver in order to support the selection of new search areas and unused parts of existing wind farm zones for future exploration of offshore wind energy. This exercise specifically focuses on the relative comparison of wind farm zones and wind farm sites and does not intend to provide an absolute LCoE analysis. Absolute LCoE analyses would require a more in-depth study with consideration of long-term offshore wind innovations and site-specific optimizations.

The sub-objectives of this LCoE study are as follows:

1. Determine the relative LCoE of the wind farm zones and wind farm sites at the new search areas, IJVN, HKNW and HKZW, both for the offshore wind farm (OWF) and the grid connection system (GCS), compared to the reference Wind Farm Zone IJmuiden Ver.
2. Determine which cost and yield parameters have the largest influence on the LCoE differences.
3. Investigate the sensitivity of the results with a wind farm site density of 6 MW/km$^2$ instead of the default 10 MW/km$^2$ (Part I only).
4. Investigate the sensitivity of the GCS LCoE results with different landing areas for the export cable instead of the default landing areas closest to the offshore substation (Part II only).

## 1.3 Structure of report

This report contains two consecutive studies on the Levelized Cost of Energy of various wind farm zones. The report is divided into general chapters which apply to both studies and study-specific chapters. Chapter 2 describes the approach and the project team. The general starting points and assumptions are described in Chapter 3.

The report follows with a Part I of the study which contains the chapters specific to the LCoE study results of the initial layouts of the new wind energy search areas. Chapter 4 shortly describes the content of Part I in the introduction, followed by the sites and layouts in Chapter 5. In Chapter 6 the yield results are presented. Finally, the OWF LCoE associated with each wind farm zone and site is described Chapter 7, together with the power density sensitivity results.

Part II of the study contains the chapters specific to the LCoE study results of the updated search areas, IJVN, HKNW and HKZW. Chapter 8 shortly describes the content of Part II in the introduction, followed by in Chapter 9 the sites and layouts. The yield results are presented in Chapter 10. Finally, the overall, OWF and GCS LCoE comparison results associated with each wind farm zone are described in Chapter 11.

The report is finalized with a discussion in Chapter 12 and conclusions in Chapter 13 which reflect on both studies.

The report is written in such a way that Part II can be read and understood without the reader having to have read Part I.

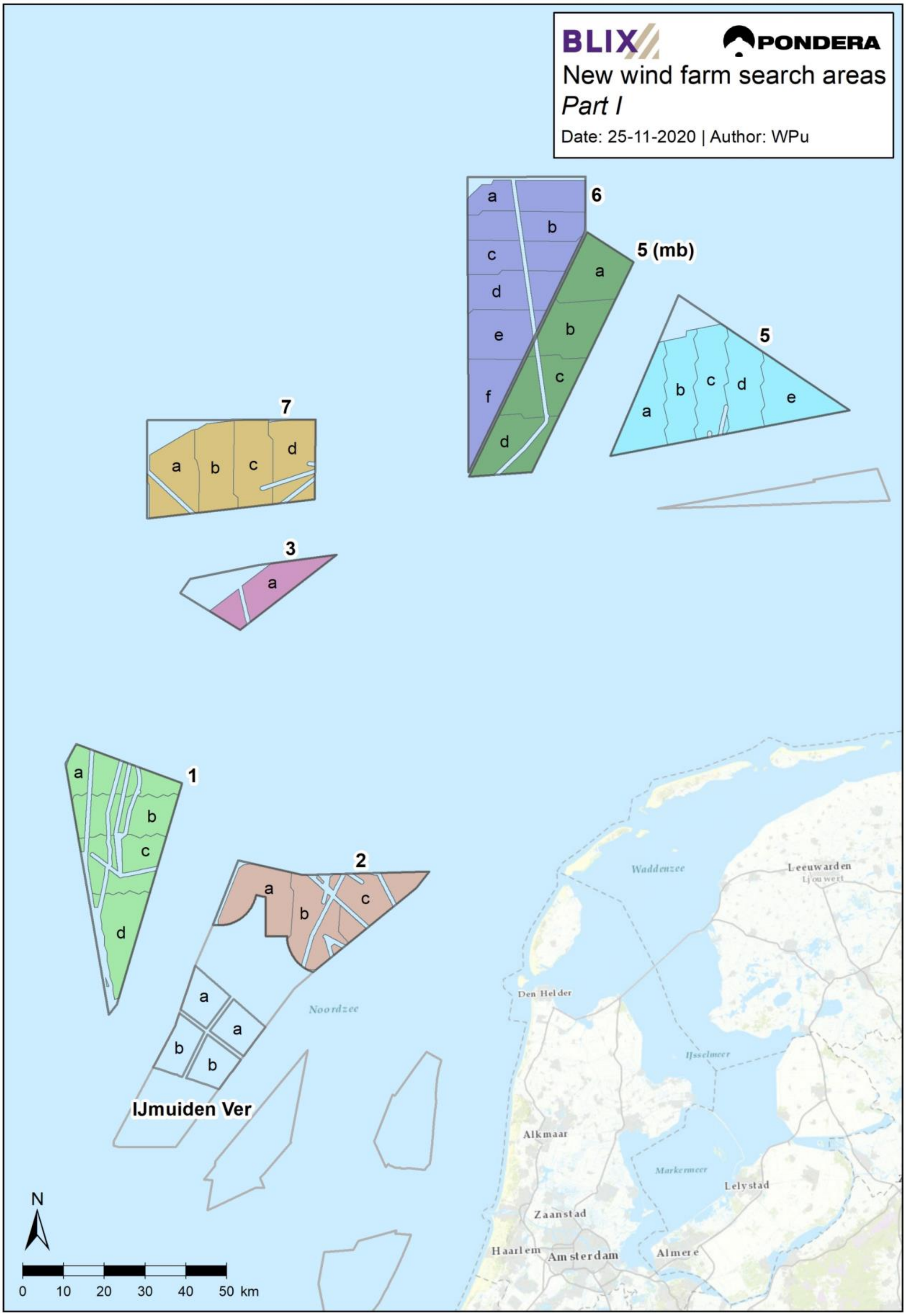

**Figure 1: Overview of the wind farm search areas studied in Part I**

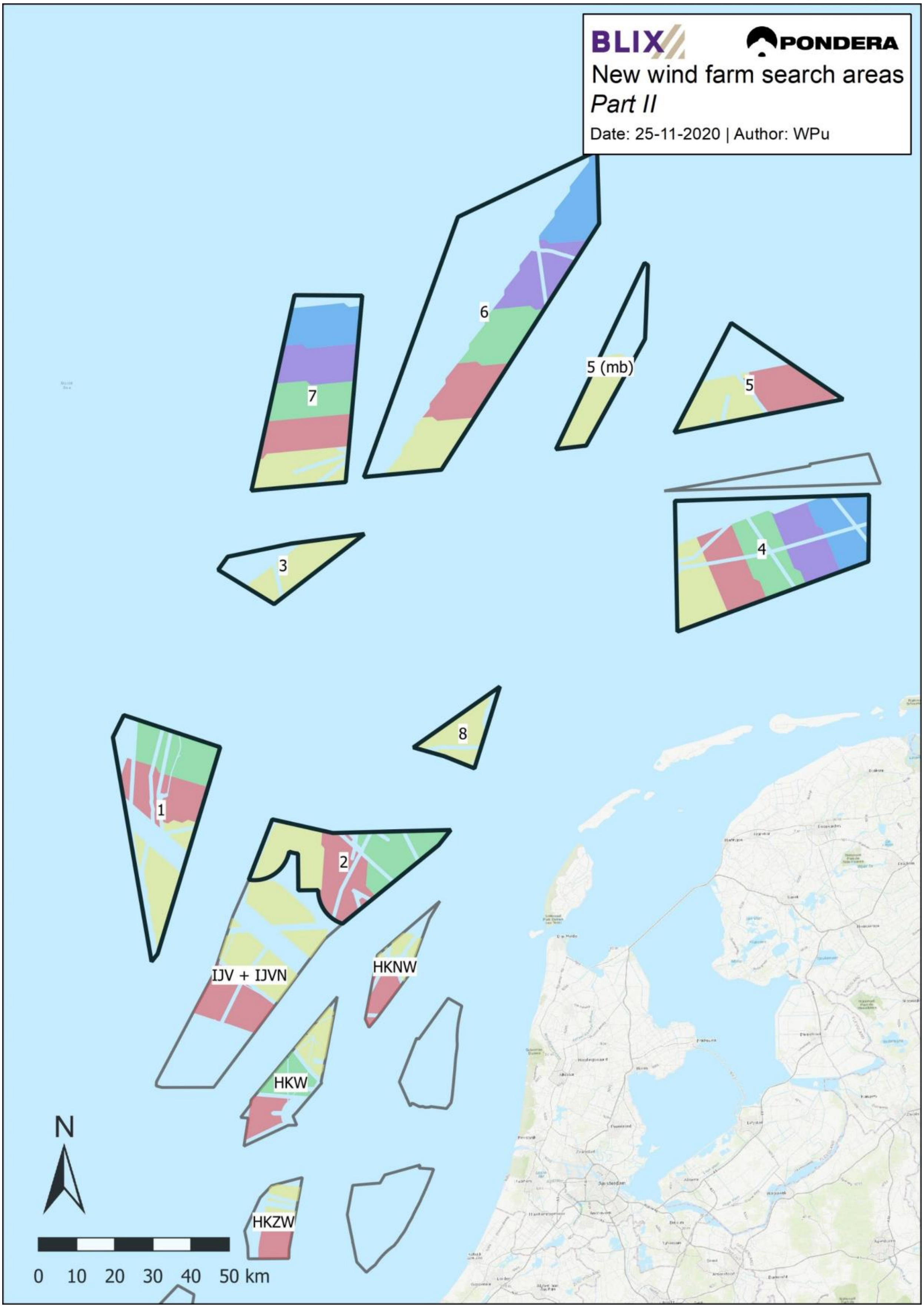

Figure 2: Overview of the wind farm search areas, IJVN, HKNW and HKZW studied in Part II

# 2 APPROACH

## 2.1 Team & partners

The objective of the project was to perform a LCoE study for wind farm zones and sites in the new search areas, Hollandse Kust (noordwest), Hollandse Kust (zuidwest) and IJmuiden Ver (noord) compared to IJmuiden Ver and Hollandse Kust (west), with a similar approach as was conducted in the LCoE study in 2018 [1] and 2020 [2] by BLIX and partners for Hollandse Kust (west), Ten noorden van de Waddeneilanden and IJmuiden Ver.

BLIX Consultancy worked together with Pondera and Energy Solutions to achieve this goal, with the support provided by TenneT TSO and by KCI the engineers (for the 2018 study [1]). The roles of all parties are as 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**: wind farm design expertise
5. **TenneT TSO**: Grid Connection System input validation

Furthermore, a reviewer from BLIX and a reviewer from Pondera, who were involved in the LCoE study of 2018 [1], were appointed to assess the assumptions and the results of the study.

## 2.2 Study approach

The study is based on the following approach:

1. Define the wind farm sites and zones

   The Working Group asked the BLIX project team to define sites for the new wind energy search areas, IJVN, HKNW and HKZW according to pre-agreed starting points and by utilizing the available space of the areas to meet the required capacity per wind farm zone as described in Table 1 and Table 2. The wind farm zones are defined as the areas covered by the sites per search area. The Working group provided the boundaries of the sites (and zones) for the reference wind farm zones IJmuiden Ver and Hollandse Kust (west).

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

   Subsequently, the project team determined for each wind farm site indicative wind farm and cable layouts based on a schematised approach with a regular turbine spacing. The energy yield was simulated 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. Customize the BLIX LCoE model

   Next step was to customize for this project the BLIX LCoE model that was also used for the LCoE study of 2018 [1] and 2020 [2]. The model includes specifically for this project a relation between the distance to port of the wind farm and the OWF Capex and Opex. Other important additions to the model are the cost assumptions for the High Voltage Direct Current ("HVDC") and High Voltage Alternating Current ("HVAC") grid connection systems, first determined based on relevant literature, supplemented with expert opinions and calculations from Energy Solutions and finally validated by TenneT.

4. Calculate the LCoE of each wind farm site

   The BLIX LCoE model was used to calculate and compare the LCoE for the OWF and GCS for each wind farm site within the wind farm zones. The OWF LCoE, GCS LCoE, overall LCoE (sum of OWF LCoE and GCS LCoE) and the impact of the parameters on the LCoE differences was analysed per site and conclusions are drawn regarding the average LCoE of the different wind farm zones. This provides a basis for decisions on the size and subdivision of the new search areas.

5. Perform sensitivity analysis on the LCoE results

   Part I of the study performed a sensitivity analysis on the impact of the power density (in MW / km2) on the OWF LCoE results and Part II examined the sensitivity of the GCS LCoE results for the selected export cable landing area.

### 2.2.1 Power density sensitivity analysis

All scenarios assume a grid of 5.5 by 5.5 times the rotor diameter (1,210 m by 1,210 m) based on a wind farm density of 10 MW/km$^2$. Allowing more space between wind turbines leads a reduction in wind farm density and wake losses.

This sensitivity analysis investigates the effect of a reduced wind farm density on the LCoE at Zone 5 (mb) and Zone 6. These two zones are selected because they are considered representative for all wind farm zones. Both sites have comparable LCoE results, the only difference between the sites is the effect of wake losses. This is especially useful as wake losses are most affected by differences in power density. Zone 5 is one of the zones with the highest wake losses and Zone 6 has the lowest wake losses after Zone 3, which consists of only 1 site and is therefore less representative for the other zones.

The distance between wind turbines is increased to 7.2 rotor diameters, or a grid of 1,580 m by 1,580 m, which leads to a wind farm density of 6 MW/km$^2$.

### 2.2.2 Landing area sensitivity analysis

Part II includes the results of a sensitivity analysis to investigate the impact of the various export cable landing sites on the GCS LCoE of the wind farm zones. Hereto, TenneT provided the selection of landing sites considered per wind farm site. In alignment with the Working Group the base assumption of the landing site for each wind farm site was chosen based on the shortest distance to the onshore substation. In practise, the actual landing site of a wind farm site is determined by TenneT based on an effect analysis which takes into account varying factors such as the remaining connection capacity of the onshore substation or the transport capacity of the onshore grid.

The starting point for the sensitivity analysis is that the export cables of Zone 1, 2, 3, 7, 8, IJVN A and IJVN B are connected to the West coast of the Netherlands and Zone 4, 5, 5 clearway and 5 (mb) are connected to the landing site Eemshaven.

The landing sites are listed below and depicted in Figure 3:

- Noordzeekanaalgebied (NZK)
- Rijnmondgebied (RNM)
- Zeeland/West-Brabant (Z/W)
- Eemshaven-Delfzijl (E-D)

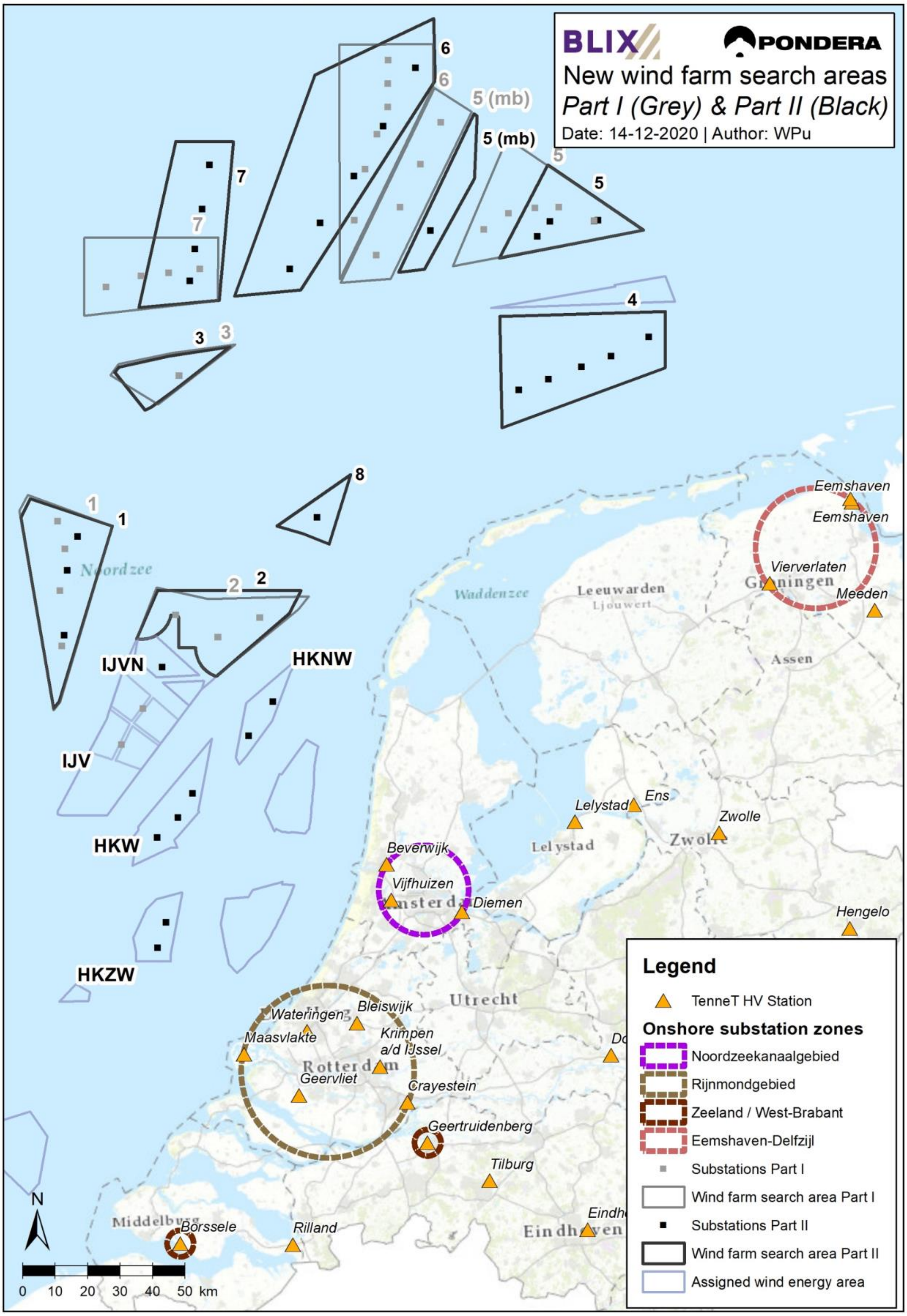

Figure 3: Overview of the wind farm zones and export cable landing sites

# 3 GENERAL STARTING POINTS AND ASSUMPTIONS

## 3.1 Introduction

This chapter describes the main general starting points and assumptions for the study applicable to both Part I and Part II. First the starting points are described, followed by an assessment of the main parameters that vary between the wind farm zones/sites and their influence on the LCoE. Then the local site conditions (wind climate, hydrodynamic and soil parameters) and the technical assumptions are elaborated upon, followed by the assumptions for the wind farm layouts and yield calculations.

## 3.2 General starting points

The following general starting points were agreed upon with the Working group:

1. The aim of the LCoE modelling is to compare relative differences between the different wind farm zones and sites, not to 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 the wind farm zones and sites. 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. At the request of the Working group, the same OWF model assumptions were used as used for the 2018 LCoE study [1] and 2020 HKW LCoE study [2] so that the results of all studies can be directly compared with each other and to meet the tight schedule of the project. The OWF model inputs are based on the latest projects BLIX participated in at that time, such as the Dutch offshore wind tenders (Borssele I&II, III&IV and Hollandse Kust (zuid) I&II), German offshore tenders and UK offshore tenders, plus experts' forecasts[1].
4. The cost modelling for the GCSs of Part II consists of an offshore substation, export cable and onshore substation. The export cable length of the grid connection is based on the distance to one of four potential landing areas and does not take into account potential limitations of the onshore grid (for detailed explanation please see paragraph 3.3.1). The analysis in Part I does not include the GCS.
5. The wind farm size is based on the standardised grid connection systems currently used by TenneT, i.e. 2 GW for high voltage direct current ("HVDC") connections and 700 MW for high voltage alternating current ("HVAC") connections excluding overplanting).

## 3.3 Main parameters of wind farm zones and wind farm sites

The study analyses results on two levels: on the wind farm zone level and on the wind farm site level. The wind farm zone level is used for comparing zones, and the wind farm site level is used for comparing sites within a zone.

---

[1] 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.

As a first step of the model schematisation, an assessment was performed of the parameters that differ between wind farm zones and wind farm sites and their expected qualitative impact on the LCoE. These are described below in Table 3 for the OWF parameters and Table 4 for the GCS parameters.

**Table 3: Main parameters for the wind farms that vary between the wind farm zones and sites**

| Parameter | Wind farm zone level | | Wind farm site level | |
|---|---|---|---|---|
| **Wake losses** | High | Differs significantly between wind zones; influences the net yield. | High | Differs significantly between wind sites; influences the net yield. |
| **Water depth of wind farm zone** | High | Differs between zones; affects the foundation cost, particularly in case of large water depth variations. | Low | Limited differences between sites; affects the foundation cost, particularly in case of large water depth variations. |
| **Infield cable length** | Low | Limited differences between zones; influences the cable installation cost. | Medium | Differs between sites; influences the cable installation cost. |
| **Number of cable crossings** | Low | Differs between zones; slightly influences the cable installation cost. | Low | Differs between sites; slightly influences the cable installation cost. |
| **IA cable losses** | Low | Differs slightly between zones; string length and number of turbines on string influence the cable (transmission) losses. | Low | Differs slightly between sites; string length and number of turbines on string influence the cable (transmission) losses. |
| **Wave conditions** | Low | Limited differences between zones; affects the foundation cost. Assumed negligible. | Low | Limited differences between sites; affects the foundation cost. Assumed negligible. |
| **Mean wind speed** | Medium | Differs between zones, with slightly higher wind speeds at northern WFZs; influences gross yield. | Low | Limited wind speed gradient across zones, leading to minor differences per site; influences gross yield. |
| **Distance to port (marshalling harbours)** | High | Differs between zones. Influences the Capex (installation) and Opex of the WTG and foundation. | Medium | Differs between sites. Influences the Capex (installation) and Opex of the WTG and foundation. |

**Table 4: Main parameters for the GCS that vary between the wind farm zones and sites**

| Parameter | Wind farm zone level | | Wind farm site level | |
|---|---|---|---|---|
| **Water depth of wind farm zone** | Medium | Differs between zones; affects the OHVS foundation costs. | Low | Limited differences between sites; affects the OHVS foundation costs. |
| **Distance to onshore substation** | High | Differs significantly between zones; affects the export cable length which affects export cable Capex, export cable Opex, export cable losses and availability. | Medium | Can differ between sites depending on the shape and location of the wind farm zone; affects the export cable Capex, export cable Opex, export cable losses and availability. |
| **Distance to port** | Limited | Limited impact on the OHVS Opex. Planned maintenance is performed in longer timeslots reducing the effect of distance. Unplanned | Limited | Limited impact on the OHVS Opex. Planned maintenance is performed in longer timeslots reducing the effect of distance. Unplanned |

| | | | | |
|---|---|---|---|---|
| | | maintenance is done by helicopter (HVDC only). Neglected in this study. | | maintenance is done by helicopter (HVDC only). Neglected in this study. |
| **Water depth of cable route** | Limited | Does not significantly affect the installation costs. Opex generally consists of surveys which are also unaffected by water depth at the assumed water depths within this study. Neglected in this study. | Limited | Does not significantly affect the installation costs. Opex generally consists of surveys which are also unaffected by water depth. Neglected in this study. |
| **Wind farm size** | High | Differs significantly between HVDC and HVAC zones. 700 MW HVAC wind farms have a relatively high Capex compared to the 2 GW HVDC wind farms due to economies of scale, indicated by wind farm size costs. | High | Differs significantly between HVDC and HVAC sites. 700 MW HVAC wind farms have a relatively high Capex compared to the 2 GW HVDC wind farms due to economies of scale, indicated by wind farm size costs. |
| **Transmission type** | High | Significantly affects the Capex of the whole GCS, especially of the OHVS. In the study these additional costs for HVDC systems are indicated as transmission type costs. | High | Significantly affects the Capex of the whole GCS, especially of the OHVS. In the study these additional costs for HVDC systems are indicated as transmission type costs. |

### 3.3.1 Distance to port

The distance of the wind farm sites to the closest marshalling harbours was newly added to the list of main varying parameters that influence the OWF LCoE (compared the approach followed in the 2018 [1] and 2020 LCoE study). The following assumptions have been made in relation to the ports for the determination of the factors in the LCoE study:

- All distances have been based on the shortest connection between the site and the closest marshalling harbour. A small correction has been applied for additional traveling distance based due to already present obstacles and infrastructure, such as shipping routes, pipelines and electrical cables.
- Gradual scales were used for the distance to the ports, with thresholds based on the preferred type of vessel (Crew Transfer Vessels or Service Operating Vessel) and the travel time.
- All hardware and equipment to be installed is assumed to be located at the marshalling harbour. No additional costs are taken into account other than in the supply costs.

## 3.4 Site conditions

The site conditions can be divided into the following categories: wind climate, water depth, wave conditions, soil conditions and current obstructions and stakeholders.

### 3.4.1 Wind climate

The wind climate is assessed as reference for the yield calculations and is determined using long-term mesoscale data of the KNMI North Sea Wind (KNW) Atlas. The KNW Atlas is based on the ERA-Interim reanalysis dataset and it covers the period 1979-2019 (up to August) with hourly intervals. The KNW Atlas has been validated against publicly available wind measurements from three tall offshore wind masts: OWEZ, FINO1 and MMIJ (Meteorological Mast IJmuiden). In this study a dataset of 15 full years in the period 01-01-2004 to 31-12-2018 is analysed.

KNMI recently launched the Dutch Offshore Wind Atlas (DOWA) as a successor to the KNW Atlas, containing 10 years of wind climatology (2008 - 2017). As 15 years of data is commonly accepted as a minimum for long-term reference for wind resource assessments, the DOWA data is not considered for this study.

At the edges of every WFZ, a selection of 'data nodes' of the KNW dataset are used to find the horizontal gradient of the wind climate. The annual mean wind speed at each wind turbine location is determined using the nearest KNW node. Appendix A shows Weibull distributions and wind roses for every wind farm zone.

Table 5, Table 6 and Table 7 summarize the most important parameters and values found in the wind resource assessment of the wind farm zones. Parameters given in the tables below are from wind climate nodes closest to shore at 140 m height. A 0.4 m/s wind speed gradient at 140 m height (Zone 5, 5 clearway, 5 (mb), 6 and 7) is observed between IJmuiden Ver and northern wind farm zone locations (Zone 5 and Zone 7). Moreover, the prevailing wind direction in the southernmost wind farm zones (IJV, IJVN, Zone 1 and Zone 2) is south-south-west; the western and west-south-western wind directions become more dominant further towards the north and northeast of the North Sea. Figure 4 graphically summarizes the wind climate at the IJmuiden Ver wind farm zone.

**Table 5: Wind parameters for all wind farm zones of Part I**

| WFZ results | IJV | Zone 1 | Zone 2* | Zone 3* | Zone 5 | Zone 5 (mb) | Zone 6 | Zone 7 |
|---|---|---|---|---|---|---|---|---|
| **Long-term average annual wind speed at wind farm area at 100 m height [m/s]** | 9.8 | 10.0 | 9.9 | 10.1 | 10.2 | 10.2 | 10.2 | 10.1 |
| **Long-term average annual wind speed at wind farm area at 140 m height [m/s]** | 10.2 | 10.4 | 10.3 | 10.5 | 10.6 | 10.6 | 10.7 | 10.6 |
| **Wind speed gradient across wind farm zone [m/s]** | 0.1 | 0.1 | 0.1 | <0.05 | 0.2 | 0.1 | 0.1 | <0.05 |
| **Prevailing wind direction** | SSW | SSW | SSW | SSW / WSW | WSW | WSW | WSW | WSW / SSW |
| **Weibull scale parameter (A)** | 11.46 | 11.78 | 11.66 | 11.88 | 11.96 | 11.98 | 11.98 | 11.91 |
| **Weibull shape parameter (k)** | 2.182 | 2.225 | 2.209 | 2.240 | 2.268 | 2.256 | 2.256 | 2.244 |

*Size, location and orientation of this zone is not adapted after Part I analysis.

Table 6: Wind parameters for all HVDC wind farm zones of Part II

| WFZ results | IJV | IJVN | Zone 1 | Zone 2* | Zone 3* | Zone 4 | Zone 5 | Zone 5 Clearway | Zone 5 (mb) | Zone 6 | Zone 7 | Zone 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Long-term average annual wind speed at 100 m [m/s]** | 9.8 | 9.9 | 10 | 9.9 | 10.1 | 10 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 9.9 |
| **Long-term average annual wind speed at 140 m [m/s]** | 10.2 | 10.3 | 10.4 | 10.3 | 10.5 | 10.4 | 10.6 | 10.6 | 10.6 | 10.6 | 10.6 | 10.3 |
| **Wind speed gradient [m/s]** | 0.1 | 0.1 | 0.1 | 0.1 | <0.05 | 0.1 | <0.05 | <0.05 | <0.05 | 0.2 | 0.1 | <0.05 |
| **Prevailing wind direction** | SSW | SSW | SSW | SSW | SSW / WSW | WSW | WSW | WSW | SSW / WSW | SSW | SSW | SSW |
| **Weibull scale parameter (A)** | 11.46 | 11.63 | 11.78 | 11.66 | 11.88 | 11.71 | 11.93 | 11.93 | 12 | 11.89 | 11.88 | 11.61 |
| **Weibull shape parameter (k)** | 2.182 | 2.189 | 2.225 | 2.209 | 2.24 | 2.264 | 2.271 | 2.271 | 2.279 | 2.244 | 2.244 | 2.213 |

*Size, location and orientation of this zone is not adapted after Part I analysis.

Table 7: Wind parameters for all HVAC wind farm zones of Part II

| WFZ results | HKW | HKNW | HKZW |
|---|---|---|---|
| **Long-term average annual wind speed at 100 m [m/s]** | 9.9 | 9.9 | 9.8 |
| **Long-term average annual wind speed at 140 m [m/s]** | 10.3 | 10.2 | 10.2 |
| **Wind speed gradient [m/s]** | <0.05 | 0.1 | 0.2 |
| **Prevailing wind direction** | SSW | SSW | SSW |
| **Weibull scale parameter (A)** | 11.59 | 11.56 | 11.56 |
| **Weibull shape parameter (k)** | 2.189 | 2.189 | 2.189 |

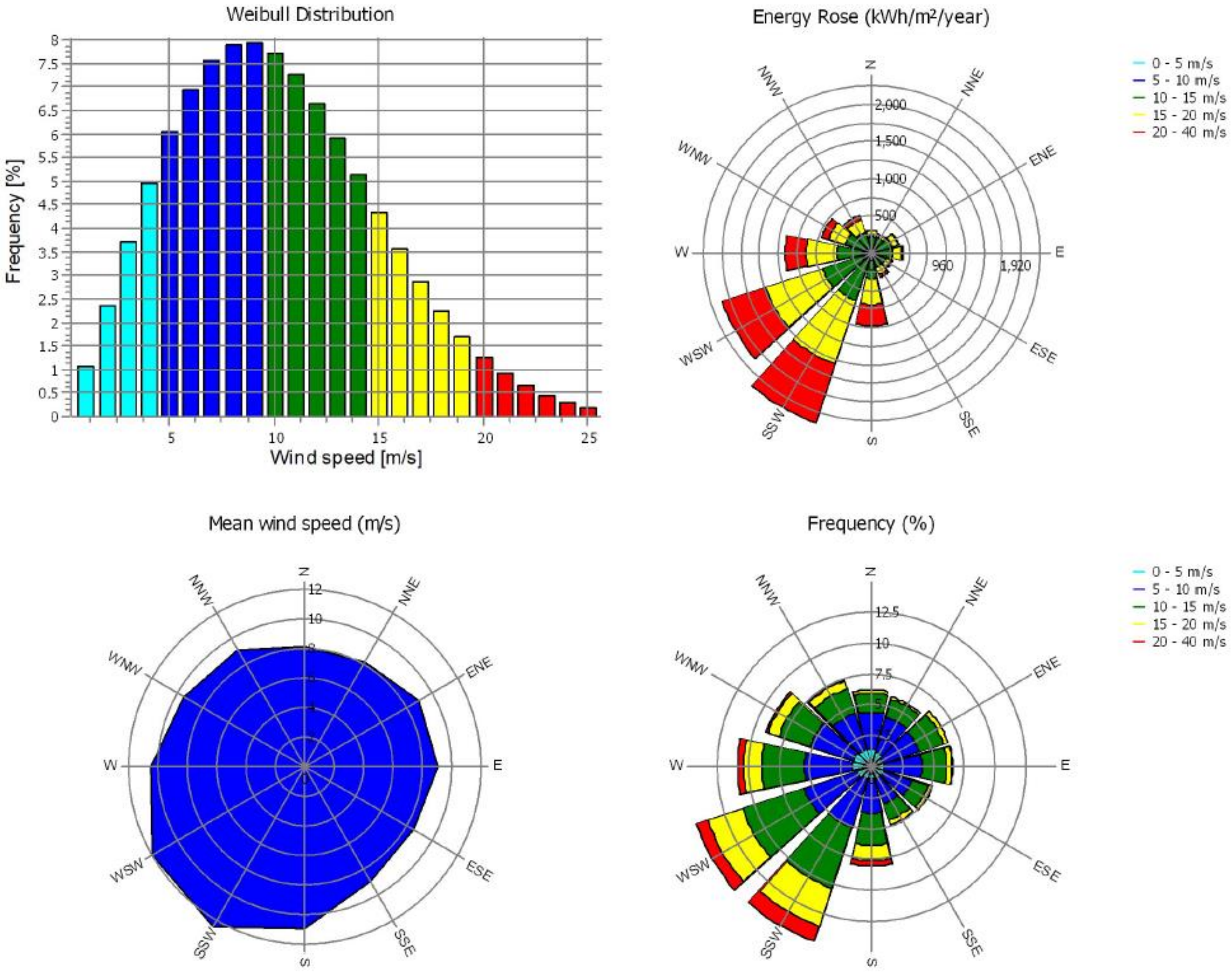

**Figure 4: Graphical summary of wind climate at IJmuiden Ver at 140 m height**

### 3.4.2 Water depth

The water depth at the wind farm zones was 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 water depths at all wind farm zones in the new search areas. The wind farm zones IJV, IJVN, Zone 1 and 2 are situated in more shallow areas (20 – 30 m), with the southwestern part of IJV located at a deeper area of the North Sea (up to 40 m). The other wind farm zones are situated in the deeper areas of the North Sea (30 – 50 m).

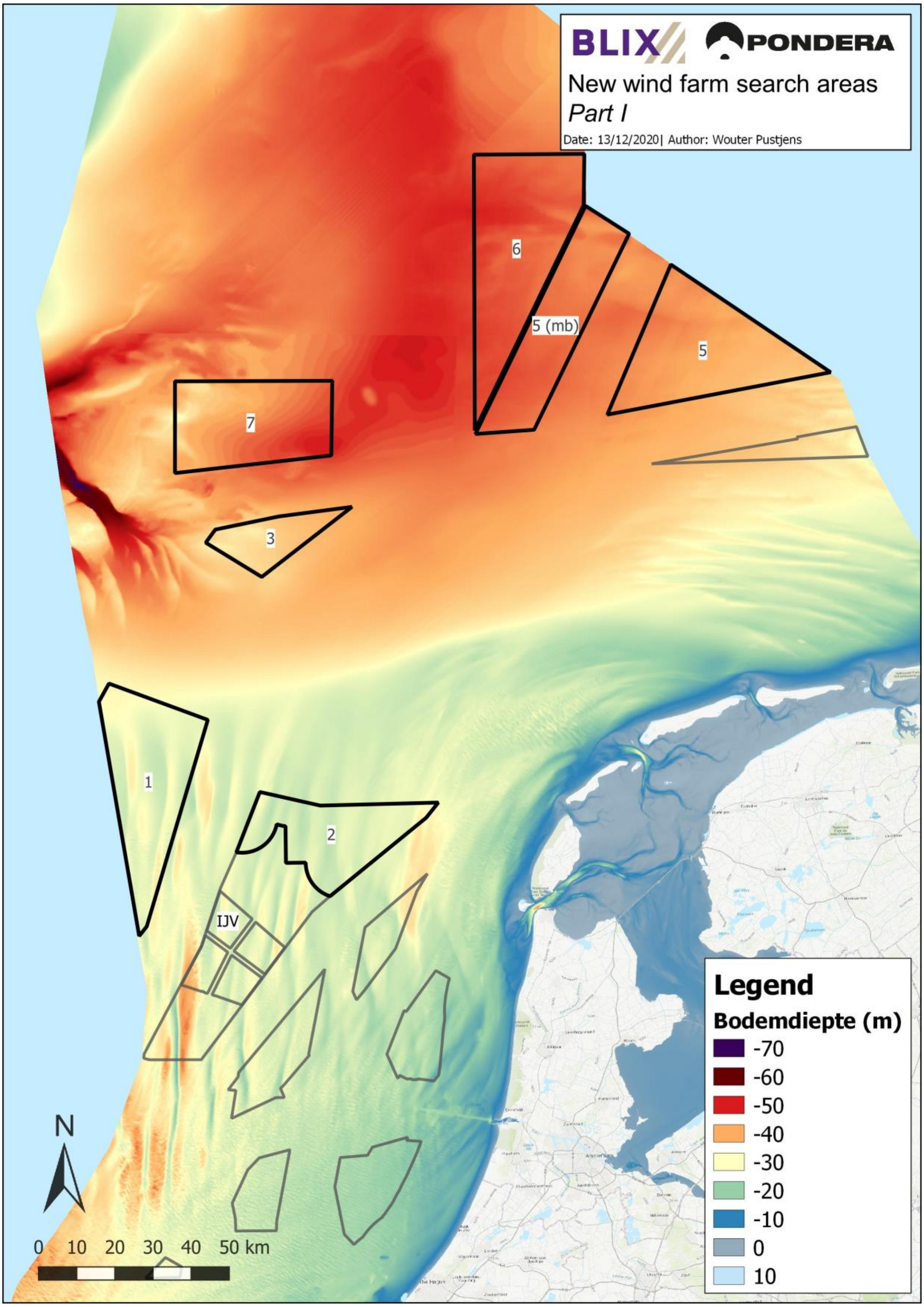

Figure 5: Water depth across all wind farm zones of Part I

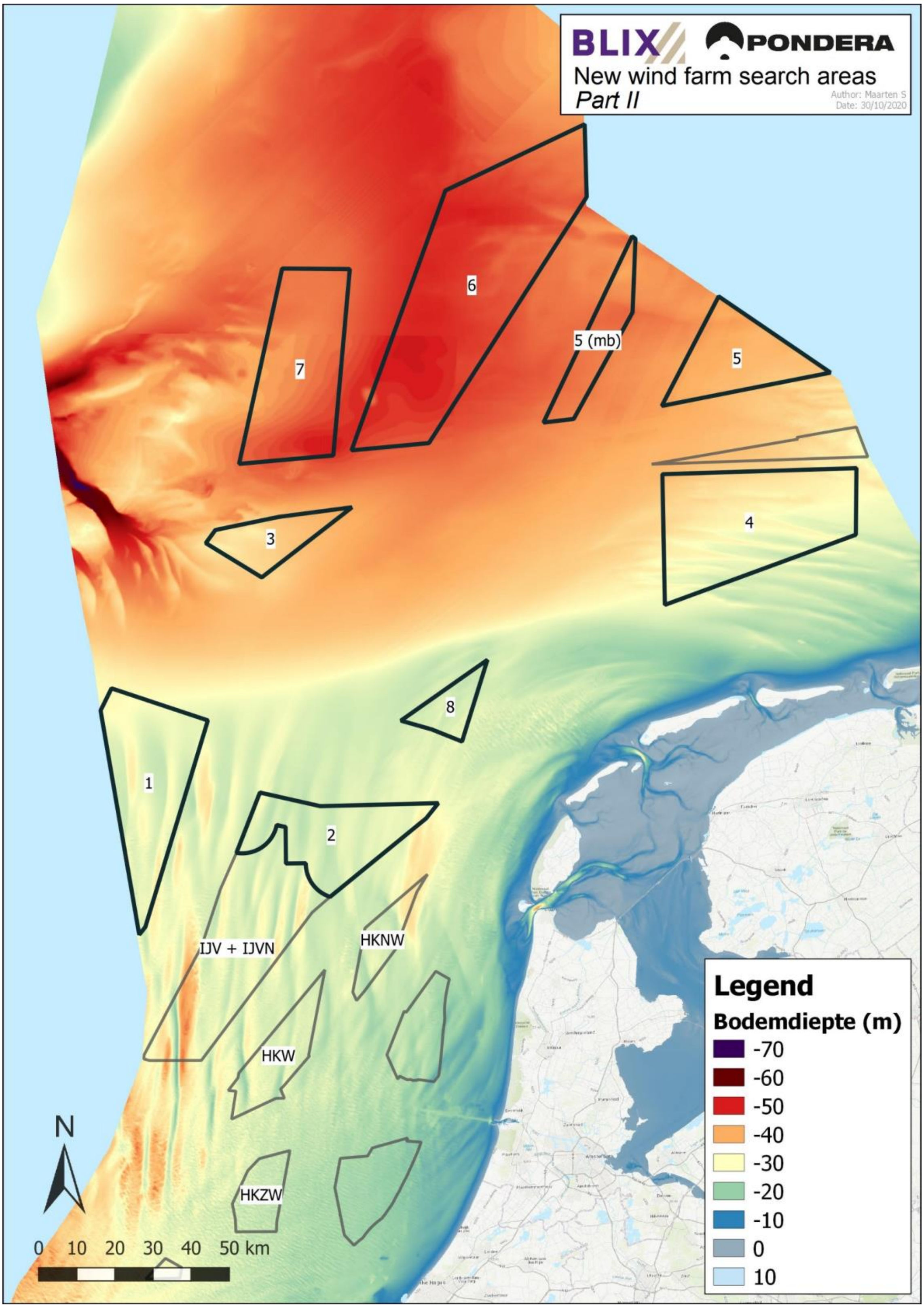

Figure 6: Water depth across all wind farm zones of Part II

### 3.4.3 Wave conditions

The wave conditions affect the loads on the foundation of a wind turbine. No site specific metocean studies have been performed, but online hindcast data is consulted.

The mean significant wave height is shown in Figure 7. The mean significant mean wave heights at the northernmost wind farm zones are ca. 1 m higher than IJV, IJVN, Zone 1 and Zone 2 (return period 10 years) as result of the larger fetch distance.

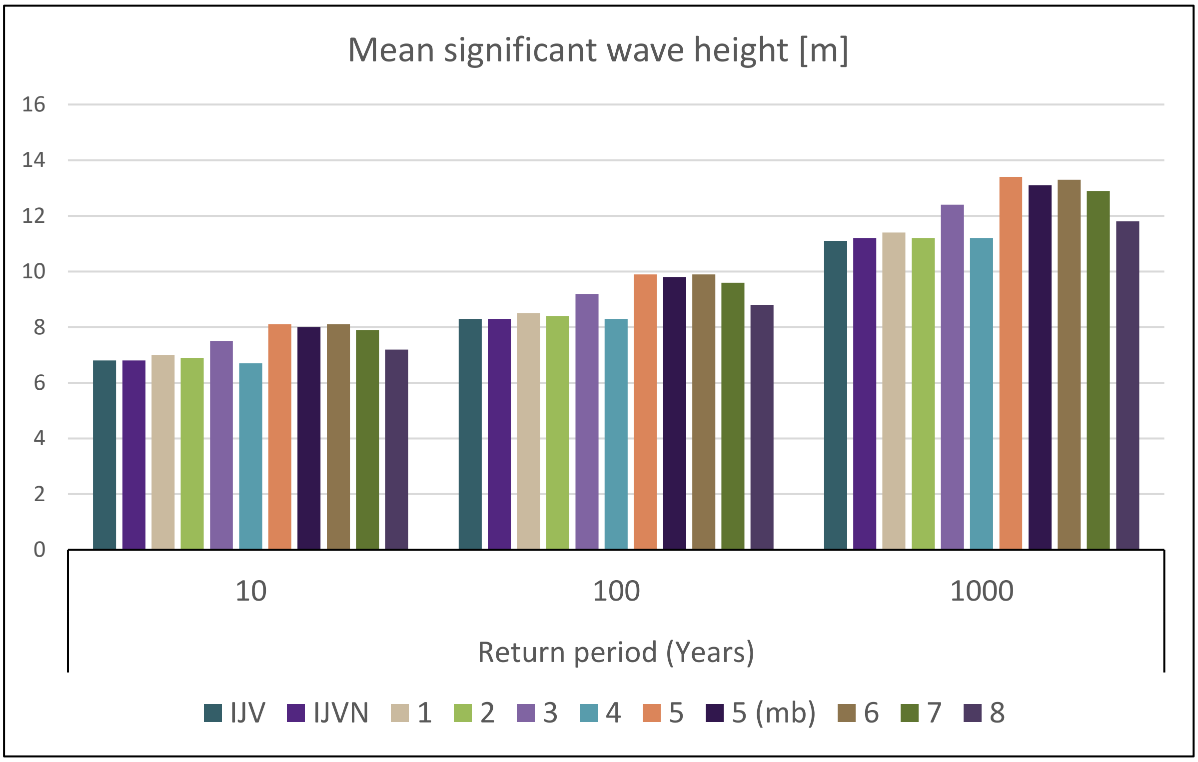

Figure 7: Mean significant wave height at all studied wind farm zones

The wave heights and currents are assumed to be uniform at each site. In reality they could differ in the order of 0.1 - 0.2 m and 0.1 - 0.2 s across the site, but these differences are assumed to lead to negligible differences between the LCoE of the wind farm zones.

### 3.4.4 Soil conditions

The soil conditions of the studied wind farm zones were considered to determine the required foundation depth (below seabed). For IJmuiden Ver the nature of seabed is assumed to be sandy surface with medium to dense sand to depth, based on the 2018 LCoE study [1] of the Roadmap 2030 wind farm zones. The corresponding soil parameters are listed in the table below.

Table 8: Assumed soil parameters

| Parameter | IJmuiden Ver |
|---|---|
| **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. Detailed soil information of the new search areas was not available at the time of this study and therefore the same nature of seabed is assumed as for IJmuiden Ver.

In reality the soil conditions may differ across the site, but in the absence of detailed soil information at the time of this study the soil parameters were assumed to be uniform.

### 3.4.5 Current obstructions and stakeholders

Figure 8 and Figure 9 show the current obstructions and stakeholders in and near the wind farm zones. Nature 2000 areas were not treated as exclusion zones in wind farm zones but are regarded as possible stakeholders. All wind farm zones are outside the Nature 2000 areas except for Zone 5 in Part I, which overlaps with the north-western part of Nature 2000 area 'Friese Front'.

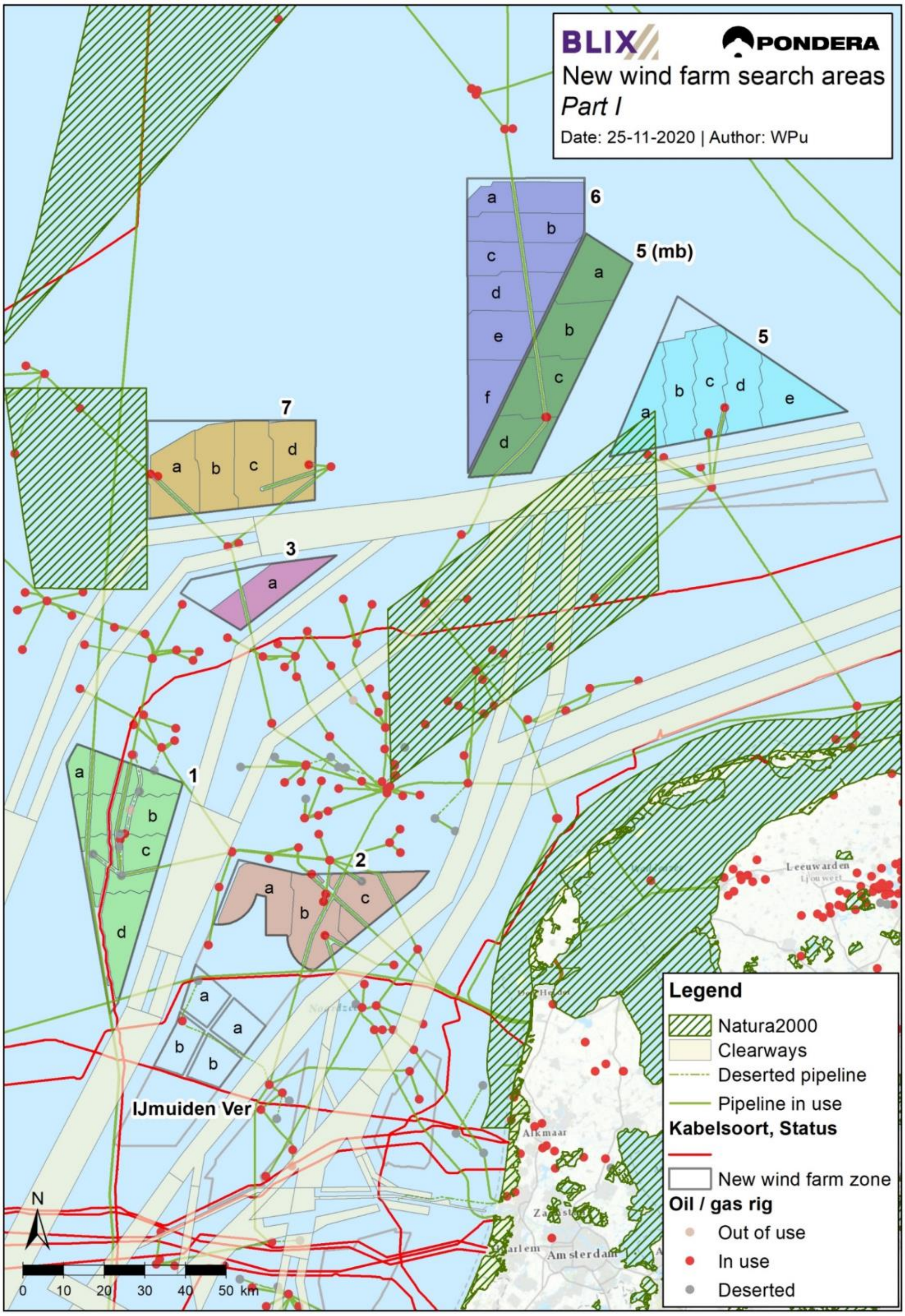

Figure 8: Obstructions wind farm zones Part I[2]

---

[2] Two additional fiberoptics cables crossing the zones 5, 5 (mb) and 6 are incorrectly not been included in the spatial obstruction analysis and figure of Part I. The impact of relocation of the concerned turbines on the LCoE results of the wind farm zones is neglectable (<0.1%).

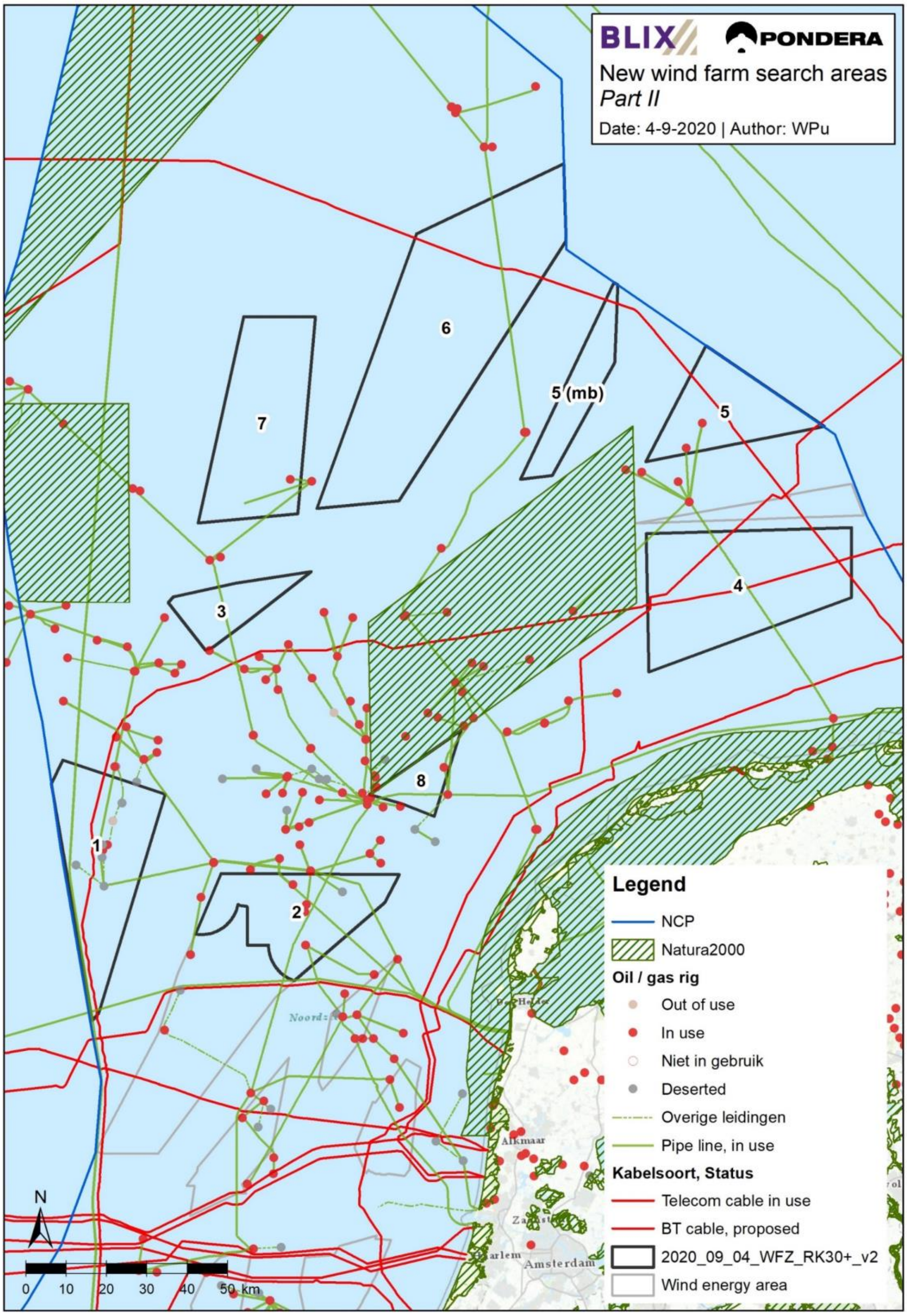

**Figure 9: Obstructions wind farm zones Part II**

## 3.5 Wind farm layouts and yield calculations

### 3.5.1 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 wind turbine level, instead of crude assumptions based on a reduction in available area for wind turbines. This level of detail is required to obtain results that distinguish detailed differences between the wind farm sites and zones and allows us to draw substantiated conclusions.

### 3.5.2 Key assumptions

The key assumption for every wind farm layout is a power density of 10 MW/km$^2$. Assuming a symmetrical grid for the placement of the turbines, this is translated to a fixed rectangular turbine grid of 5.5 rotor diameters by 5.5 rotor diameters. In Part I, the rectangular grids are oriented along the longest boundary of each wind farm zone. In Part II, the grids are oriented along the boundary of each wind farm zone closest to the shore, in line with the methodology used for the filling of the search areas. (The impact of this change in grid orientation methodology is considered limited; a sensitivity analysis performed on IJmuiden Ver (noord) with the grid oriented in southwest and south direction respectively showed a difference in average wake losses of the wind farm zone of ~0.1%.)

The installed capacity for each HVDC wind farm site is 2,010 MW (134 turbines with a capacity of 15 MW) and for each HVAC wind farm site 750 MW (50 turbines with a capacity of 15 MW). In case of overcapacity, wind turbines located furthest from the coast have been removed from the wind farm zone to keep the OWF Opex and export cable costs, losses and non-availability as low as possible. This ensures each wind farm zone to have at least one wind farm site with the desired amount of installed capacity, located as close to the coast as possible. Figure 1 and Figure 2 show all wind farm zones and their subdivision in sites.

The shape of the wind farm zones is mainly determined by the IMO shipping lanes running through the North Sea. The layouts comply with applicable rules and regulations; i.a. wind turbine positions comply with maintenance distances from existing pipelines and telecommunication cables (500 m), nor do turbine blades exceed the boundaries of the WFZ. Helicopter routes in the North Sea are not considered as obstructions in this assignment, as possibilities exist to adapt these routes. Nature 2000 areas were not treated as exclusion zones in wind farm zones, but are regarded as possible stakeholders. The 5.5 rotor diameter difference assures technical feasibility (i.e. staying below turbulence limits).

The wind farm layouts and yield calculations are based on the technical assumptions described in Table 9.

**Table 9: Technical assumptions for wind farm layouts and yield**

| Parameter | Assumption | Reference |
|---|---|---|
| **Wind turbine** | | |
| Wind Turbine capacity | 15 MW | Power curve generalised and extrapolated based on current state of technology. |
| Rotor diameter | 220 m | Based on currently available information. |
| Hub height | 140 m | Based on 30 m clearance. |
| Power curve | Confidential | Upscaled version based on available prototype. |
| **Wind farm layout** | | |
| Power density | 10 MW / km2 (translated to a fixed grid size) | In consultation with the Working group |

| | | |
|---|---|---|
| Turbine grid size | 5.5 by 5.5 rotor diameters | Fixed rectangular grid, in consultation with the Working group |
| Turbine grid orientation | Part I: Along the longest boundary of each wind farm zone<br>Part II: Along the boundary of each wind farm zone closest to shore | In consultation with the Working group |
| Filling of search area with sites | From the boundary of the wind farm zone closest to shore | In consultation with the Working group |
| Distance to existing cables and pipelines | 500 m | In consultation with the Working group |
| Distance wind turbine from WFZ boundary | 110 m (blade length) | In consultation with the Working group |
| **Electrical layout** | | |
| Capacity per wind farm site | HVDC: 2 x 1,005 MW (2 transformers on 1 OHVS)<br>HVAC: 1 x 750 MW | Overplanting is assumed as reference in consultation with the Working group. |
| Infield cables | 66 kV, 6 WTG/string | Based on assessment of Ensol (assuming 800A switchgear in turbines). |
| Construction & maintenance ports | Rotterdam, Eemshaven, IJmuiden (maintenance only), Den Helder (maintenance only). | Based on currently available information. |
| Export cable routes | Not taken into account. | In consultation with the Working group |
| **Model parameters** | | |
| 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. |
| IA cable losses | Use of an increased losses formula when more wind turbines feed power over an inter-array cable. Formula is confidential. | Provided by Ensol. |

### 3.5.3 OWF yield assumptions

After determination of the wind farm layouts, the cabling layout is defined. The locations of the TenneT substations of the two IJmuiden Ver sites were provided by the client in close collaboration with TenneT. The locations of the substations of the wind farm zones were, after agreement with the client, positioned by the project team in the centre of the sites.

Each station contains two transformers with a combined capacity of 2,010 MW resp. 750 MW. The wind turbines are connected to the substation through array cabling. Each array cable connects six 15 MW wind turbines to the substation. The detailed wind farm and cabling layouts are shown in paragraph 5.2.

With turbine positions and cabling determined, the gross annual energy yield for each turbine has been calculated using WindPRO and WAsP. The calculations included the present, albeit relatively small, wind speed gradients across the wind farm zones. 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 via the relation *(1-loss1)*(1-loss2)*(1-…)*. The following loss factors are considered:

**Wake losses**

The dominant OWF 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 wind turbines on each other. In consultation with the client it was decided to consider each wind farm zone without its neighbouring wind farm zones in new search areas. The existing offshore wind farms Windpark Egmond aan Zee (OWEZ), Prinses Amalia wind farm, Luchterduinen windfarm, Gemini 1&2, Hollandse Kust (noord), Hollandse Kust (zuid) were included, in order to include their wake effects in the calculations. The actual built wind turbine types and hub heights were used for these wind farms. The wake effects of the already planned wind farms of IJmuiden Ver and Hollandse Kust (west) were also taken into account in the modelling, based on indicative wind farm layouts. The wind farm zone from neighbour countries (e.g. United Kingdom and Germany) were not taken into account.

**Inter-array cable losses**

Electrical losses in power cables occur due to heat build-up in the cables, increasing the cable resistance. The inter-array cable losses have been calculated for each wind farm zone specifically and are listed in Table 13.

**Wind turbine non-availability**

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

**Other losses**

Wind turbines suffer from several environment-related losses such as blade degradation losses due to contamination and deterioration, shutdown events due to lightning or hail or wind speed hysteresis (fluctuations of wind speeds around cut-off wind speed). In the model a total loss of 1.5% is taken into account for these losses.

### 3.5.4 GCS yield assumptions

The addition of grid connection systems to the scope of Part II results in several additional parameters affecting the yield calculations. The GCS yield parameters that have been added in Part II are listed below.

**Export cable losses**

The export cable losses differ between HVDC and HVAC systems. For DC export cables the losses are considered linear whereas for the AC export cables the losses are relatively higher for larger distances. In this study the cable losses are based on 100% power transmission not based on modelling the full wind climate. The impact of this simplification on the results is assumed to be small.

**GCS non-availability**

The GCS non-availability consists of the non-availability of the onshore and offshore substation (e.g. due to planned and unplanned maintenance) and the non-availability of the export cable. The latter differs per wind farm zone and site since there is a larger risk for failures with a longer export cable The substation non-availability is equal for wind farm zones with the same GCS. For HVDC systems the non-availability is higher than for HVAC systems due the higher complexity of the system and higher number of components.

## 3.6 LCoE modelling

The LCoE calculations have been conducted with the BLIX LCoE model. This model has been developed throughout the years, used for many projects, and has been validated several times for projects BLIX worked on. Due to the in-depth and 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.

The GCS model inputs are based on the reports (Deliverable 1.3: Synthesis of available studies on offshore meshed HVDC grids, 2020) [3] for the HVDC system and (Connecting Offshore Wind Farms, 2019) [4] for the HVAC system, supplemented with expert opinions and calculations from Energy Solutions. Subsequently, the study inputs were validated by TenneT.

For this study it is assumed that the wind farm and grid connection 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.

### 3.6.1 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*

*r = required return/WACC*

*Capex = Capital Expenditure (Investments)*

*Opex = Operational Expenditure (Operational costs)*

---

[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)

### 3.6.2 OWF cost assumptions

In below Table 10 the main cost assumptions of the offshore wind farm are briefly 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.

Table 10: Costs assumptions for OWF LCoE

| Parameter | Assumption | Reference |
|---|---|---|
| Capital Expenditure (Capex) | | |
| **Cost of turbine** | Includes supply, transport & installation and dependency on distance to port. Costs are 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 specific soil conditions and relation water depth and wave conditions. Formula is confidential | Based on BLIX price database |
| **Foundation costs** | Includes supply, transport & installation of foundations and dependency on distance to port. 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 |
| **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. Includes dependency on distance to port. 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 |

The inputs of Table 10 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 site is calculated by dividing the discounted costs by the discounted yield per site. After calculating the LCoE per site, the LCoE per wind farm zone will be determined, compared and analysed.

The yield and costs are calculated on a per wind turbine basis. The main varying parameters are the yield (through wake losses), the foundation costs (through water depth differences and distance to port), inter-array cable length and losses, number of inter-array cable crossings and wind turbine installation and maintenance costs (through distance to port). Other Capex such as the turbine prices do have a large impact on the absolute level of LCoE but are not expected to differ (significantly) between the wind farm zones and sites. 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 wind farm zone and site).

### 3.6.3 GCS cost assumptions

In addition, the main cost assumptions on the GCS have been added to the study with Part II. These assumptions are based on the latest literature and expert opinions and have been validated by two parties. 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 11).

Table 11: Costs assumptions for financial model

| Parameter | Assumption | Reference |
|---|---|---|
| Capital Expenditure (Capex) | | |
| **Cost of OHVS** | Includes the cost for the topside, jacket, convertor, HV equipment and auxiliary systems. Cost of the foundation (jacket) is dependent on the water depth. | Based on expert input by Ensol and validation by TenneT. |
| **Cost of land station** | Includes the cost for land procurement, civil works, convertor and HV equipment. | Based on expert input by Ensol and validation by TenneT. |
| **Export cable length** | Based on the distance from offshore substation to onshore substation multiplied by a landing area specific factor to account for optimal cable routing with respect to obstacles and soil conditions. | Based on experience from previous projects and validation by TenneT. |
| **Export cable cost** | Cost of export cable per kilometre based on production and installation cost. Includes a differentiation between offshore and nearshore installation cost. | Based on expert input by Ensol and validation by TenneT. |
| **Surveying (incl. UXO)** | Based on landing area and cost per kilometre. | Based on expert input by Ensol and validation by TenneT. |
| **Other Capex** | Various items (e.g. project management, insurances and Devex). Percentages of other Capex cost. | Based on expert input by Ensol and validation by TenneT. |
| **Capex Contingency level** | Percentage of investment costs based on market conform levels | Based on expert input by Ensol and validation by TenneT. |
| Operational Expenditure (Opex) | | |
| **O&M costs of OHVS and land station** | Based on a percentage of investment cost | Based on expert input by Ensol and validation by TenneT. |

| | | |
|---|---|---|
| **O&M costs of export cable** | Based on a percentage of investment cost | Based on expert input by Ensol and validation by TenneT. |
| **<u>Other Assumptions</u>** | | |
| **GCS electrical losses** | Includes electrical losses for transformers, reactors and auxiliary equipment as a percentage of electricity production. Cable losses are based on a percentage per kilometre. | Based on expert input by Ensol and validation by TenneT. |
| **GCS non-availability** | Includes non-availability for convertors, transformers and export cable non-availability. Export cable non-availability depends on export cable length. | Based on expert input by Ensol and validation by TenneT. |

# Part I

# 4 INTRODUCTION PART I

Part I contains the results from a first study into the LCoE of offshore wind farms at the search areas, LCoE analyses of the grid connection systems was not included in this assessment. The wind farm zones and sites are listed in Table 12 and shown in Figure 10.

Table 12: Wind farm zones considered in Part I

| Wind farm zone | Abbreviation | Number of sites | Total capacity |
|---|---|---|---|
| **IJmuiden Ver** | IJV | 2 | 4 GW |
| **Zone 1** | | 4 | 8 GW |
| **Zone 2** | | 3 | 6 GW |
| **Zone 3** | | 1 | 2 GW |
| **Zone 5** | | 5 | 10 GW |
| **Zone 5 (mb)** | | 4 | 8 GW |
| **Zone 6** | | 6 | 12 GW |
| **Zone 7** | | 4 | 8 GW |

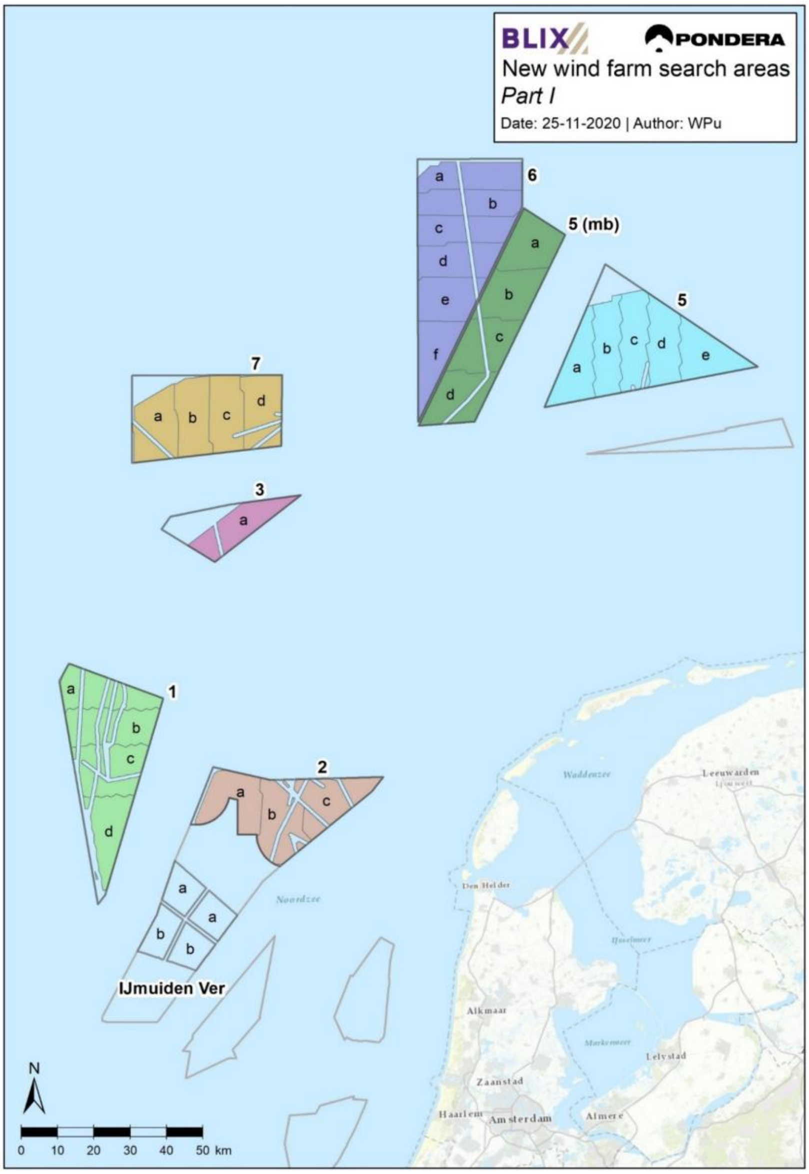

Figure 10: Overview of the wind farm search areas studied in Part I

# 5 WIND FARM LAYOUTS

As indicated in paragraph 3.4, the same fixed rectangular grid of 5.5 by 5.5 rotor diameters is used for the layout of every wind farm zone. The offshore wind energy search areas are filled with a multitude of sites with a connection capacity of 2,010 MW from the boundary closest to shore. The remaining part of the search area is excluded from the design. The orientation of the applied turbine grid for the analysis of Part I is along the longest boundary of each wind farm zone.

The wind farm layouts of all wind farm zones are shown below, in Figure 11 to Figure 18.

The layouts of the zones analysed for the power density sensitivity are shown in Figure 19 and Figure 20.

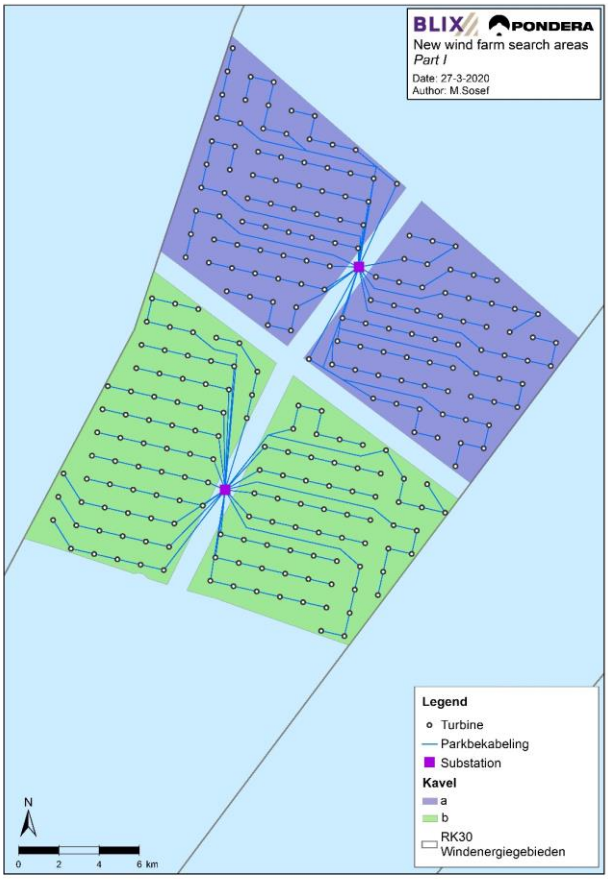

Figure 11: Layout WFZ IJmuiden Ver

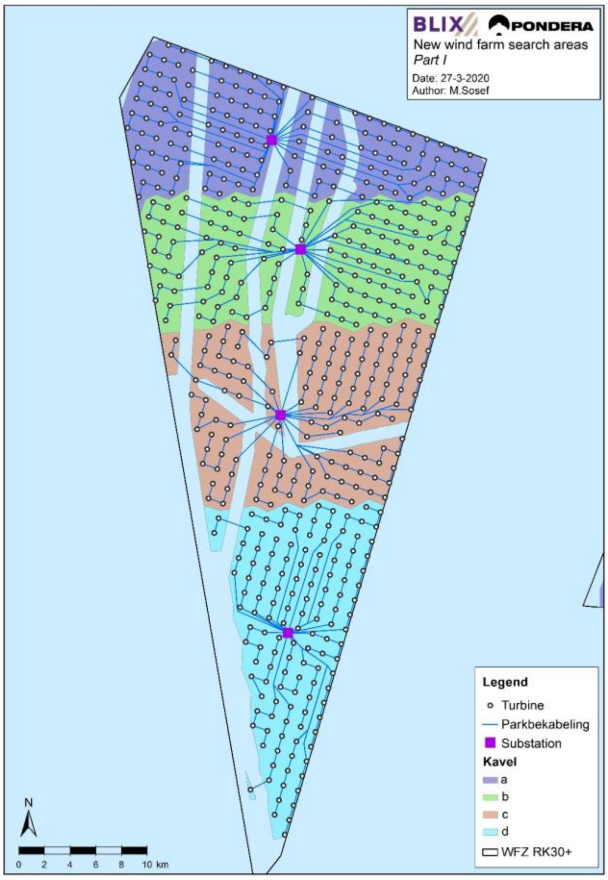

Figure 12: Layout WFZ Zone 1

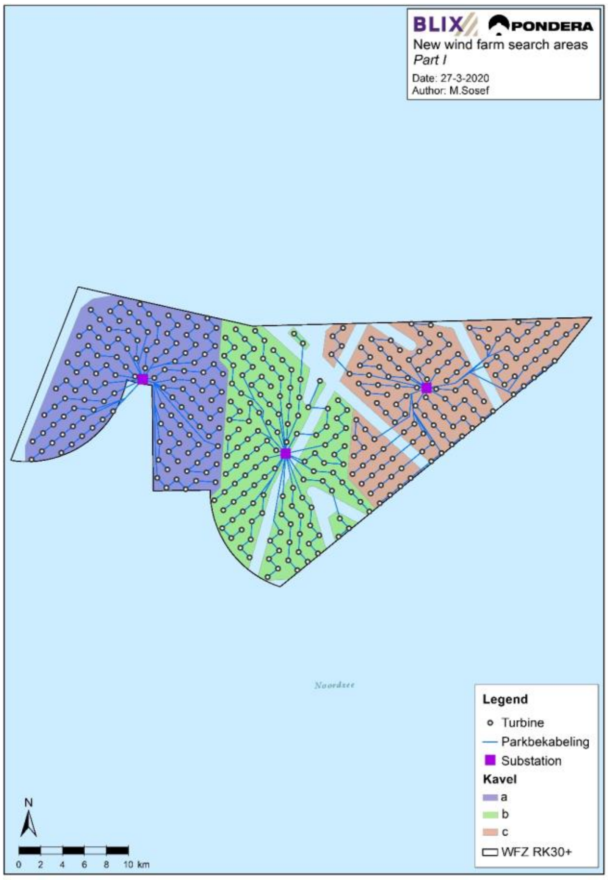

Figure 13: Layout WFZ Zone 2

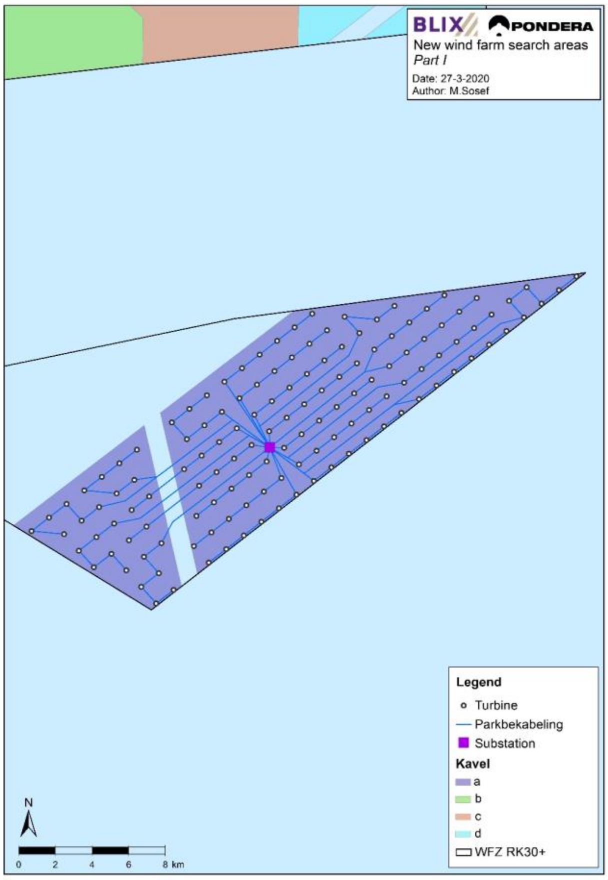

Figure 14: Layout WFZ Zone 3

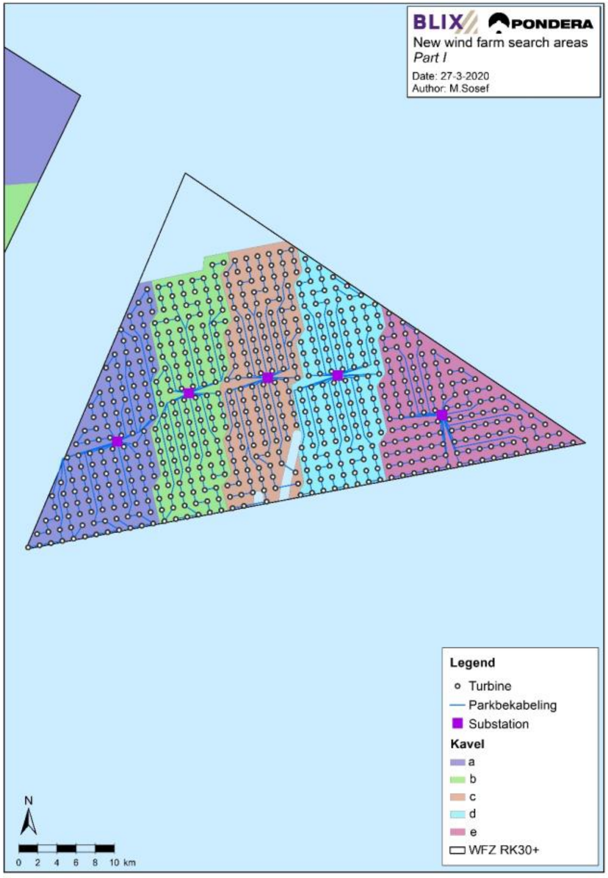

Figure 15: Layout WFZ Zone 5

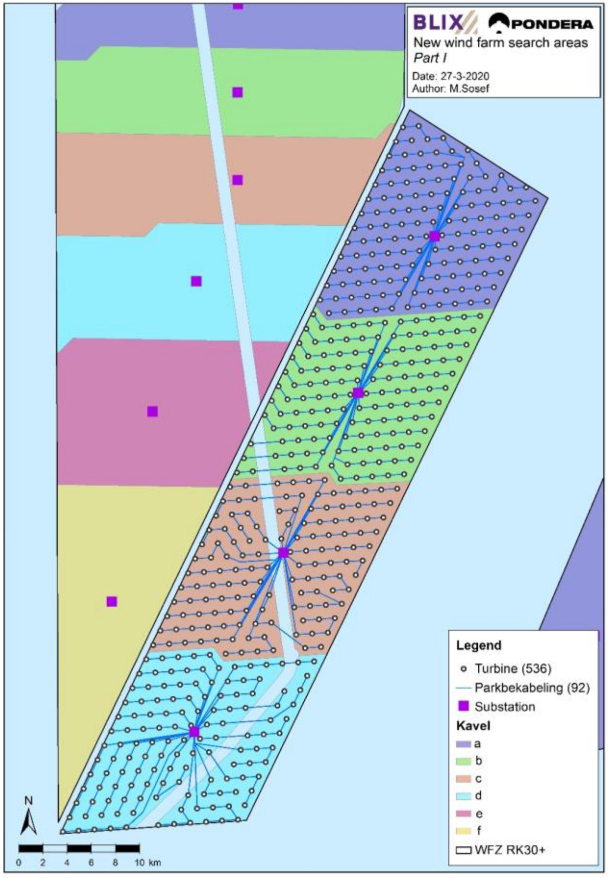

Figure 16: Layout WFZ Zone 5 (mb)

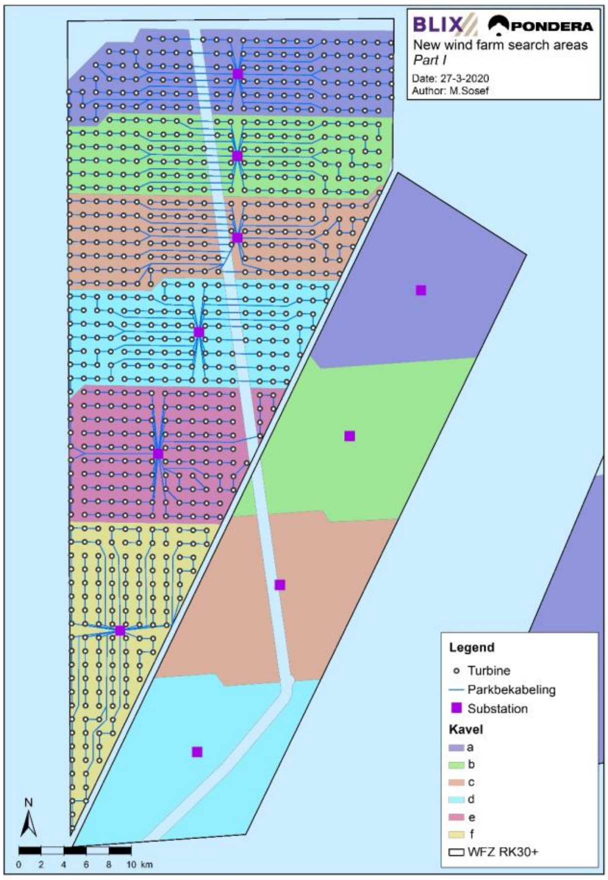

**Figure 17: Layout WFZ Zone 6**

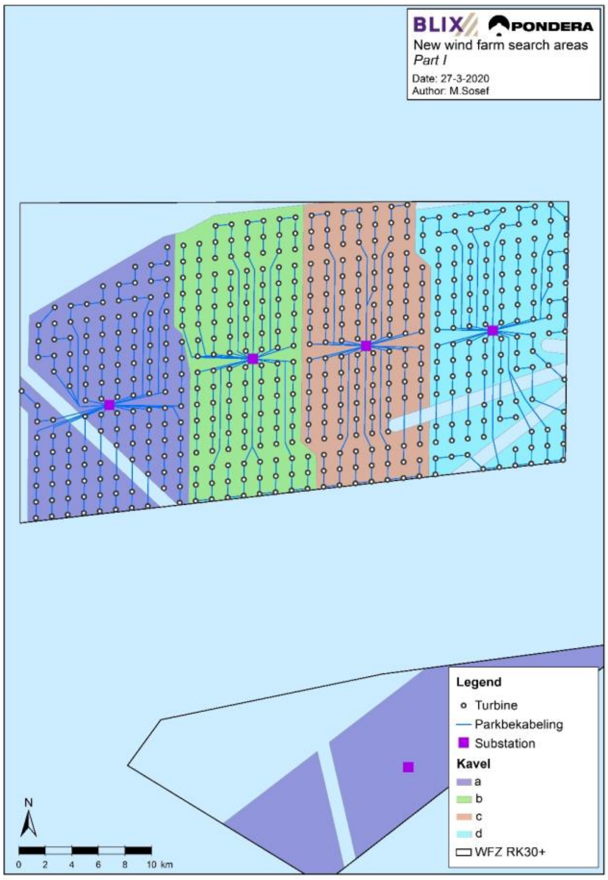

**Figure 18: Layout WFZ Zone 7**

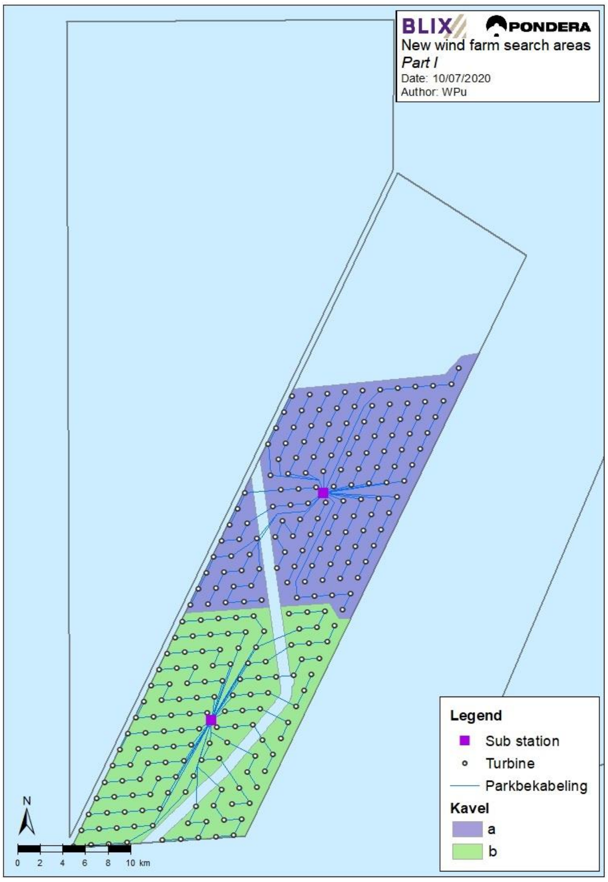

**Figure 19: Layout WFZ Zone 5 (mb) assuming 7 MW/km$^2$**

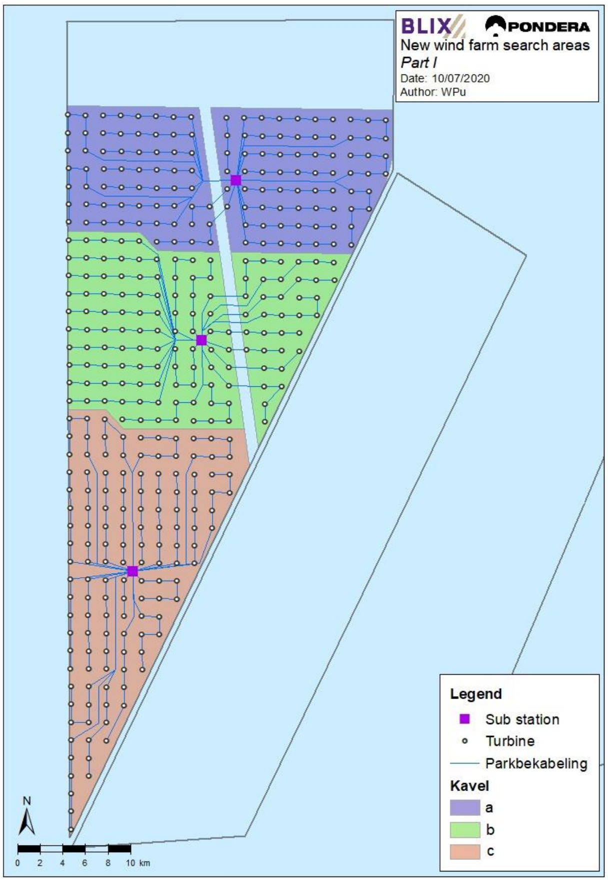

**Figure 20: Layout WFZ Zone 6 assuming 6 MW/km$^2$**

# 6 YIELD ANALYSIS

## 6.1 Yield results of the wind farm zones

The eight wind farm zones, i.e. seven new search areas and IJmuiden Ver, have been modelled and analysed. The main characteristics and the results for each wind farm zone (with the averages based on the wind farm sites) are shown in Table 13.

Table 13: Wind farm layout and yield characteristics of new search areas and IJmuiden Ver

| Wind farm zone | IJmuiden Ver | Zone 1 | Zone 2 | Zone 3 | Zone 5 | Zone 5 (mb) | Zone 6 | Zone 7 |
|---|---|---|---|---|---|---|---|---|
| **Layout** | | | | | | | | |
| **Area [$km^2$]** | 374 | 766 | 625 | 294 | 1,052 | 791 | 1,196 | 857 |
| **Area filled [$km^2$]** | 374 | 760 | 604 | 192 | 974 | 791 | 1,159 | 776 |
| **# of turbines** | 268 | 536 | 402 | 134 | 670 | 536 | 804 | 536 |
| **# wind farm sites** | 2 | 4 | 3 | 1 | 5 | 4 | 6 | 4 |
| **Minimal turbine spacing [x rotor diameter]** | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| **Total infield cable length [km]** | 473 | 1,051 | 725 | 266 | 1,275 | 965 | 1,529 | 969 |
| **# of crossings** | 3 | 110 | 24 | 6 | 3 | 26 | 48 | 26 |
| **Substation distance to port (total) [km]** | 163 | 449 | 184 | 119 | 636 | 610 | 1033 | 595 |
| **Substation distance to port (average per site) [km]** | 82 | 112 | 61 | 119 | 127 | 153 | 172 | 149 |
| **Foundation depth (average per WTG) [m]** | (28) | (28) | (27) | (37) | (40) | (44) | (46) | (43) |
| **Energy yield** | | | | | | | | |
| **Mean wind speed at hub height (m/s)** | 10.2 | 10.4 | 10.3 | 10.5 | 10.6 | 10.6 | 10.7 | 10.6 |
| **Gross annual yield (total) [GWh/y]** | 21,620 | 44,486 | 32,992 | 11,218 | 57,297 | 45,686 | 68,740 | 45,256 |
| **Gross annual yield (average per site) [GWh/y]** | 10,810 | 11,121 | 10,997 | 11,218 | 11,459 | 11,421 | 11,457 | 11,314 |
| **Wake losses [%]** | 13.1 | 12.8 | 12.8 | 10.2 | 14.4 | 12.5 | 13.9 | 14.1 |
| **Cable losses [%]** | 0.64 | 0.68 | 0.63 | 0.66 | 0.65 | 0.61 | 0.65 | 0.63 |
| **Non-availability [%]** | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| **Other losses [%]** | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| **Net annual yield (total) [GWh/y]** | 17,465 | 36,055 | 26,739 | 9,361 | 45,595 | 37,159 | 55,009 | 36,164 |
| **Net annual yield (average per site) [GWh/y]** | 8,733 | 9,014 | 8,913 | 9,361 | 9,119 | 9,290 | 9,168 | 9,041 |
| **Net annual yield (average per WTG) [GWh/y]** | 65.2 | 67.3 | 66.5 | 69.9 | 68.1 | 69.3 | 68.4 | 67.5 |

The following findings are considered to be most significant:

- There is a 0.4 m/s wind speed difference between all wind farm zones. The highest annual mean wind speeds occur in the northernmost wind farm zones (Zone 5, Zone 5 (mb), Zone 6, Zone 7), located furthest away from the mainland.
- The difference in gross and net annual yield between all wind farm zones can easily be explained by the differences in sizes (and subsequently number of turbines) of the wind farm zones. The highest total net energy yield is found in wind farm Zone 6, which contains 804

wind turbines (55,009 GWh/yr), while the highest average net energy yield per wind farm site is found for Zone 3 (9,361 GWh/yr).

- The differences in wake effects can be explained by the size, shape and orientation of the wind farm zone.
  Larger wind farm zones with many sites suffer from more severe wake effects than smaller wind farm zones. For example, wind farm Zone 3 is relatively small and consists of only one site and therefore experiences lower wake losses (10.2%). Wind farm zones Zone 5, Zone 6 and Zone 7 have multiple sites (5, 6, and 4 resp.) and experience higher wake losses (~14%). Also, the shape and orientation of the wind farm zones, or more precisely the border length-to-area ratio in relation to the prevailing wind direction, influences the average wake effect. For instance, wind farm Zone 5 (mb) is stretched from north to south. This layout contains many wind turbines at the edge of the wind farm zone compared to the amount of wind turbines inside the wind farm zone. The wind turbines at the borders do not suffer from wake effects in certain wind directions, reducing the site's overall (wind sector-weighted) wake loss. Square-shaped or triangular-shaped wind farm zones, such as Zone 5 and Zone 7 respectively, have fewer wind turbines at the border of the wind farm zone and more inside the wind farm zone compared to Zone 5 (mb); this means that more wind turbines suffer from wake effects from wind turbines in all wind directions. The orientation of the borders with respect to the prevailing wind direction (SSW to WSW) is especially important here. A long border will be extra effective if aligned perpendicular to the main wind direction – e.g. in NW-SE direction.
- Because of the lower wake losses and (to lesser extent) wind speed differences, the highest net yield per wind turbine is found in wind farm zones Zone 3 and Zone 5 (mb) (69.3 and 69.9 GWh/WTG/yr respectively).

## 6.2 Yield results of the power density sensitivity

The layouts of Zone 5 (mb) and Zone 6 have been modelled and analysed based on a reduced wind farm density. The main characteristics and the results for each wind farm zone are shown in Table 14.

Table 14: Wind farm layout and yield characteristics of sensitivity analysis of Zone 5 (mb) and Zone 6

| Wind farm zone | Zone 5 (mb) | Zone 5 (mb) - 6 MW/km$^2$ | Zone 6 | Zone 6 - 6 MW/km$^2$ |
|---|---|---|---|---|
| **Layout** | | | | |
| **Area filled [km$^2$]** | 791 | -27.5% | 1,159 | -15.5% |
| **# of turbines** | 536 | -50.0% | 804 | -50.0% |
| **# wind farm sites** | 4 | -50.0%<br>(2 sites) | 6 | -50.0%<br>(3 sites) |
| **Minimal turbine spacing [x rotor diameter]** | 6.0 | +20.9%<br>(7.2x) | 5.5 | +32.0%<br>(7.2x) |
| **Total infield cable length [km]** | 965 | -41.0% | 1,529 | -44.7% |
| **# of crossings** | 26 | -42.3% | 48 | -60.4% |
| **Substation distance to port (average per site) [km]** | 153 | -5.3% | 172 | -2.6% |
| **Energy yield** | | | | |
| **Gross annual yield (total) [GWh/y]** | 45,686 | -50.1% | 68,740 | -50.0% |
| **Gross annual yield (average per site) [GWh/y]** | 11,421 | -0.2% | 11,457 | -0.1% |
| **Wake losses [%]** | 12.5 | -29.2%<br>(8.9% loss) | 13.9 | -36.8%<br>(8.8% loss) |
| **Cable losses** | 0.61% | +13.5% | 0.65% | +4.5% |

| | | | | |
|---|---|---|---|---|
| **Net annual yield (total) [GWh/y]** | 37,159 | -48.0% | 55,009 | -47.1% |
| **Net annual yield (average per site) [GWh/y]** | 9,290 | +2.9% | 9,168 | +2.9% |
| **Net annual yield (average per WTG) [GWh/y]** | 69.3 | +3.9% | 68.4 | +5.9% |

The following findings are considered to be most significant:

- A lower wind farm density leads to a less efficient filling of the wind farm zones, as the remainder of the wind farm zone cannot contain a 2x1 GW wind farm site. The number of sites is reduced by -50% with the lower densities for both Zone 5 (mb) and Zone 6, containing 2 and 3 sites respectively.
- The average net area per site for Zone 6 with a density of 6 MW/km$^2$ is 69% larger than for the Zone 6 sites with a 10 MW/km$^2$ wind farm density. For Zone 5 (mb) the average net area per site is 45% larger with a density of 6 MW/km$^2$ than with a 10 MW/km$^2$ wind farm density.
- The overall net annual yield of wind farm Zone 6 decreases with -47.1% with a reduced wind farm density of 6 MW/km$^2$. For Zone 5 (mb), the overall net annual yield of the wind farm zone is -48.0% with a reduced density of 6 MW/km$^2$.
- The net average annual yield per wind turbine increases with the lower densities with +5.9% for Zone 6 and +3.9% for Zone 5 (mb), which are a result of lower wake losses of -5.1%-point and -3.7%-point respectively compared to the benchmark density of 10 MW/km$^2$.

Based on these results, for the other wind farm zones an increase in average annual yield per wind turbine between +4%-point and +6%-point is to be expected with a density of 6 MW/km$^2$ instead of 10 MW / km$^2$ (except for Zone 3, which consists of only 1 site).

# 7 COMPARISON OF LEVELIZED COST OF ENERGY

## 7.1 Relative LCoE impact of the Offshore Wind Farm (OWF)

For an in-depth comparison of the wind farm zones we investigated the relative LCoE of the OWF per turbine and compared the average relative LCoE impact per site and per wind farm zone with the reference IJmuiden Ver.

The following paragraphs describe the relative LCoE per wind turbine, the results of the comparison between wind farm sites and between wind farm zones. Finally, the last paragraph summarizes the results of the sensitivity analysis performed on the density of the wind farm zones.

### 7.1.1 Relative OWF LCoE per turbine

First, the Levelized Cost of Energy per turbine is investigated. The LCoE per turbine incorporates both the net yield and the cost of each turbine foundation. The costs calculated per site, namely for cable length, cable crossings, installation and maintenance of wind turbines, are evenly distributed over all turbines of the relevant site.

Figure 21 through Figure 28 show a series of plots in which the relative LCoE per turbine is visualised with colours. In all plots the LCoE per wind turbine is relative to the maximum LCoE of all wind farm zones, which is found in wind farm Zone 7. A relative LCoE of 100% implies the highest LCoE of all turbines across all zones.

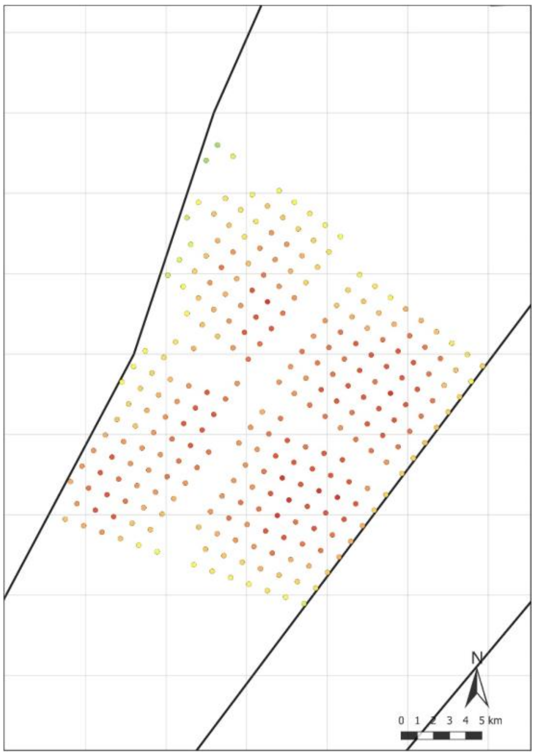

Figure 21: Relative LCoE WFZ IJV

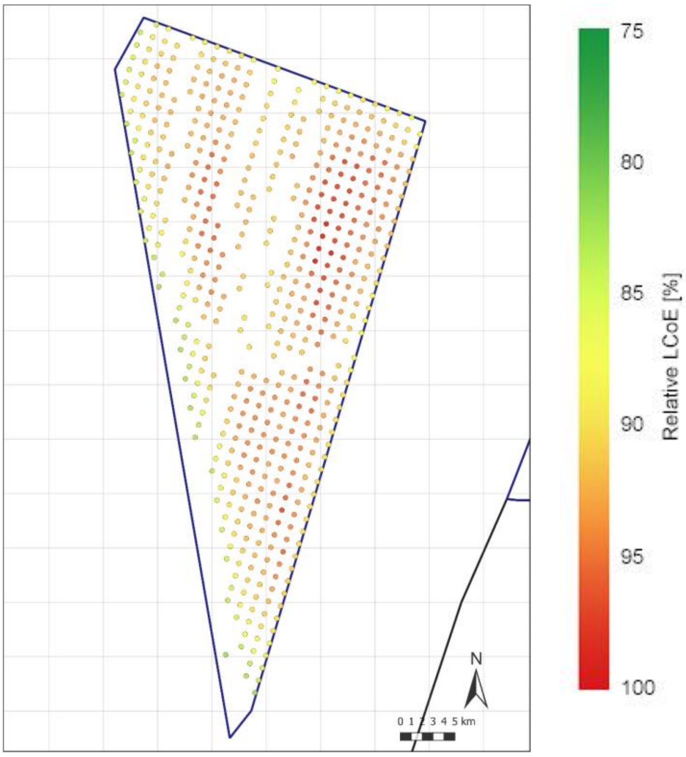

Figure 22: Relative LCoE WFZ Zone 1

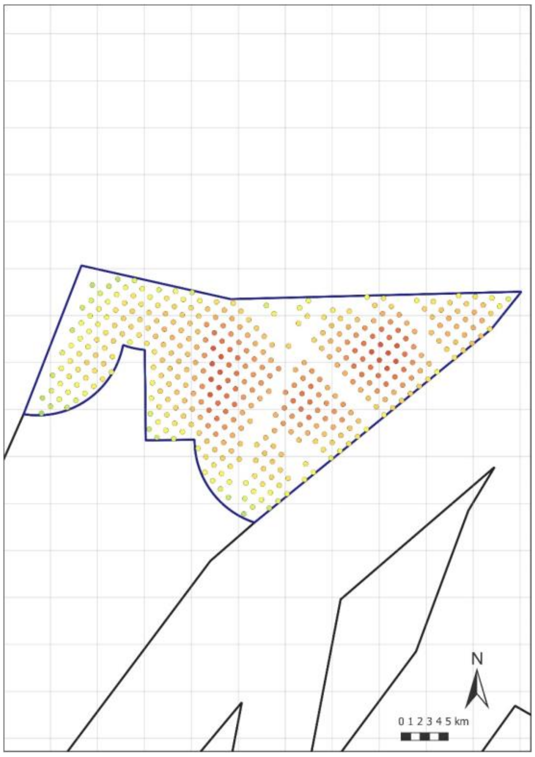

Figure 23: Relative LCoE WFZ Zone 2

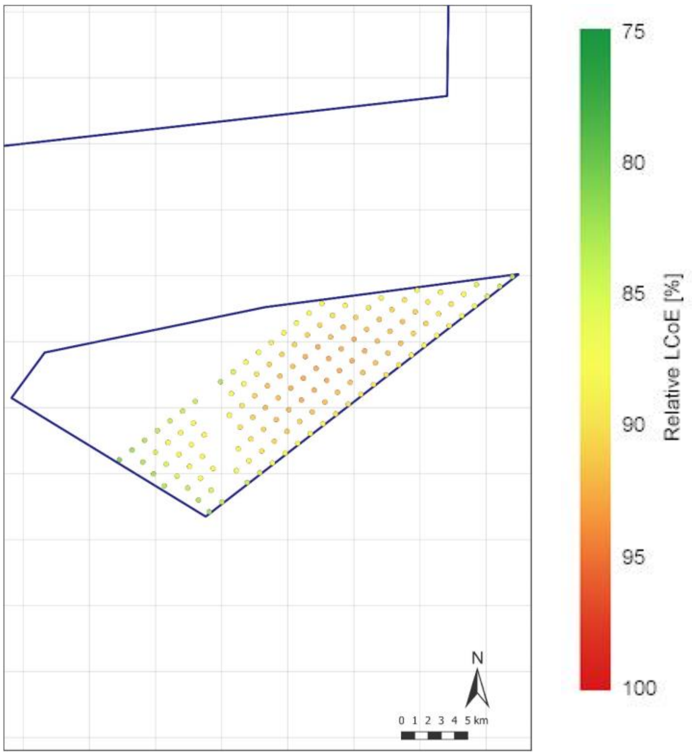

Figure 24: Relative LCoE WFZ Zone 3

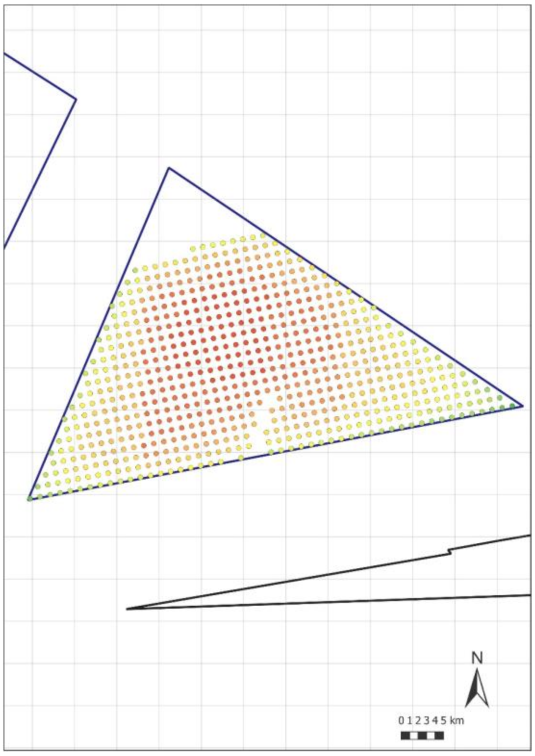

Figure 25: Relative LCoE WFZ Zone 5

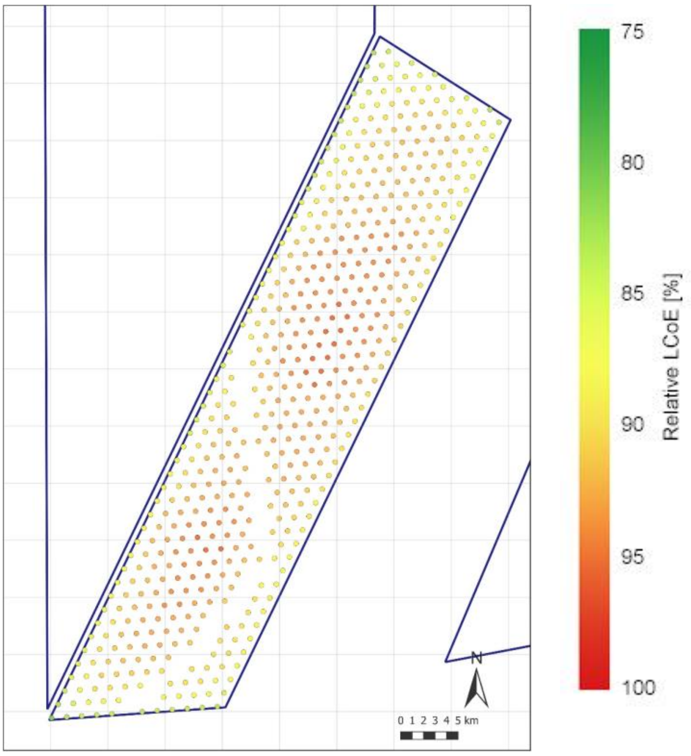

Figure 26: Relative LCoE WFZ Zone 5 (mb)

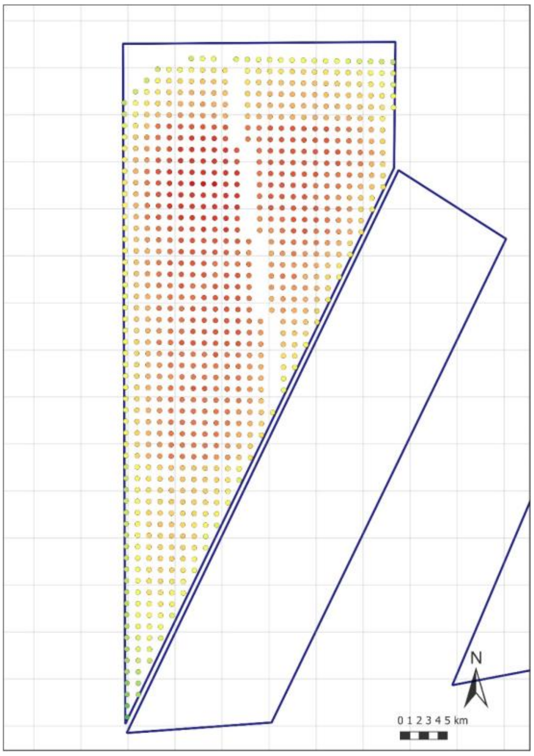

Figure 27: Relative LCoE WFZ Zone 6

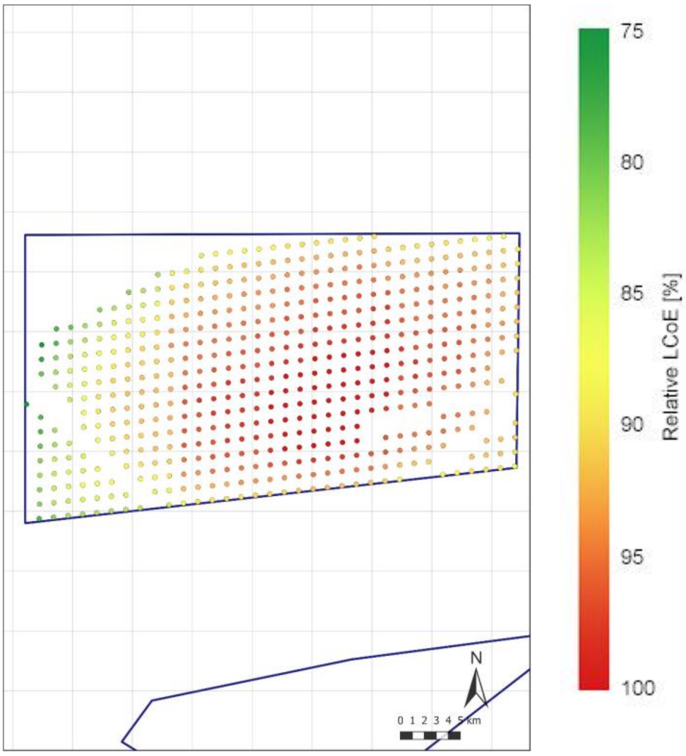

Figure 28: Relative LCoE WFZ Zone 7

From the figures above large differences in levelized cost per energy unit within a site can be observed. The lowest LCoE per turbine are located at the outer sides of the areas, especially in the main wind direction WSW. This indicates that the differences in yield are dominant over differences in foundation cost within a site.

### 7.1.2 Comparison between sites

This paragraph summarizes the main results of the wind farm site analysis. Table 15 and Figure 29 show the LCoE differences of the individual wind farm sites and the impact of the parameters on these differences, compared to the reference IJmuiden Ver site with the lowest LCoE, which is site IJmuiden Ver A. Several factors are assumed to be different between the zones/sites and have an impact on the LCoE (based on Table 15) while others are expected to remain the same, the latter are therefore not listed in the table below.

The following conclusions can be drawn:

- The LCoE varies significantly between the wind farm sites with +1.3% to -4.4% difference compared to the reference IJmuiden Ver A.
- The positive effect of the favourable wind climate of the distant sites (all wind farm zones except Zone 1 and Zone 2) is largely offset by the increase in cost. Especially the foundation cost variations have a distinct impact on the LCoE, resulting from the variations in water depth and installation costs. The WTG installation and maintenance are also significant for these sites due to the larger distance to the marshalling harbour.
- The differences in cable losses and cable cost only have a negligible impact on the LCoE because of the assumed fixed turbine grid, the rectangular shaped sites and almost no obstacles at the sites; only for Zone 1 these costs have an impact on the LCoE because these sites don’t have a rectangular shape, and several existing cables have to be crossed.
- IJmuiden Ver B has a slightly higher LCoE than IJmuiden Ver A because of the slightly less advantageous wind conditions.

- The LCoE of Zone 3 A is the lowest and 4.4% lower than the LCoE of IJmuiden Ver A even considering the similar density. This is due to the favourable shape and orientation, and the lack of neighbouring sites, resulting in low wake losses. (The numbers in Table 15 and Table 16 and Figure 29 and Figure 30 differ slightly because of the difference in comparing with the site IJmuiden Ver A only or with the WFZ IJmuiden Ver including IJmuiden Ver B.)
- Sites in the middle of the wind farm Zone 5 (B, C, D), Zone 6 (B, C, D) and Zone 7 (B, C) have the highest LCoE because these sites experience the negative wake effects of neighbouring sites. However, the gross yield for these sites is relatively high so the LCoE difference is still less than +/-0.1%, except for site Zone 7 C, which has the highest LCoE and 1.3% higher than the reference LCoE of IJmuiden Ver A.
- The LCoE is significantly lower for the wind farm sites Zone 3 A, Zone 5 A, Zone 5 (mb) D, Zone 6 F and Zone 7 A compared to IJmuiden Ver A, with an LCoE between –3.0% and –4.4%. These sites are all located in the windy northern part of the North Sea), closest to a port (compared to other sites within their zone) and at an outer edge of a zone (without a neighbouring site in the dominant wind direction WSW that causes wake losses).

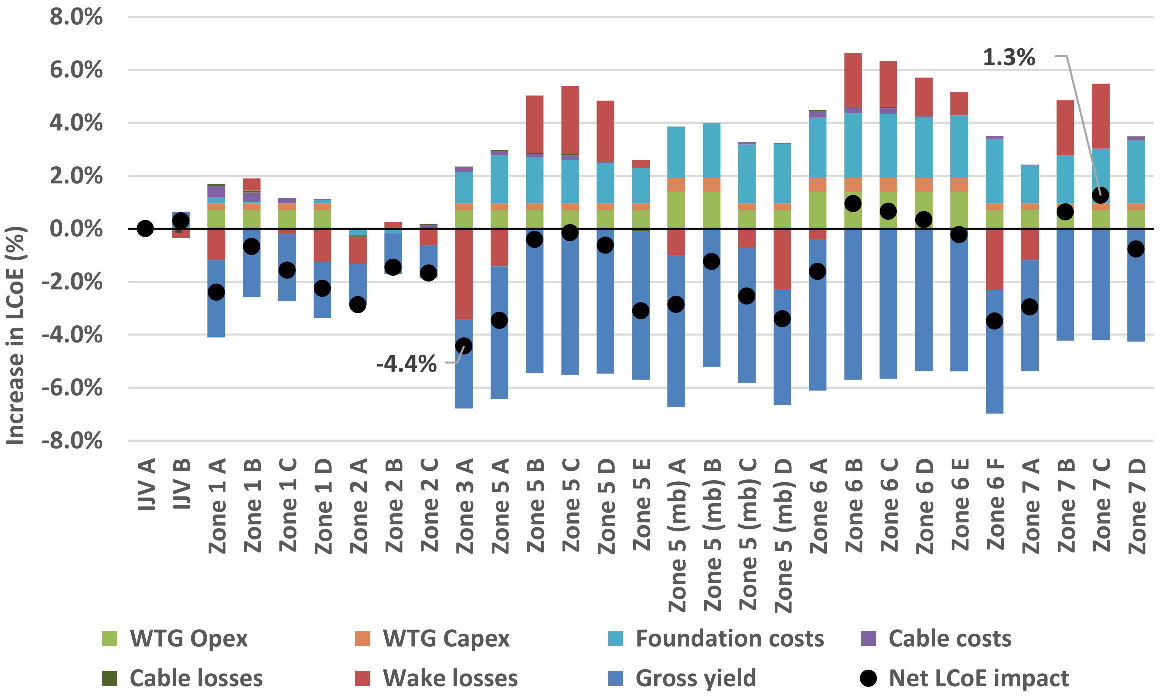

Figure 29: LCoE of the new search areas wind farm sites and IJmuiden Ver A and B

Table 15: LCoE of the new search areas wind farm sites and IJmuiden Ver A and B

| Site | Net LCoE impact | Cable costs | Foundation costs | WTG Capex | WTG Opex | Gross yield | Wake losses | Cable losses |
|---|---|---|---|---|---|---|---|---|
| **IJV A** | - | - | - | - | - | - | - | - |
| **IJV B** | 0.3% | -0.0% | 0.1% | - | - | 0.5% | -0.3% | -0.0% |
| **Zone 1 A** | -2.4% | 0.4% | 0.2% | 0.3% | 0.7% | -2.9% | -1.2% | 0.1% |
| **Zone 1 B** | -0.7% | 0.4% | 0.0% | 0.3% | 0.7% | -2.6% | 0.5% | 0.1% |
| **Zone 1 C** | -1.6% | 0.2% | -0.0% | 0.3% | 0.7% | -2.5% | -0.2% | 0.0% |
| **Zone 1 D** | -2.3% | 0.0% | 0.1% | 0.3% | 0.7% | -2.1% | -1.3% | -0.0% |
| **Zone 2 A** | -2.9% | -0.0% | -0.2% | - | - | -1.6% | -1.0% | -0.0% |
| **Zone 2 B** | -1.5% | 0.0% | -0.2% | - | - | -1.5% | 0.2% | -0.0% |
| **Zone 2 C** | -1.7% | 0.1% | 0.0% | - | - | -1.2% | -0.6% | 0.0% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Zone 3 A** | -4.4% | 0.2% | 1.2% | 0.3% | 0.7% | -3.4% | -3.4% | 0.0% |
| **Zone 5 A** | -3.5% | 0.2% | 1.8% | 0.3% | 0.7% | -5.0% | -1.4% | 0.0% |
| **Zone 5 B** | -0.4% | 0.1% | 1.7% | 0.3% | 0.7% | -5.4% | 2.2% | 0.0% |
| **Zone 5 C** | -0.2% | 0.2% | 1.6% | 0.3% | 0.7% | -5.5% | 2.5% | 0.1% |
| **Zone 5 D** | -0.6% | 0.1% | 1.5% | 0.3% | 0.7% | -5.5% | 2.3% | 0.0% |
| **Zone 5 E** | -3.1% | -0.0% | 1.3% | 0.3% | 0.7% | -5.6% | 0.3% | -0.0% |
| **Zone 5 (mb) A** | -2.9% | -0.0% | 1.9% | 0.5% | 1.4% | -5.7% | -0.9% | -0.0% |
| **Zone 5 (mb) B** | -1.2% | -0.0% | 2.0% | 0.5% | 1.4% | -5.2% | 0.0% | -0.0% |
| **Zone 5 (mb) C** | -2.5% | 0.1% | 2.2% | 0.3% | 0.7% | -5.1% | -0.7% | -0.0% |
| **Zone 5 (mb) D** | -3.4% | 0.1% | 2.2% | 0.3% | 0.7% | -4.4% | -2.3% | -0.0% |
| **Zone 6 A** | -1.6% | 0.2% | 2.3% | 0.5% | 1.4% | -5.7% | -0.4% | 0.0% |
| **Zone 6 B** | 0.9% | 0.2% | 2.5% | 0.5% | 1.4% | -5.7% | 2.0% | 0.0% |
| **Zone 6 C** | 0.7% | 0.2% | 2.4% | 0.5% | 1.4% | -5.7% | 1.7% | 0.0% |
| **Zone 6 D** | 0.3% | 0.1% | 2.3% | 0.5% | 1.4% | -5.4% | 1.4% | 0.0% |
| **Zone 6 E** | -0.2% | -0.1% | 2.4% | 0.5% | 1.4% | -5.2% | 0.9% | -0.1% |
| **Zone 6 F** | -3.5% | 0.1% | 2.4% | 0.3% | 0.7% | -4.7% | -2.3% | -0.0% |
| **Zone 7 A** | -3.0% | 0.0% | 1.4% | 0.3% | 0.7% | -4.2% | -1.2% | -0.0% |
| **Zone 7 B** | 0.6% | 0.0% | 1.8% | 0.3% | 0.7% | -4.2% | 2.1% | -0.0% |
| **Zone 7 C** | 1.3% | -0.0% | 2.1% | 0.3% | 0.7% | -4.2% | 2.5% | -0.0% |
| **Zone 7 D** | -0.8% | 0.1% | 2.4% | 0.3% | 0.7% | -4.2% | -0.0% | 0.0% |

### 7.1.3 Comparison between zones

In this paragraph the main results of the analysis on wind farm zone level are described. For the wind farm zones of the new search areas, the average LCoE differences of the wind farm zone with respect to the reference alternative wind area IJmuiden Ver and the impact of the different parameters are shown in Table 16 and Figure 30.

The following main conclusions can be drawn:

- The LCoE is in general lowest for the wind farm zones with the lowest wake losses. This observation also indicates that the effect of yield is dominant over variations in cost.
- The LCoE vary considerably between the wind farm zones but they all have an LCoE lower than the reference IJmuiden Ver; -0.6% to -4.6% difference compared to the reference IJmuiden Ver mainly due to the higher gross yield resulting from the more favourable wind climate at these zones.
- Zone 3 and Zone 5 (mb) have on average the lowest LCoE with –4.6% and –2.7% compared to IJmuiden Ver, followed by the wind farm zones Zone 2 and Zone 1 with –2.1% and –1.9%. These differences are mainly caused by the higher gross yield and relatively low wake effects compared to IJmuiden Ver. Wind farm Zone 5 also has a significantly lower LCoE of -1.7% compared to the reference, especially due to the high gross yield.
- Zone 7 and Zone 6 have on average a slightly lower Levelized Cost of Energy than IJmuiden Ver, -0.6% and -0.7% respectively. The average gross yields are substantially higher for these wind farm zones but this is largely offset by the higher wake effect and higher foundation costs. There is however a large variation between the sites in these zones.

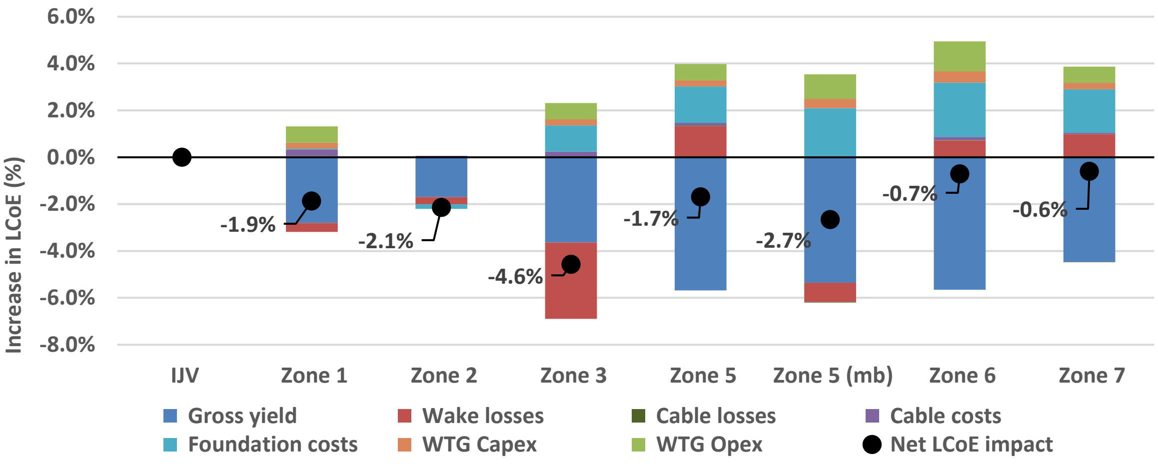

Figure 30: LCoE of the new search areas wind farm zones and IJmuiden Ver

Table 16: LCoE of the new search areas wind farm zones and IJmuiden Ver

| WFZ | Net LCoE impact | Cable costs | Foundation costs | WTG Capex | WTG Opex | Gross yield | Wake losses | Cable losses |
|---|---|---|---|---|---|---|---|---|
| IJV | - | - | - | - | - | - | - | - |
| Zone 1 | -1.9% | 0.3% | 0.0% | 0.3% | 0.7% | -2.8% | -0.4% | 0.0% |
| Zone 2 | -2.1% | 0.1% | -0.2% | - | - | -1.7% | -0.3% | 0.0% |
| Zone 3 | -4.6% | 0.2% | 1.1% | 0.3% | 0.7% | -3.6% | -3.3% | 0.0% |
| Zone 5 | -1.7% | 0.1% | 1.6% | 0.3% | 0.7% | -5.7% | 1.3% | 0.0% |
| Zone 5 (mb) | -2.7% | 0.1% | 2.1% | 0.4% | 1.0% | -5.4% | -0.8% | -0.0% |
| Zone 6 | -0.7% | 0.1% | 2.3% | 0.5% | 1.3% | -5.7% | 0.7% | 0.0% |
| Zone 7 | -0.6% | 0.1% | 1.9% | 0.3% | 0.7% | -4.5% | 1.0% | -0.0% |

The black dots in Figure 30 show the net LCoE impact, matching the numbers in the first column of the tables.

## 7.2 Power density sensitivity of the OWF LCoE results

A sensitivity analysis was performed to investigate the impact of the wind turbine density on the average levelized cost of energy of the wind farm Zone 6 and Zone 5 (mb)

Figure 31 to Figure 34 show the relative LCoE per turbine of Zone 6 and Zone 5 (mb) with densities of 10 MW/km$^2$ and 6 MW/km$^2$. In Figure 35 a breakdown of the average LCoE differences of Zone 6 and Zone 5 (mb) with 6 MW/km$^2$ are presented with respect to the benchmark 10 MW/km$^2$ sites.

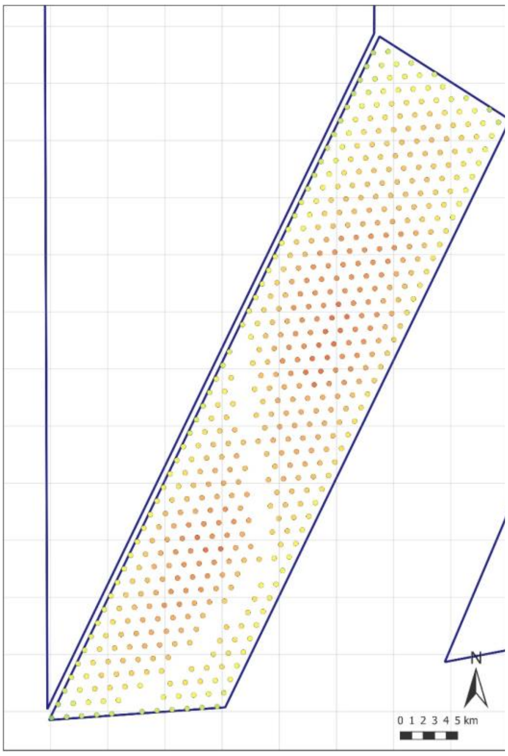

Figure 31: Relative LCoE WFZ Zone 5 (mb) assuming 10 MW/km²

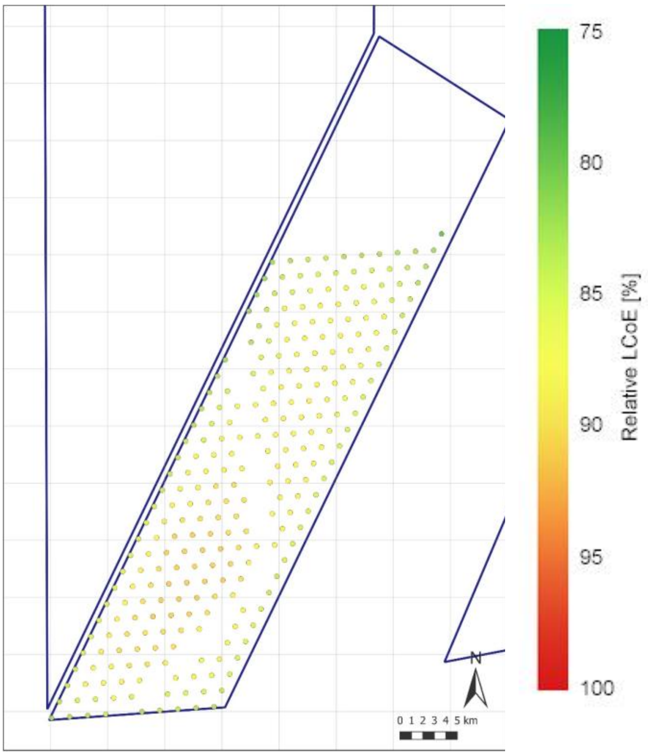

Figure 32: Relative LCoE WFZ Zone 5 (mb) assuming 6 MW/km²

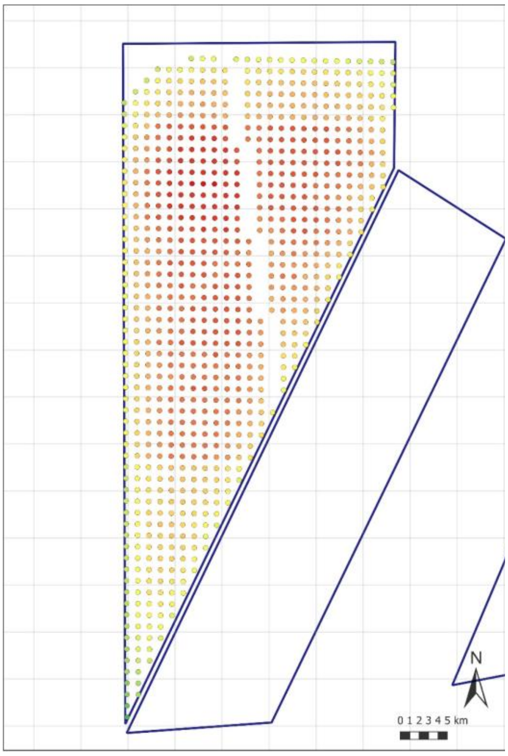

Figure 33: Relative LCoE WFZ Zone 6 assuming 10 MW/km²

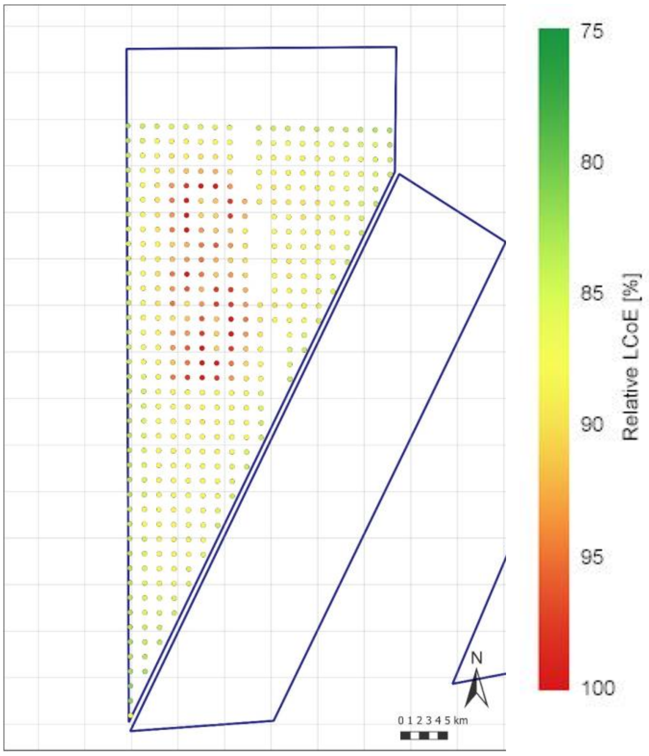

Figure 34: Relative LCoE WFZ Zone 6 assuming 6 MW/km²

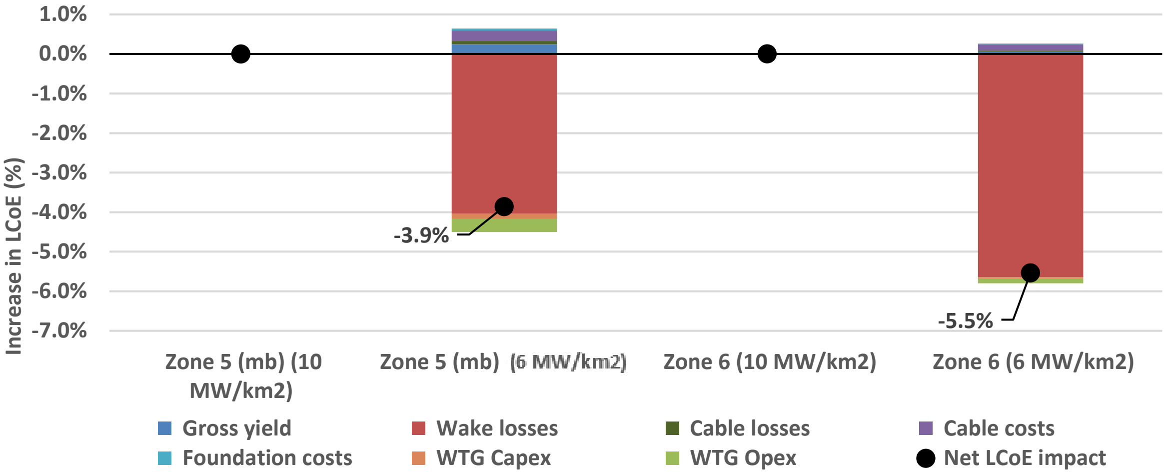

**Figure 35: LCoE impact of reduced densities for wind farm zones Zone 5 (mb) and Zone 6**

The following findings are considered to be most important:

- The lower LCoEs with a density of 6 MW/km$^2$ for Zone 6 and Zone 5 (mb) are predominantly caused by the higher net yields per turbine due to the lower wake losses. The differences in foundation cost, inter-array cable cost WTG Opex and WTG Capex are very limited compared to the difference in net yield.
- For Zone 6 we observe the largest difference in average LCoE of the two analysed densities due to the relatively high wake losses for Zone 6 with a density of 10 MW/km$^2$ which reduce significantly with a density of 6 MW/km$^2$. The average LCoE at a density of 6 MW/km$^2$ is -5.5% lower than the LCoE at a density of 10 MW/km$^2$.
- For Zone 5 (mb), the average LCoE at a density of 6 MW/km$^2$ is also significantly lower than the LCoE at a density of 10 MW/km$^2$, namely -3.9%, but the impact is smaller compared to Zone 6 because the wake losses are less dominant.
- When comparing the average LCoE of Zone 6 and Zone 5 (mb) with a density of 6 MW/km$^2$ with Zone 6 and Zone 5 (mb) with a density of 10 MW/km$^2$ (by not taking into account the northernmost site to compare about the same area), the differences in average LCoE increases to -6.1% for Zone 6 and -4.2% for Zone 5 (mb). This is because the top sites have a relatively low LCoE.

Based on the above results, for the other wind farm zones a decrease in LCoE between -4%-point and -5.5%-point is to be expected with a density of 6 MW/km$^2$ instead of 10 MW / km$^2$ (except for Zone 3, which consists of only 1 site).

# Part II

# 8 INTRODUCTION PART II

Part II contains the results from the follow up LCoE study which considers analyses of the LCoE of both the offshore wind farms and grid connection systems of the adapted search areas, IJmuiden Ver (noord), Hollandse Kust (noordwest) and Hollandse Kust (zuidwest) compared to the LCoE of zone IJmuiden Ver for HVDC and Hollandse Kust (west) for HVAC.

Zones and search areas were added and most of the search areas considered in Part I were adapted in size, shape, orientation and location based on the results from Part I and the outcomes of discussions with stakeholders. See list below for the main changes compared to the LCoE study of Part I:

- IJmuiden Ver Noord: newly added by the Working group
- Zone 1: shipping passage added
- Zone 2*: old layout from Part I
- Zone 3*: old layout from Part I
- Zone 4: newly added by the Working group
- Zone 5: size adapted based on Part I results
- Zone 5 clearway: new variant of Zone 5 with shipping passage
- Zone 5 (mb): location moved to the east by the Working group to allow for a shipping passage
- Zone 6: size and shape adapted by the Working group
- Zone 7: size, shape and orientation adapted based on Part I results
- Zone 8: newly added by the Working group
- Hollandse Kust (noordwest): newly added by the Working group
- Hollandse Kust (zuidwest): newly added by the Working group

The wind farm zones studied in Part II are listed in Table 17 and shown in Figure 36 with their subdivision into sites.

Table 17: Wind farm Zones considered in Part II

| Wind farm Zone | Abbreviation | Number of sites | Total capacity |
|---|---|---|---|
| **HVDC** | | | |
| **IJmuiden Ver (reference)** | IJV | 2 | 4 GW |
| **IJmuiden Ver (noord)** | IJVN | 1 | 2 GW |
| **Zone 1** | | 3 | 6 GW |
| **Zone 2*** | | 3 | 6 GW |
| **Zone 3*** | | 1 | 2 GW |
| **Zone 4** | | 5 | 10 GW |
| **Zone 5** | | 2 | 4 GW |
| **Zone 5 clearway** | | 2 | 4 GW |
| **Zone 5 (mb)** | | 1 | 2 GW |
| **Zone 6** | | 5 | 10 GW |
| **Zone 7** | | 5 | 8 GW |
| **Zone 8** | | 1 | 2 GW |
| **HVAC** | | | |
| **Hollandse Kust (west) (reference)** | HKW | 3 | 2.1 GW |
| **Hollandse Kust (noordwest)** | HKNW | 2 | 1.4 GW |
| **Hollandse Kust (zuidwest)** | HKZW | 2 | 1.4 GW |

*Zone is identical to the one analysed in Part I; size, location and orientation were not adapted after Part I analysis.

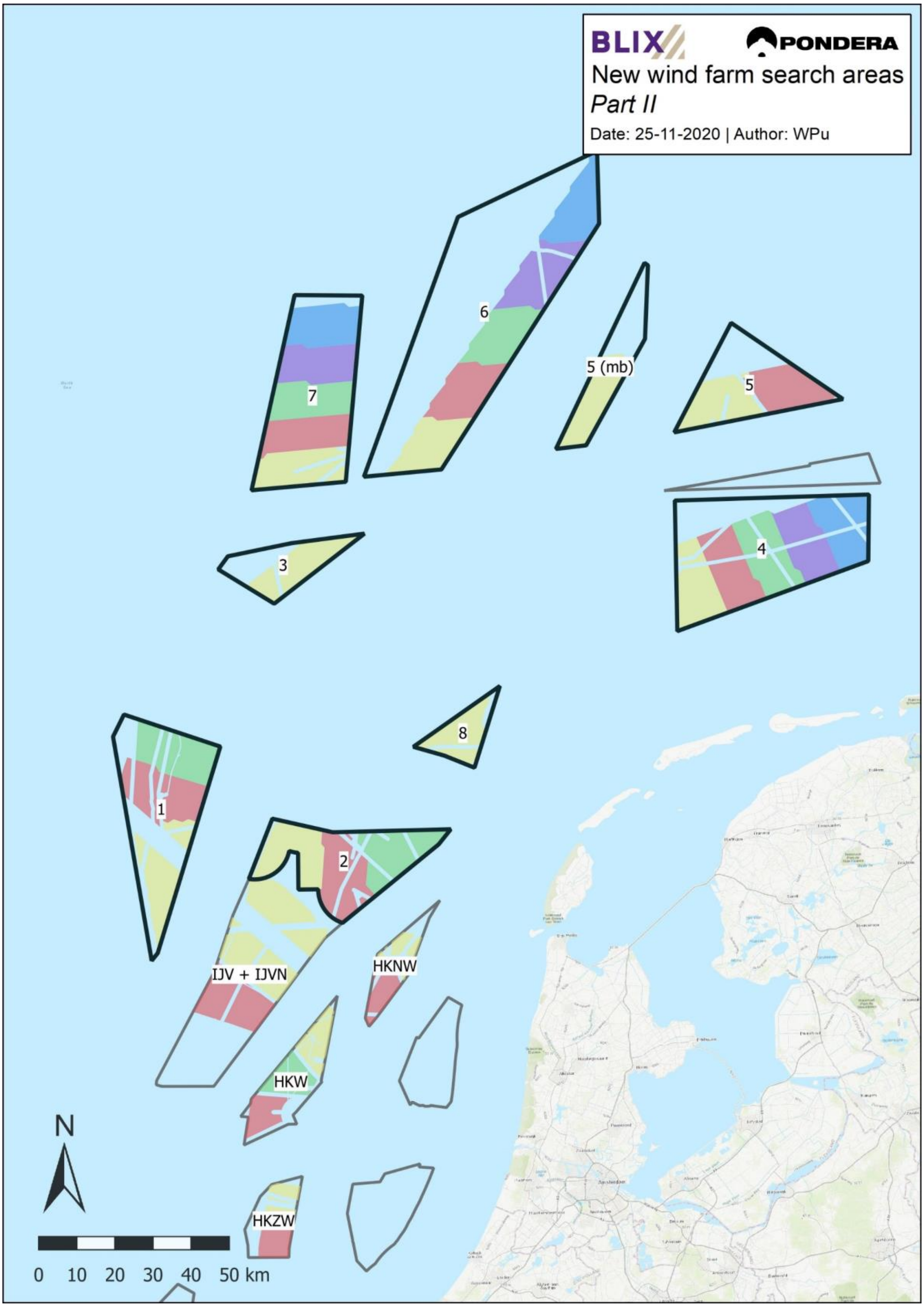

Figure 36: Overview of the wind farm search areas studied in Part II

# 9 WIND FARM LAYOUTS

As indicated in paragraph 3.4, the same fixed rectangular grid of 5.5 by 5.5 rotor diameters is used for the layout of every wind farm zone. The orientation of the applied turbine grid for the analysis of Part II is along the boundary of each wind farm zone closest to shore.

**HVDC Wind farm zones**

The HVDC offshore wind energy search areas are filled with a multitude of sites with a connection capacity of 2,010 MW from the boundary closest to shore. Zone 6 is an exception to this because the maximum capacity of this search area was set at 10 GW. The remaining part of the search areas is excluded from the design, but could be used in future optimisations to reduce wake losses.

The wind farm layouts of the wind farm zones with HVDC connections are shown in Figure 37 to Figure 48.

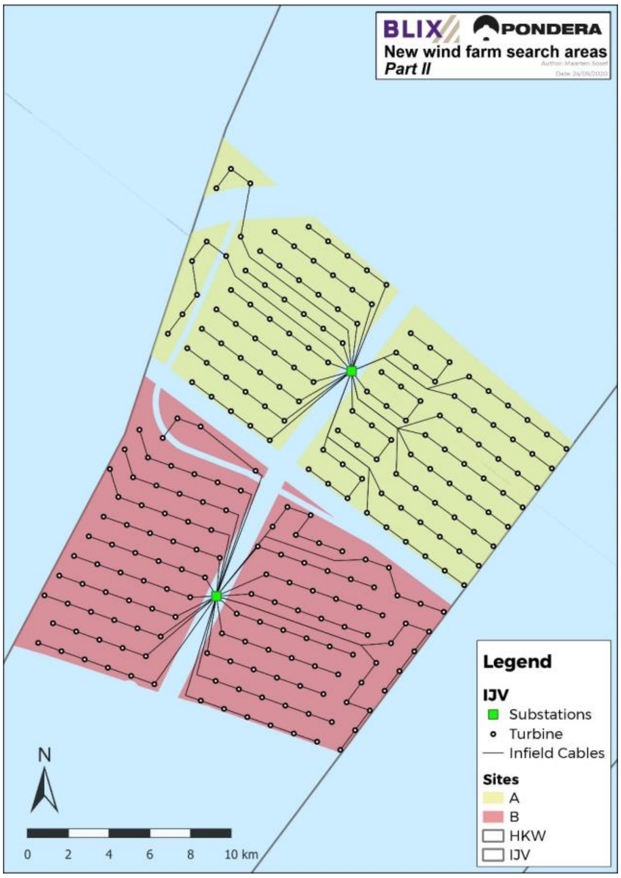

Figure 37: Layout Zone IJV (reference)

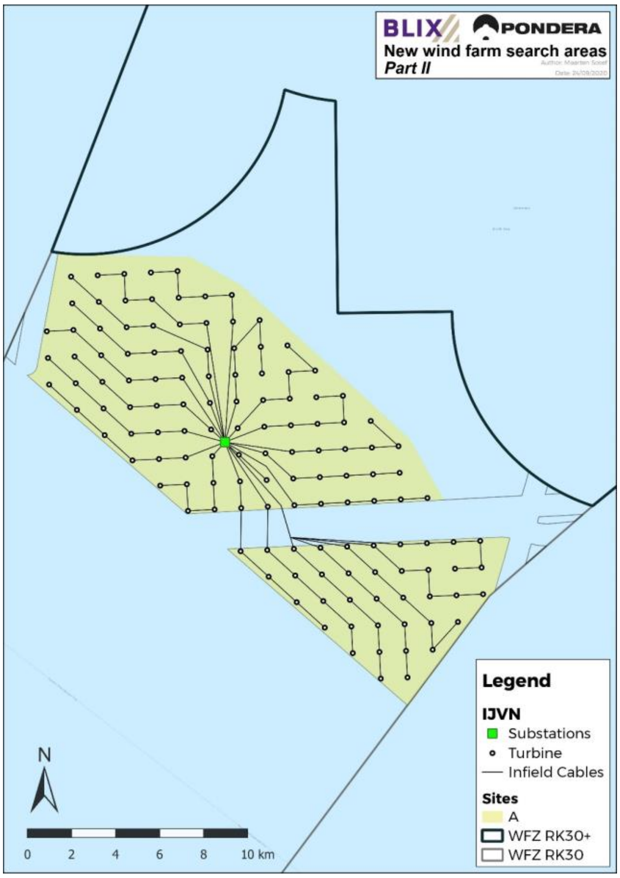

Figure 38: Layout Zone IJVN

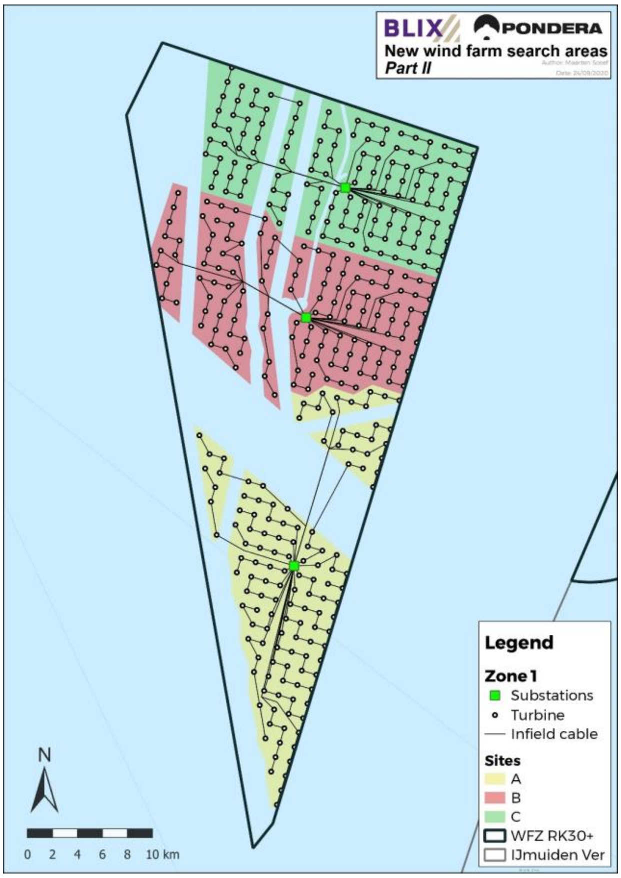

Figure 39: Layout Zone 1

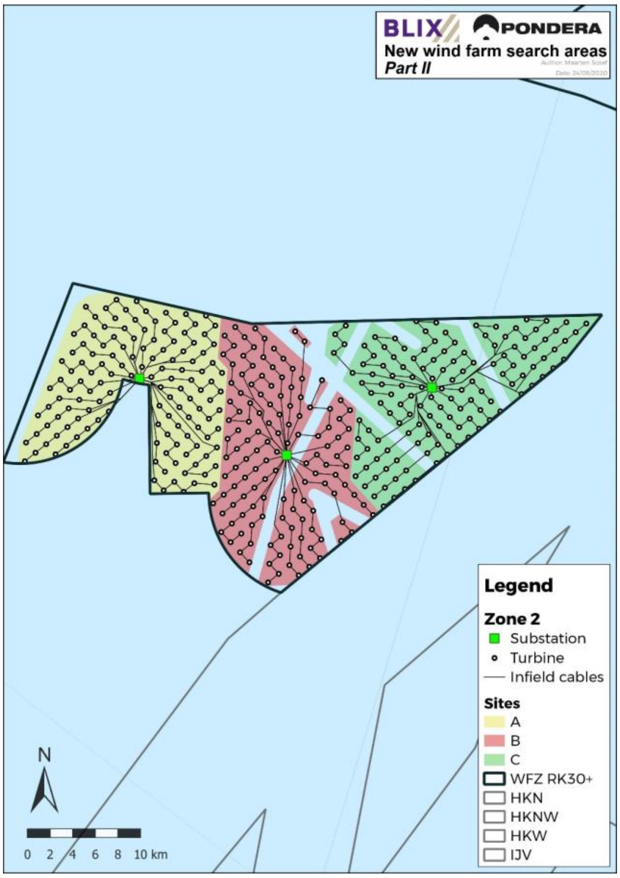

Figure 40: Layout Zone 2

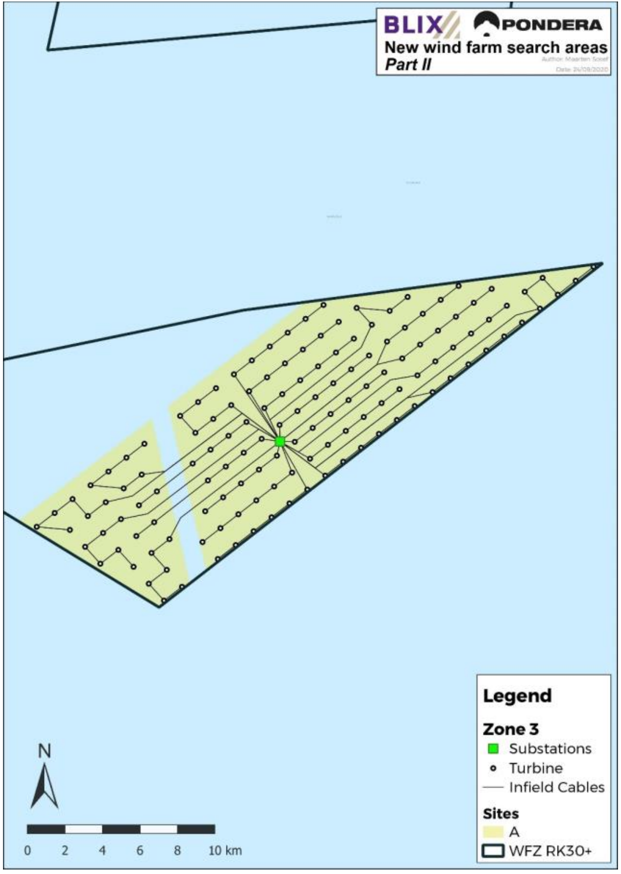

Figure 41: Layout Zone 3

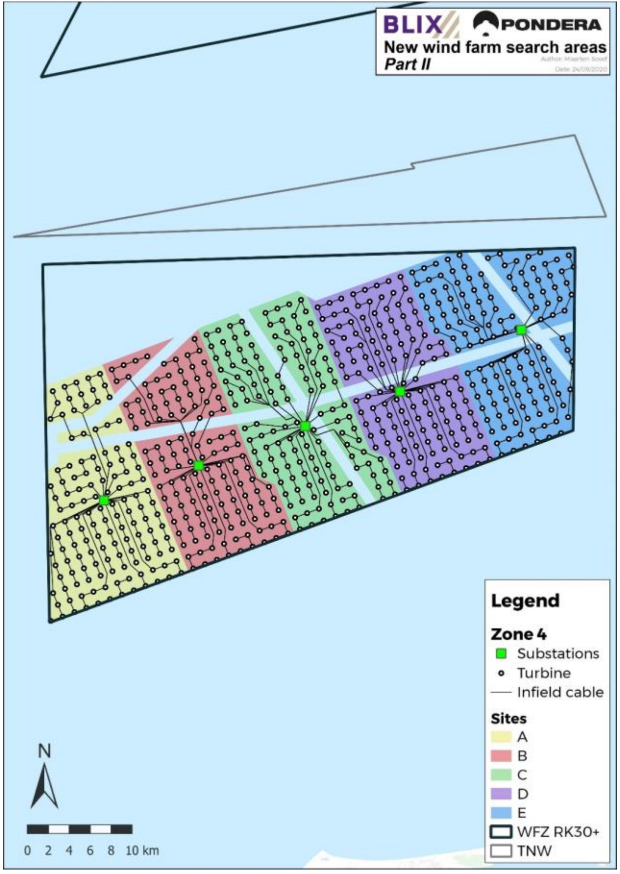

Figure 42: Layout Zone 4

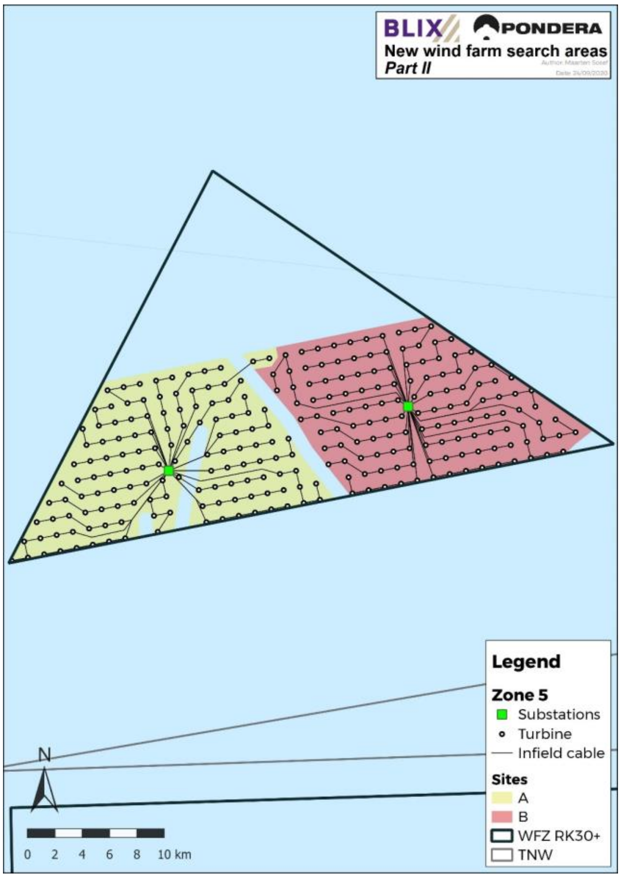

Figure 43: Layout Zone 5

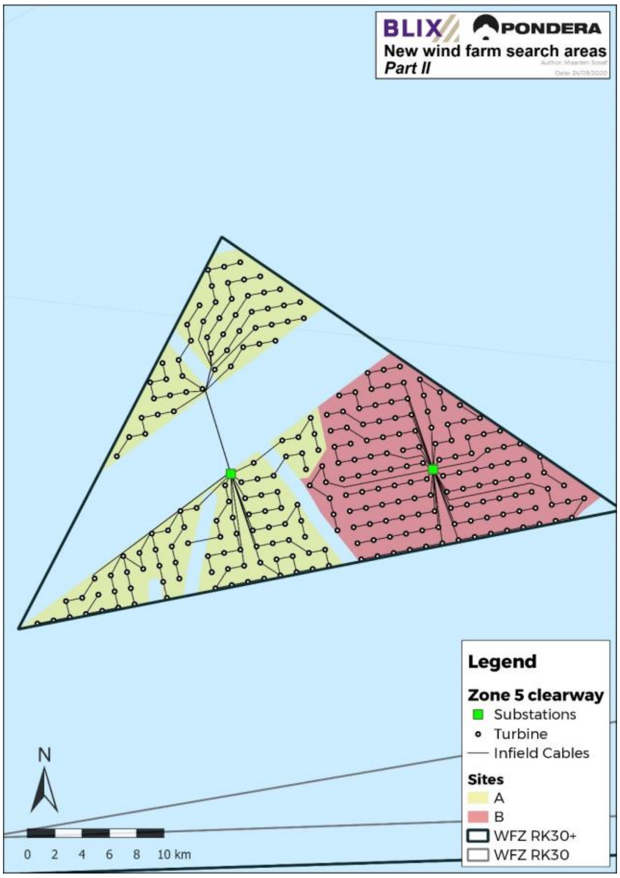

Figure 44: Layout Zone 5 clearway

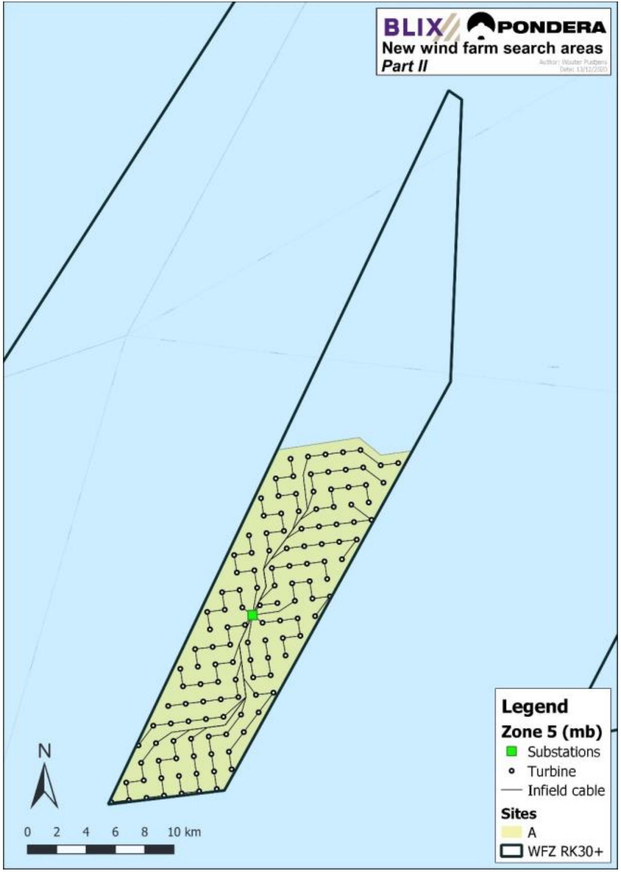

Figure 45: Layout Zone 5 (mb)

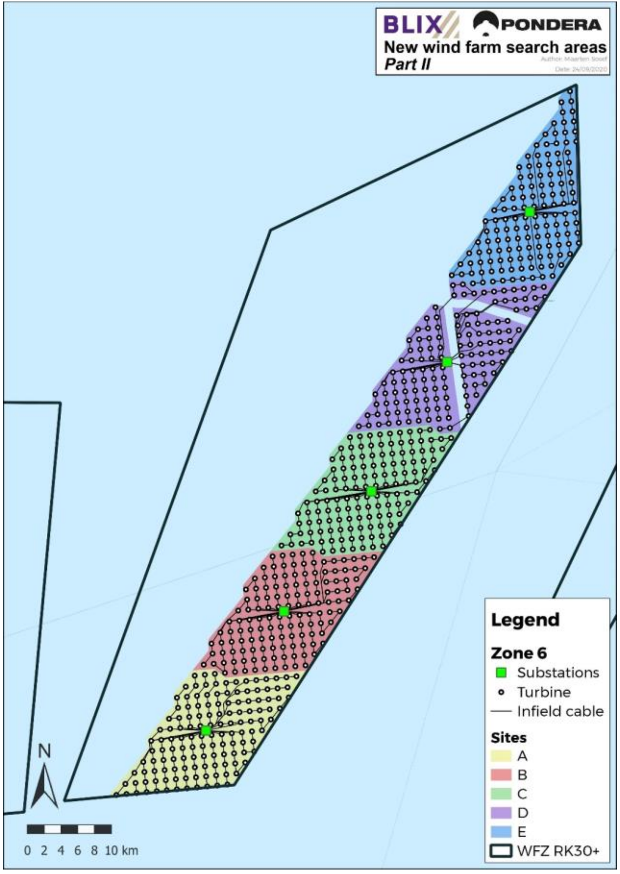

Figure 46: Layout Zone 6

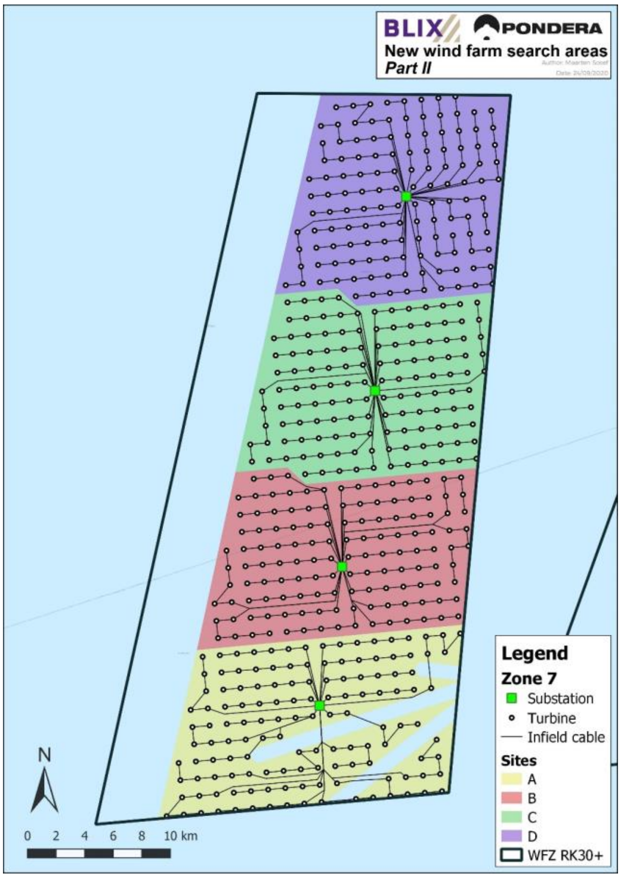

Figure 47: Layout Zone 7

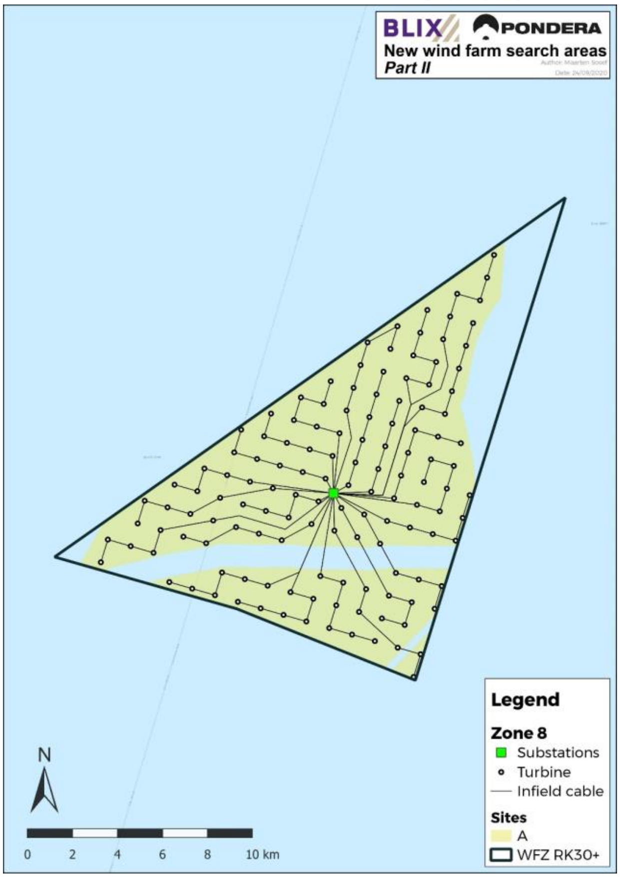

Figure 48: Layout Zone 8

**HVAC Wind farm zones**

The HVAC offshore wind farm zones are filled with a multitude of sites with a connection capacity of 750 MW from the boundary closest to shore, with the remaining part of the zones excluded from the design.

The wind farm zone layouts with HVAC connections are shown in Figure 49, Figure 50 and Figure 51.

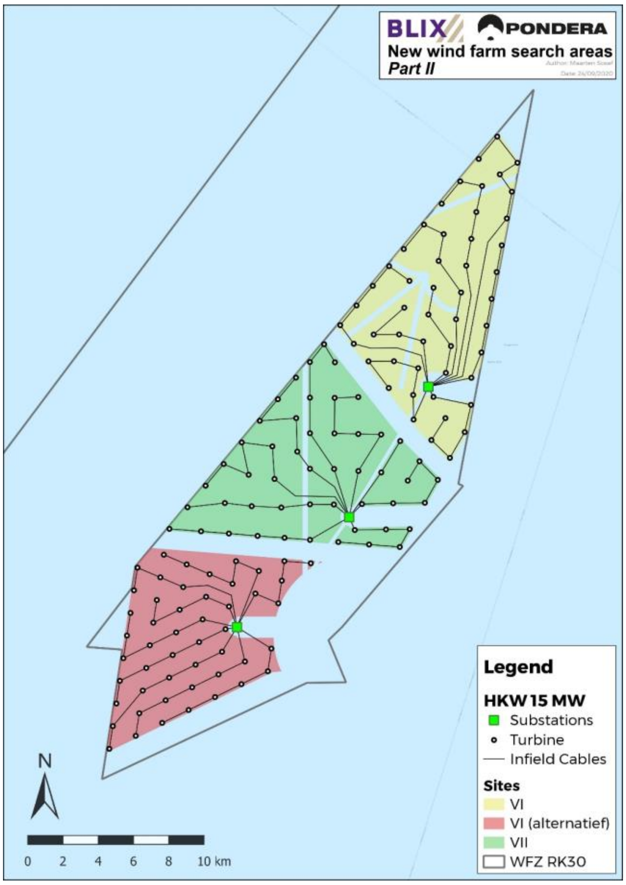

Figure 49: Layout Zone HKW

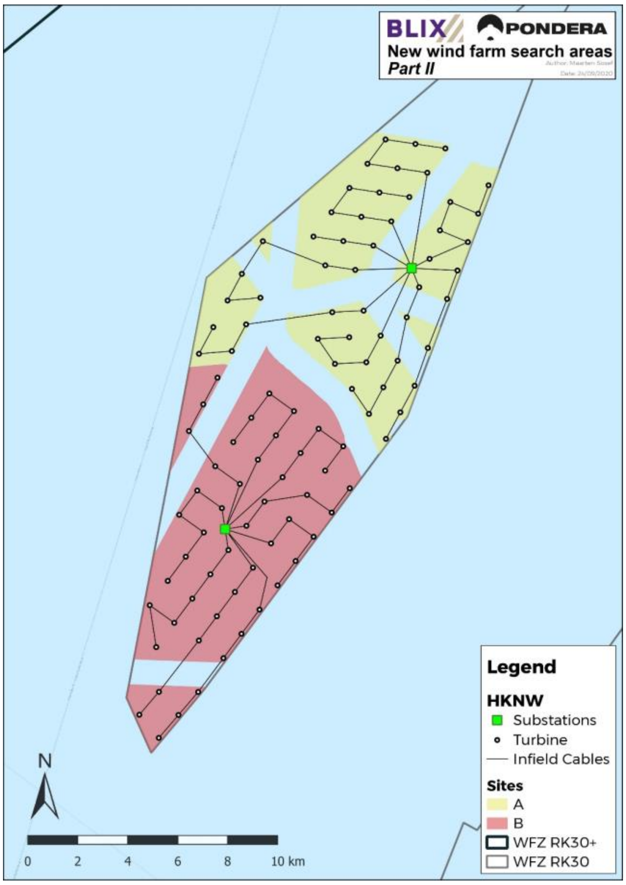

Figure 50: Layout Zone HKNW

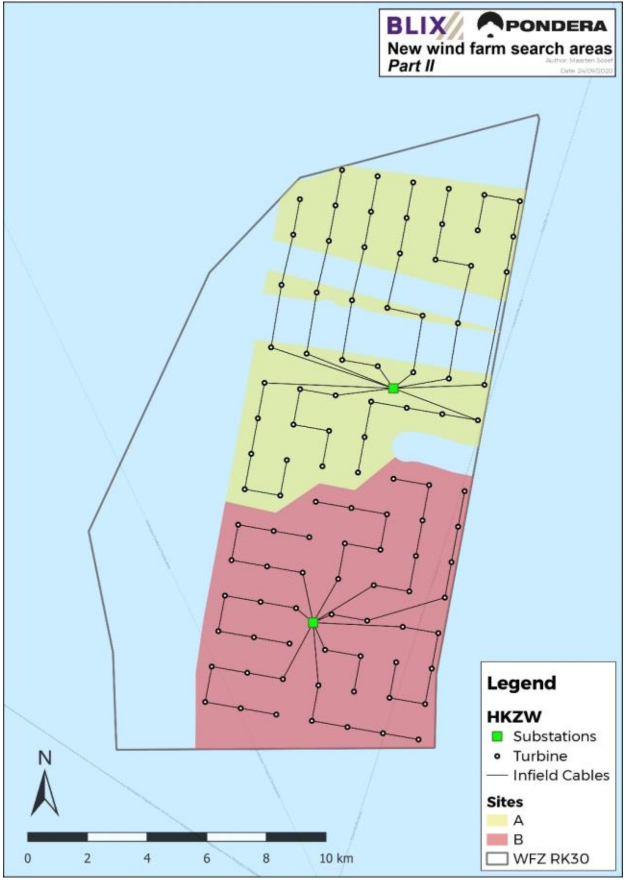

Figure 51: Layout Zone HKZW

# 10 YIELD ANALYSIS

## 10.1 Yield results

**HVDC Wind farm zones**

The HVDC zones IJV, IJVN and the wind farm zones in search areas 1 to 8 have been modelled and analysed. IJmuiden Ver serves as the reference for the other wind farm zones. The main characteristics and the results for each wind farm zone are shown in Table 18 (averages based on the wind farm sites).

The following findings are considered to be most significant:

- There is a 0.4 m/s wind speed difference between all wind farm zones. The highest annual mean wind speeds are found in the northernmost wind farm zones (5 to 7), located furthest away from the mainland. The wind speeds are lowest at the zones IJVN, 2 and 8, which are closest to the mainland.
- The difference in gross and net annual yield between the wind farm zones can simply be explained by the differences in sizes (and subsequently numbers of turbines) of the wind farm zones. The highest total net energy yield is found in wind farm zones 4 and 6 (43,32 and 44,032 GWh respectively) which both contain 804 wind turbines, while the highest average net energy yield per wind farm site is found for Zone 5 (mb) (9,144 GWh/yr).
- The differences in wake effects can be explained by the size, shape and orientation of the wind farm zone. Larger wind farm zones with many sites suffer from more severe wake effects than smaller wind farm zones. For example, wind farm zones 3 and 5 (mb) are relatively small and consist of only one site and therefore experience lower wake losses (10.2% and 11.1% respectively). Also, the shape and orientation of the wind farm zones, or more precisely the border length-to-area ratio in relation to the prevailing wind direction, influences the average wake effect. Wake losses are lower at wind farm zones that contain many wind turbines at the edge of the wind farm zone compared to the amount of wind turbines inside the wind farm zone. The wind turbines at the borders do not suffer from wake effects in certain wind directions, reducing the sites overall (wind sector-weighted) wake loss. For example, wind farm Zone 8 also has 1 wind farm site, similar to Zone 3 and 5, but as the shape of this site is less stretched (i.e. more compact) than the sites of Zones 3 and 5, higher wake effects are observed at the centre of the wind farm, thereby increasing the overall wake loss.
- Because of the lower wake losses and wind speed differences, the highest net yield per wind turbine is found in wind farm Zone 5 (71.14 GWh/WTG/year).

**Table 18: Wind farm layout and yield characteristics of HVDC wind farm zones and IJV**

| Wind farm zone | IJV | IJVN | 1 | 2 | 3 | 4 | 5 | 5 Clearway | 5 (mb) | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout** | | | | | | | | | | | | |
| **Area [km²]** | 374 | 280 | 665 | 625 | 294 | 1,184 | 538 | 391 | 344 | 2,189 | 1,028 | 154 |
| **Area filled [km²]** | 374 | 188 | 606 | 604 | 192 | 986 | 382 | 389 | 201 | 991 | 803 | 151 |
| **# of turbines** | 268 | 134 | 402 | 402 | 134 | 670 | 268 | 268 | 134 | 670 | 536 | 134 |
| **# wind farm sites** | 2 | 1 | 3 | 3 | 1 | 5 | 2 | 2 | 1 | 5 | 4 | 1 |
| **Minimal turbine spacing [x rotor diameter]** | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 4.8 |
| **Total infield cable length [km]** | 473 | 224 | 828 | 725 | 266 | 1,240 | 521 | 534 | 274 | 1,199 | 927 | 206 |
| **# of crossings** | 3 | 7 | 62 | 24 | 6 | 55 | 9 | 18 | - | 16 | 15 | 6 |
| **Substation distance to port (total) [km]** | 163 | 72 | 356 | 184 | 119 | 577 | 303 | 309 | 142 | 801 | 623 | 58 |
| **Substation distance to port (average per site) [km]** | 82 | 72 | 119 | 61 | 119 | 115 | 151 | 154 | 142 | 160 | 156 | 58 |
| **Foundation depth (average per WTG) [m]** | (28) | (27) | (28) | (27) | (37) | (30) | (39) | (39) | (44) | (47) | (44) | (26) |
| **Energy yield** | | | | | | | | | | | | |
| **Mean wind speed at hub height [m/s]** | 10.2 | 10.3 | 10.4 | 10.3 | 10.5 | 10.4 | 10.6 | 10.6 | 10.6 | 10.6 | 10.6 | 10.3 |
| **Gross annual yield (total) [GWh/y]** | 21,620 | 10,940 | 33,267 | 32,992 | 11,218 | 56,098 | 21,718 | 22,818 | 11,395 | 56,771 | 45,176 | 10,984 |
| **Gross annual yield (average per site) [GWh/y]** | 10,810 | 10,940 | 11,089 | 10,997 | 11,218 | 11,220 | 10,859 | 11,409 | 11,395 | 11,354 | 11,294 | 10,984 |
| **Wake losses [%]** | 13.1 | 0.6 | 11.8 | 12.8 | 10.2 | 14.3 | 13.1 | 11.1 | 10.0 | 12.6 | 13.6 | 12.9 |
| **IA Cable losses [%]** | 0.6 | 0.6 | 0.7 | 0.6 | 0.7 | 0.6 | 0.7 | 0.7 | 0.7 | 0.6 | 0.6 | 0.5 |
| **WTG non-availability [%]** | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| **WF Other losses [%]** | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| **Export cable losses [%]** | 0.7 | 0.7 | 0.6 | 0.5 | 0.7 | 0.4 | 0.5 | 0.5 | 0.7 | 0.8 | 1.0 | 0.5 |
| **GCS non-availabilities [%]** | 3.5 | 3.5 | 3.3 | 2.8 | 3.7 | 2.7 | 3.1 | 3.1 | 3.4 | 3.8 | 4.2 | 3.0 |
| **Net annual yield (total of the zone) [GWh/y]** | 16,740 | 8,567 | 26,188 | 25,875 | 8,950 | 43,325 | 17,969 | 18,178 | 9,144 | 44,032 | 34,451 | 8,594 |
| **Net annual yield (average per site) [GWh/y]** | 8,370 | 8,567 | 8,729 | 8,625 | 8,950 | 8,665 | 8,985 | 9,089 | 9,144 | 8,807 | 8,613 | 8,594 |
| **Net annual yield (average per WTG) [GWh/y]** | 62.46 | 63.93 | 65.14 | 64.37 | 66.79 | 64.66 | 67.05 | 67.83 | 68.24 | 65.72 | 64.28 | 64.13 |
| **Net annual yield (average per WTG) [GWh/y]** | 62.46 | 63.93 | 65.14 | 64.37 | 66.79 | 64.66 | 67.05 | 67.83 | 68.24 | 65.72 | 64.28 | 64.13 |

Note: The differences in net yield results for IJV, Zone 2 and Zone 3 compared to Table 13 of Part I are the logical result of taking into account the GCS of each zone and thus including the export cable losses and GCS non-availability losses.

## HVAC Wind farm zones

The wind farm areas HKW, HKNW and HKZW have been modelled and analysed. The reference is a wind farm layout of Hollandse Kust (west) with three wind farm sites using 15 MW turbines. The main characteristics and the results for each wind farm zone are shown in Table 19 (averages based on the wind farm sites).

Table 19: Wind farm layout and yield characteristics of HVAC wind farm zones

| Wind farm zone | HKW | HKNW | HKZW |
|---|---|---|---|
| **Layout** | | | |
| **Area [km$^2$]** | 246 | 134 | 182 |
| **Area filled [km$^2$]** | 246 | 124 | 133 |
| **# of turbines** | 150 | 100 | 100 |
| **# wind farm sites** | 3 | 2 | 2 |
| **Minimal turbine spacing [x rotor diameter]** | 5.1 | 5.5 | 5.5 |
| **Total infield cable length [km]** | 278 | 147 | 149 |
| **# of crossings** | 13 | 18 | 12 |
| **Substation distance to port (total) [km]** | 233 | 87 | 91 |
| **Substation distance to port (average per site) [km]** | 78 | 44 | 46 |
| **Foundation depth (average per WTG) [m]** | (27) | (26) | (25) |
| **Energy yield** | | | |
| **Mean wind speed at hub height [m/s]** | 10.3 | 10.2 | 10.2 |
| **Gross annual yield (total) [GWh/y]** | 12,219 | 8,122 | 7,944 |
| **Gross annual yield (average per site) [GWh/y]** | 4,073 | 4,061 | 3,972 |
| **Wake losses [%]** | 8.3 | 9.8 | 10.7 |
| **IA Cable losses [%]** | 0.62 | 0.50 | 0.53 |
| **WTG non-availability [%]** | 5.0 | 5.0 | 5.0 |
| **WF Other losses [%]** | 1.5 | 1.5 | 1.5 |
| **Export cable losses [%]** | 2.4 | 2.2 | 2.5 |
| **GCS non-availabilities [%]** | 0.9 | 0.8 | 0.9 |
| **Net annual yield (total of the zone) [GWh/y]** | 10,120 | 6,637 | 6,408 |
| **Net annual yield (average per site) [GWh/y]** | 3,373 | 3,318 | 3,203 |
| **Net annual yield (average per WTG) [GWh/y]** | 67.47 | 66.37 | 64.08 |
| **Net annual yield (average per WTG) [GWh/y]** | 67.47 | 66.37 | 64.08 |

The following findings are considered to be most significant:

- The difference between HKW and the wind farm zones HKNW and HKZW is that the HKW site boundaries are the result of an optimisation process performed during the 2020 HKW LCoE study [2]. Because HKNW and HKZW are in an earlier development stage , this optimisation process has not been applied for these sites yet. Therefore, the sites boundaries of HKNW and HKZW are determined in this study based on the wind farm layout assumptions of paragraph 3.5. Following this, the HKW layout is the only layout with deviating turbine spacing of 5.1 by 5.1 rotor diameters, whereas the sites of HKNW and HKZW are based on the same rectangular grid of 5.5 by 5.5 rotor diameters as applied bij the HVDC sites.
- The highest wake losses are found at HKZW due to the more rectangular shape, which results in higher wake effects in the centre. HKNW is more stretched out, which causes a reduction in wake losses relative to HKZW.
- Based on the KNW Atlas, a 0.3 m/s wind speed gradient is observed across all three wind farm zones. HKW is furthest away from the mainland and therefore experiences the highest annual mean wind speed.
- The higher annual mean wind speed, the lower wake losses and the optimized wind farm layout lead to HKW as the most productive HVAC wind farm zone (67.47 GWh/WTG/year). The energy yield of HKNW and HKZW is likely to increase after wind farm layout optimization.

## 10.2 Wake effects

### HVDC Wind farm zones

Figure 52 to Figure 63 show a series of plots in which the individual wake losses per wind turbine have been visualised. The wake losses have been expressed as percentages related to the gross energy yield. The legends in all figures have been normalised, i.e. the colours in all maps correspond to the same loss percentages.

The highest wake losses are generally found in the centre of wind farm zones. An exception is wind farm Zone 1, where the highest losses are found more towards the northeast of the zone. This is due to the shipping passage and the maintenance zones of existing infrastructure, which reduce the accumulation of wake effects of multiple rows, as seen from the southwest.

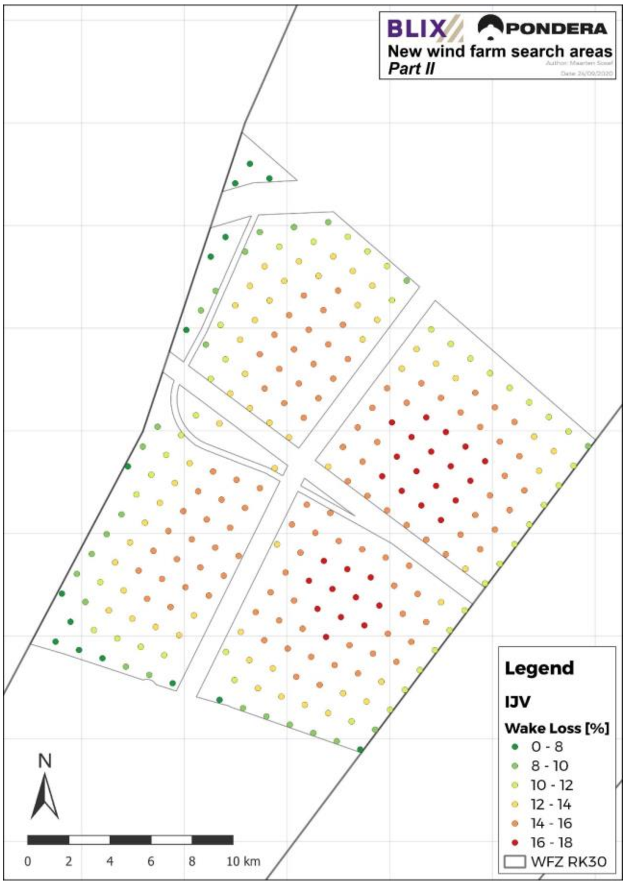

Figure 52: Wake losses Zone IJV

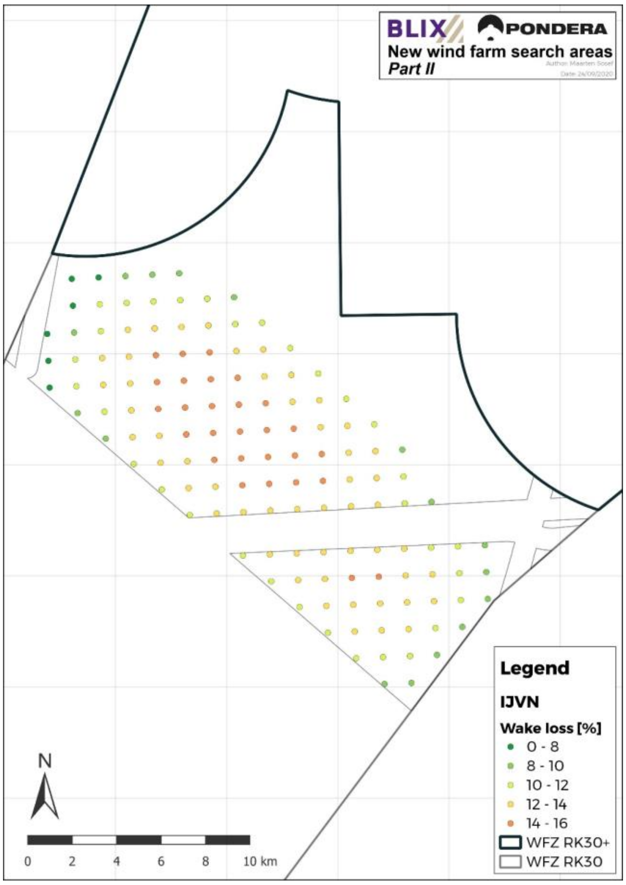

Figure 53: Wake losses Zone IJVN

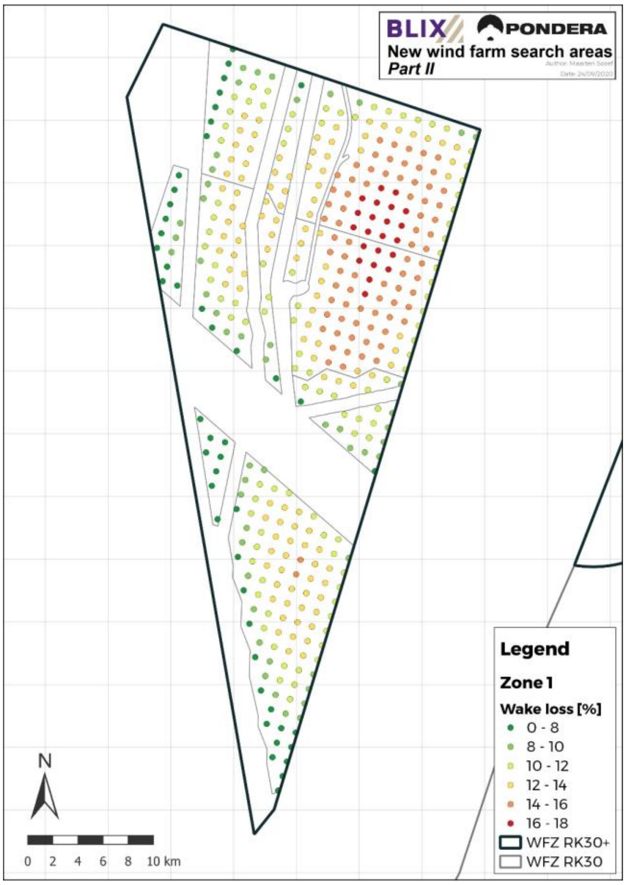

Figure 54: Wake losses Zone 1

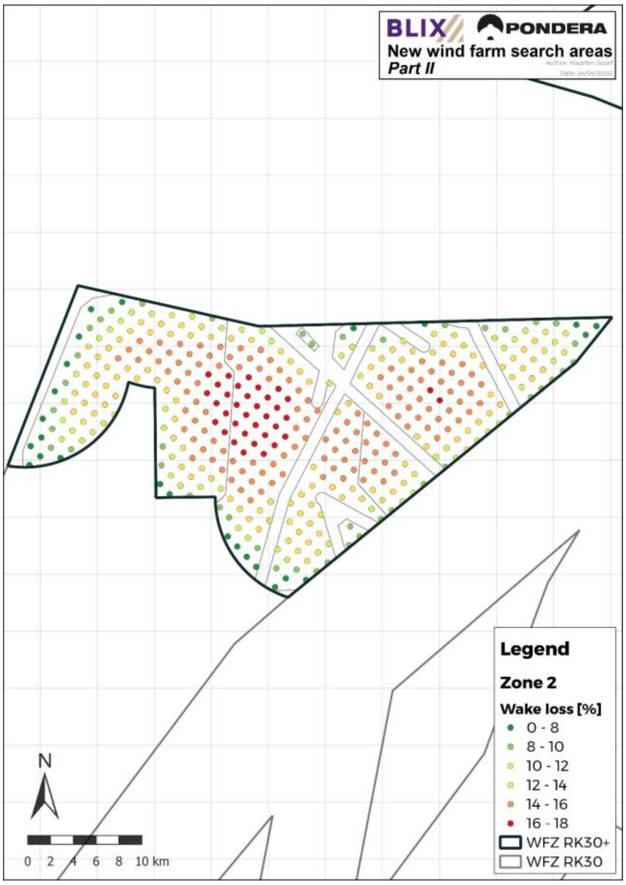

Figure 55: Wake losses Zone 2

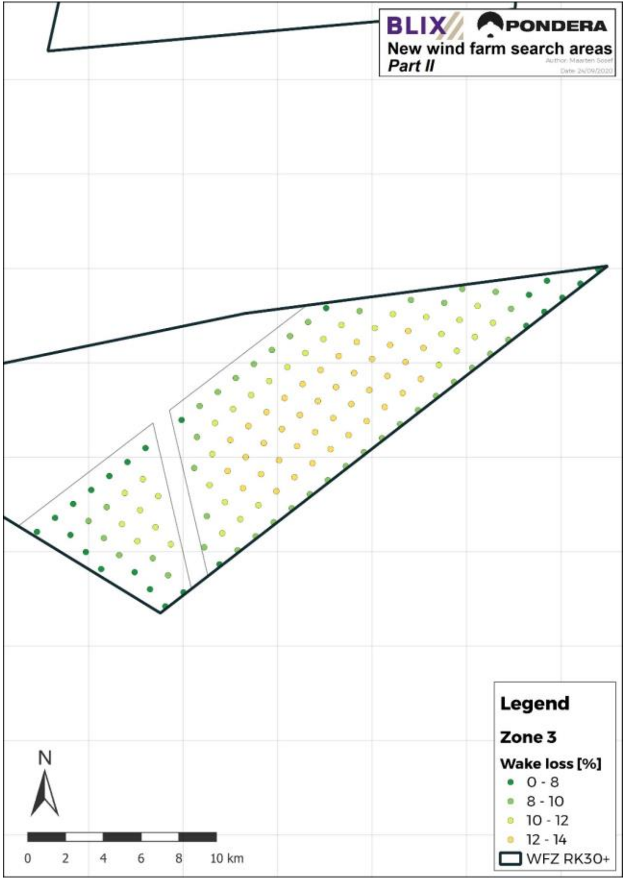

Figure 56: Wake losses Zone 3

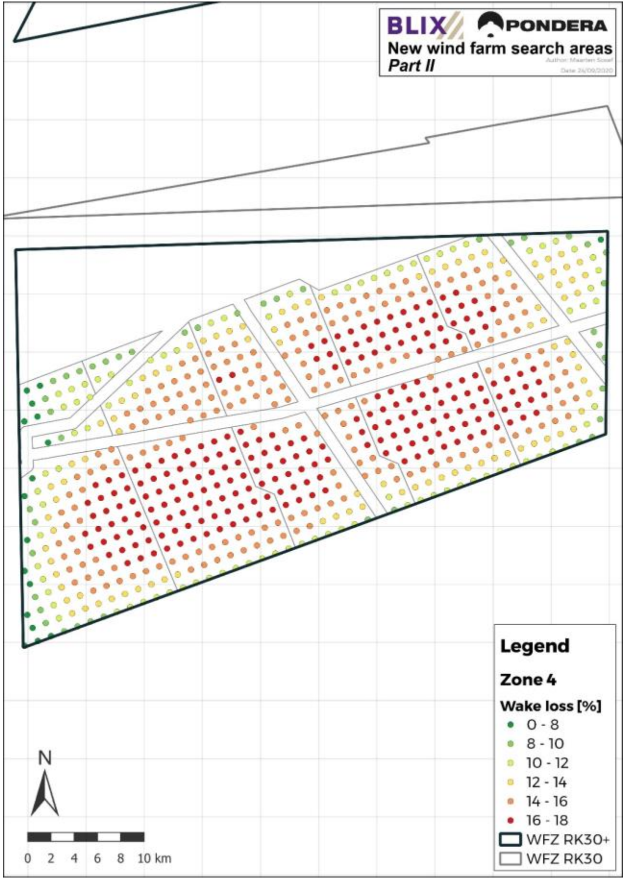

Figure 57: Wake losses Zone 4

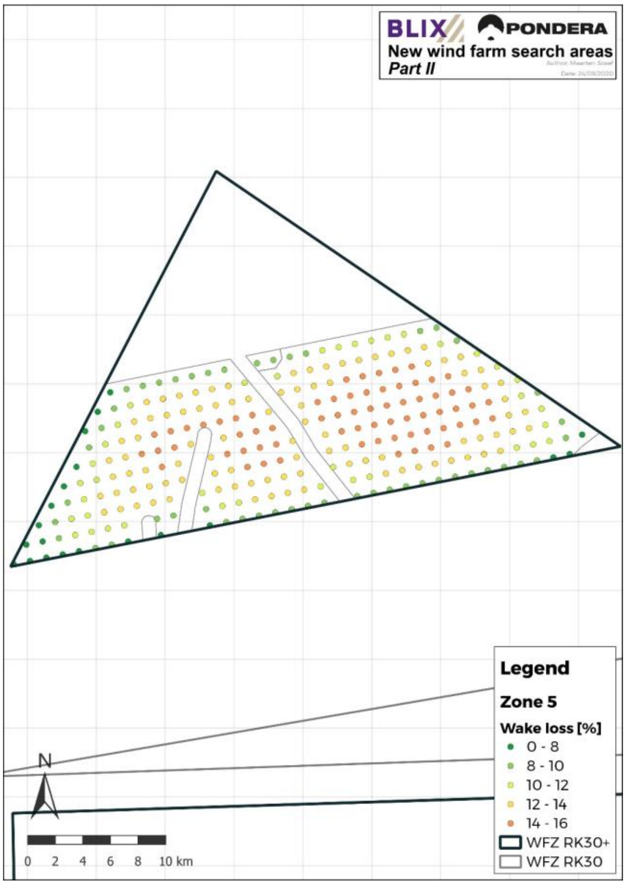

Figure 58: Wake losses Zone 5

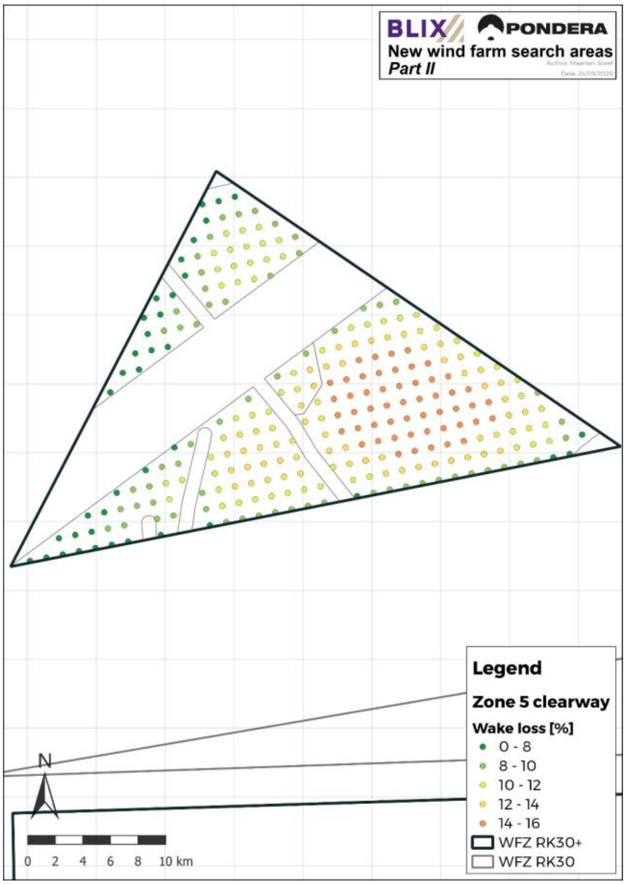

Figure 59: Wake losses Zone 5 clearway

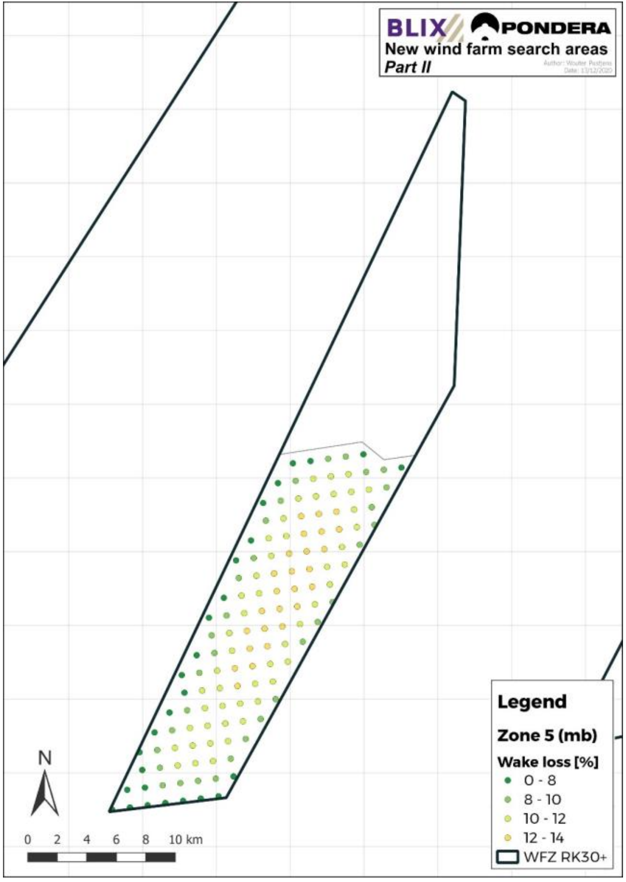

Figure 60: Wake losses Zone 5 (mb)

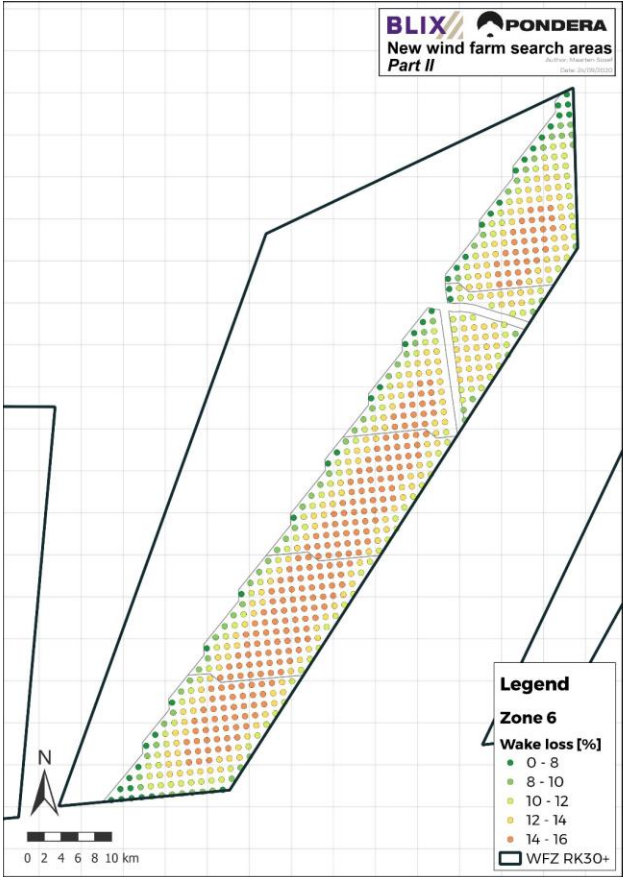

Figure 61: Wake losses Zone 6

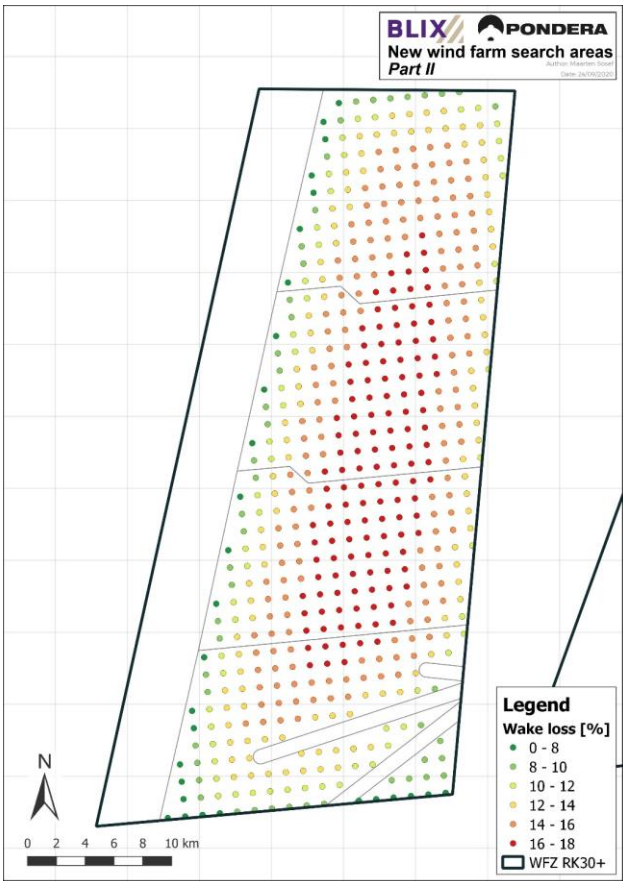

Figure 62: Wake losses Zone 7

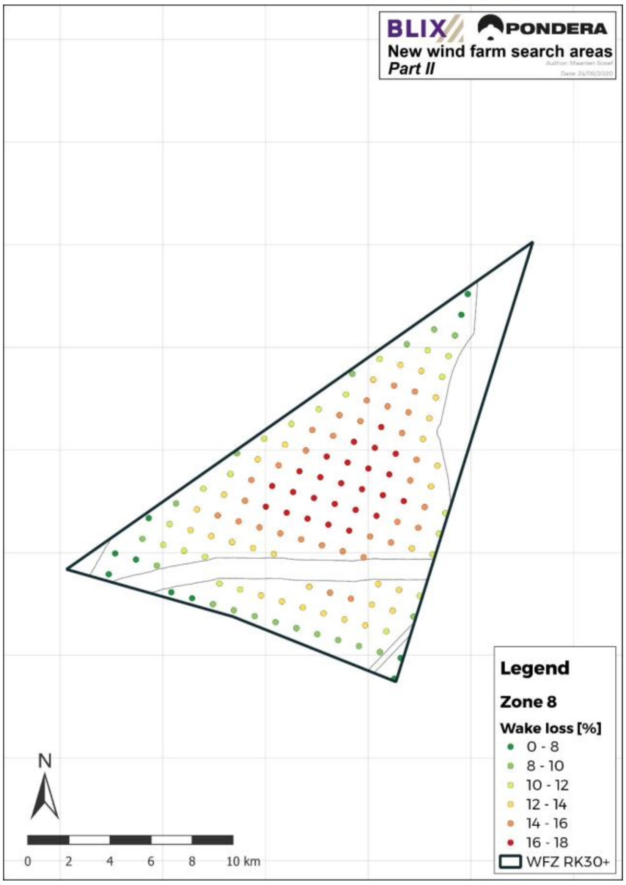

Figure 63: Wake losses Zone 8

### HVAC wind farm zones

Figure 64 through Figure 66 show a series of plots in which the individual wake losses per wind turbine have been visualised for all HVAC wind farm zones. In general, the wake losses are found to be lower than the HVDC wind farm zones. Wake losses are reduced due to the shape and orientation of the HVAC zone in the prevailing wind direction and due to the fixed grid in combination with the presence of a large number of maintenance zones, especially for HKNW.

Figure 64: Wake losses Zone HKW (reference)

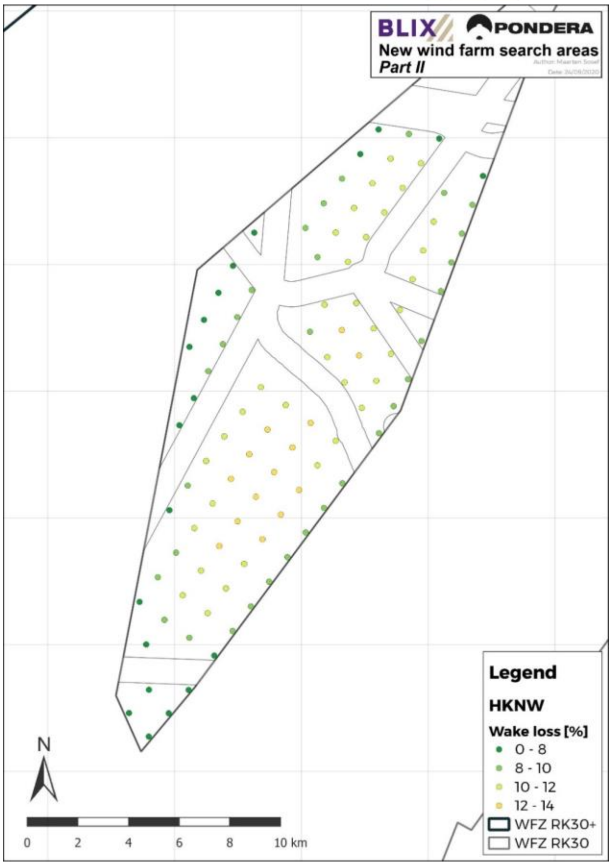

Figure 65: Wake losses Zone HKNW

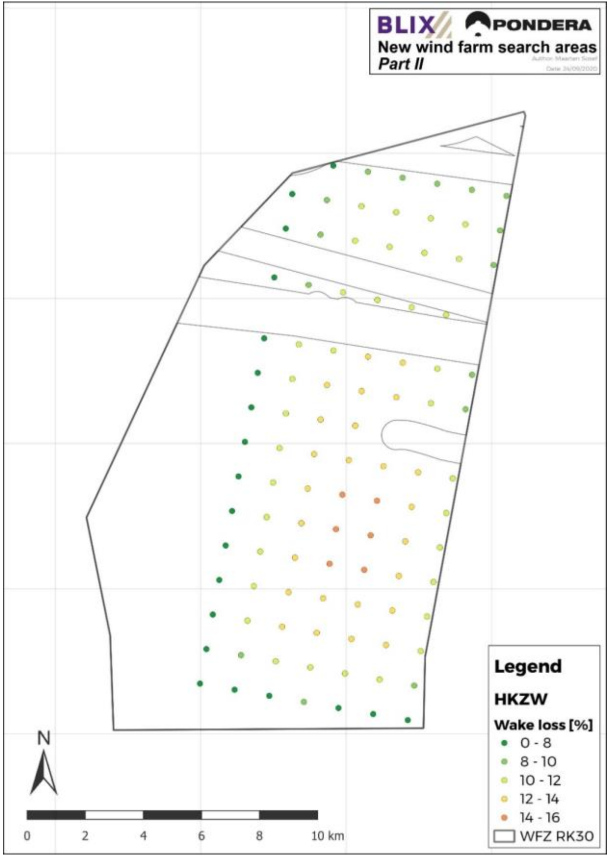

Figure 66: Wake losses Zone HKZW

A wake map of all wind farm zones is shown in Figure 67. Please take note that all wind farm zones have been modelled individually. This means that accumulation of wake effects from one wind farm zone to the other are disregarded in this analysis.

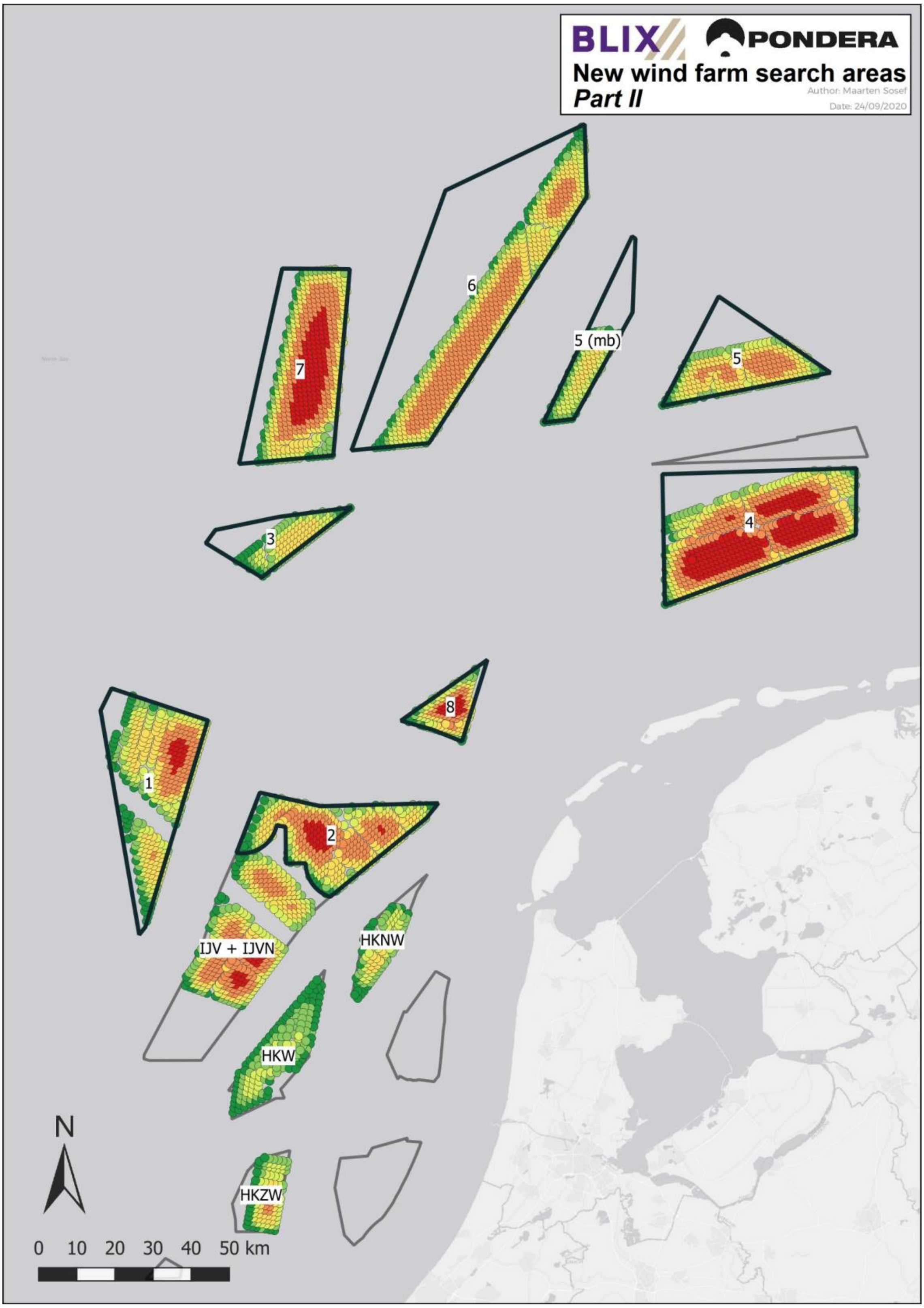

Figure 67: Wake losses of all wind farm zones in Part II

# 11 COMPARISON OF LEVELIZED COST OF ENERGY

For an in-depth comparison of the wind energy search areas, IJVN, HKNW and HKZW we investigated the overall LCoE, the LCoE of the Offshore Wind Farm (OWF) and the LCoE of the Grid Connection System (GCS) per site and compared the results per site and per wind farm zone with respectively the reference site IJmuiden Ver A and the reference zone IJmuiden Ver. In addition, the impact of the different yield and cost parameters on the LCoE differences is determined.

The following paragraphs describe the results of the LCoE comparison between wind farm zones of the overall LCoE (paragraph 11.1), OWF LCoE (paragraph 11.2) and GCS LCoE (paragraph 11.3). Finally, the last paragraph (paragraph 11.4) summarizes the results of the export cable landing area sensitivity analysis performed on the GCS LCoE of the wind farm sites.

The results of the LCoE comparison between wind farm sites of the overall LCoE, OWF LCoE and GCS LCoE can be found in Appendix B. These results can support a follow-up study for the further optimization of the search areas.

## 11.1 Relative overall LCoE impact

In this paragraph the relative “overall LCoE” (defined as the LCoE of the OWF plus the LCoE of the GCS) are described with a comparison between zones.

Please see paragraphs 11.2 and 11.3 for a comprehensive LCoE impact analysis of the yield and cost parameters.

**HVDC zones**

In Figure 68 and Table 20, the overall LCoE comparison results of the HVDC zones are shown compared to reference IJmuiden Ver.

The following main conclusions can be drawn on wind farm zone level for the HVDC zones:

- All HVDC zones have a net overall LCoE (OWF + GCS) lower than the reference IJmuiden Ver, except Zone 7. Due to the relatively high GCS and OWF costs, Zone 7 has an overall LCoE of 2.3% higher than IJmuiden Ver.
- Of the HVDC zones, Zones 2, 4 and 5, 5 clearway and 5(mb) have the lowest net overall LCoE due to the high (net) yield and low GCS costs.
- Differences in yield and GCS costs are dominant over differences in OWF costs.

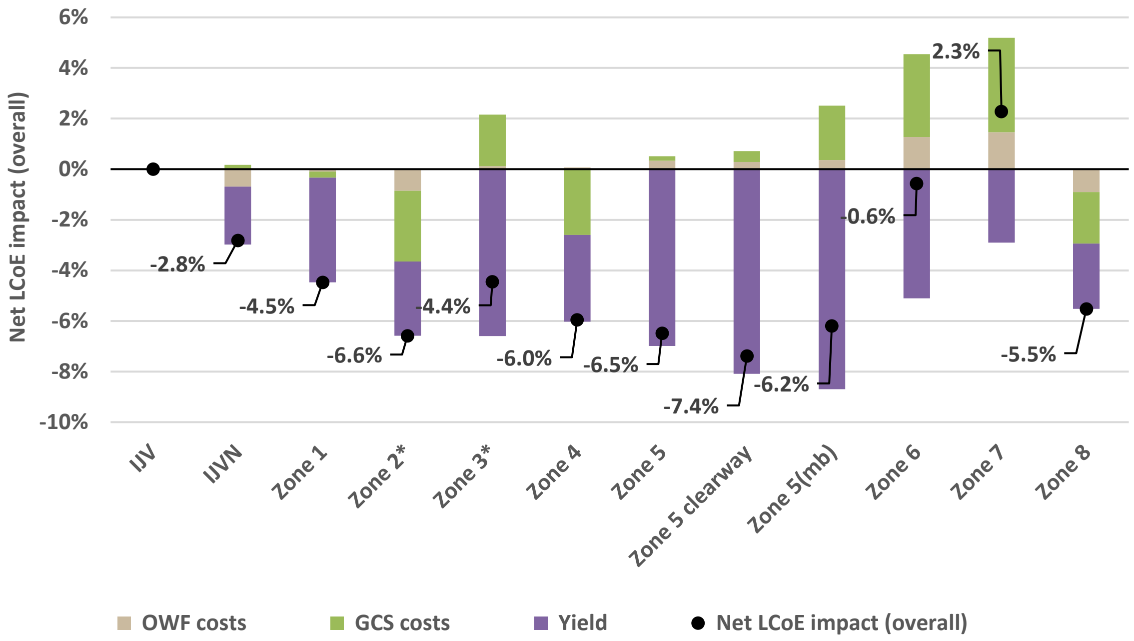

**Figure 68: Comparison of the overall LCoE of the HVDC wind farm zones and IJmuiden Ver**

**Table 20: Comparison of the overall LCoE of the HVDC wind farm zones and IJmuiden Ver**

| Zone | Net LCoE impact | OWF | GCS | Yield |
|---|---|---|---|---|
| **IJV** | - | - | - | - |
| **IJVN** | -2.8% | -0.7% | 0.2% | -2.3% |
| **Zone 1** | -4.5% | -0.1% | -0.2% | -4.1% |
| **Zone 2*** | -6.6% | -0.9% | -2.8% | -2.9% |
| **Zone 3*** | -4.4% | 0.1% | 2.0% | -6.6% |
| **Zone 4** | -6.0% | 0.1% | -2.6% | -3.4% |
| **Zone 5** | -6.5% | 0.3% | 0.2% | -7.0% |
| **Zone 5 clearway** | -7.4% | 0.3% | 0.4% | -8.1% |
| **Zone 5 (mb)** | -6.2% | 0.4% | 2.2% | -8.7% |
| **Zone 6** | -0.6% | 1.3% | 3.3% | -5.1% |
| **Zone 7** | 2.3% | 1.5% | 3.7% | -2.9% |
| **Zone 8** | -5.5% | -0.9% | -2.0% | -2.6% |

*Size, location and orientation of this zone is not adapted after Part I analysis.

### HVAC zones

In Figure 69 and Table 21, the overall LCoE comparison results of the HVAC zones are shown compared to reference IJmuiden Ver.

The following main conclusions can be drawn on wind farm zone level for the HVAC zones:

- All HVAC zones have a net overall LCoE (OWF + GCS) significantly lower than the reference HVDC zone IJmuiden Ver due to their relatively low GCS costs of a HVAC GCS compared to a HVDC GCS.
- HKNW and HKW have a similar net overall LCoE which is -16,1% lower than IJmuiden Ver.
- The lower yield of HKZW results in a net overall LCoE higher than HKW and HKNW, but with -12,7% still significantly lower than IJV.
- Differences in yield are greatest, differences in OWF and GCS costs are small to negligible.

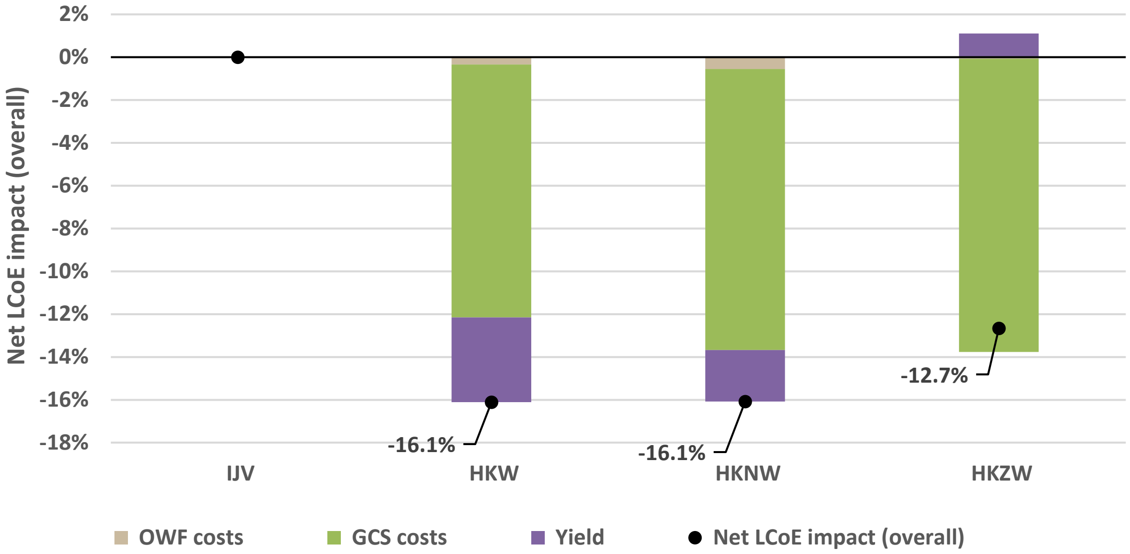

Figure 69: Comparison of the overall LCoE of the HVAC wind farm zones and IJmuiden Ver

Table 21: Comparison of the overall LCoE of the HVAC wind farm zones and IJmuiden Ver

| Zone | Net LCoE impact | OWF | GCS | Yield |
|---|---|---|---|---|
| **IJV** | - | - | - | - |
| **HKW** | -16.1% | -0.3% | -11.8% | -4.0% |
| **HKNW** | -16.1% | -0.6% | -13.1% | -2.4% |
| **HKZW** | -12.7% | -0.1% | -13.7% | 1.1% |

## 11.2 Relative LCoE impact of the Offshore Wind Farm (OWF)

In this paragraph the relative OWF LCoE results are described with a comparison between zones.

### HVDC zones

In Figure 70 and Table 22 the OWF LCoE comparison results of the HVDC zones are shown compared to reference IJmuiden Ver.

The following main conclusions can be drawn on wind farm zone level for the HVDC zones:

- All HVDC wind farm zones have a net OWF LCoE lower than the reference zone IJmuiden Ver.
- Zone 3, 5, 5 clearway and 5 (mb) have the lowest net OWF LCoE in the range of -4.1% and -5.8% compared to IJmuiden Ver. Zone 4 and 7 have the highest net OWF LCoE, respectively -1.3% and -0.9% compared to IJV.
- The differences in wake losses are the largest due to big differences in orientation of the zones (towards the prevailing wind direction) and shape of the zones.
- The differences in cost of foundation are a result from the variation in water depth and the large differences in gross yield are caused by differences in wind climate.
- The impact of differences in WTG Capex and Opex, IA cable costs and IA cable losses is limited.

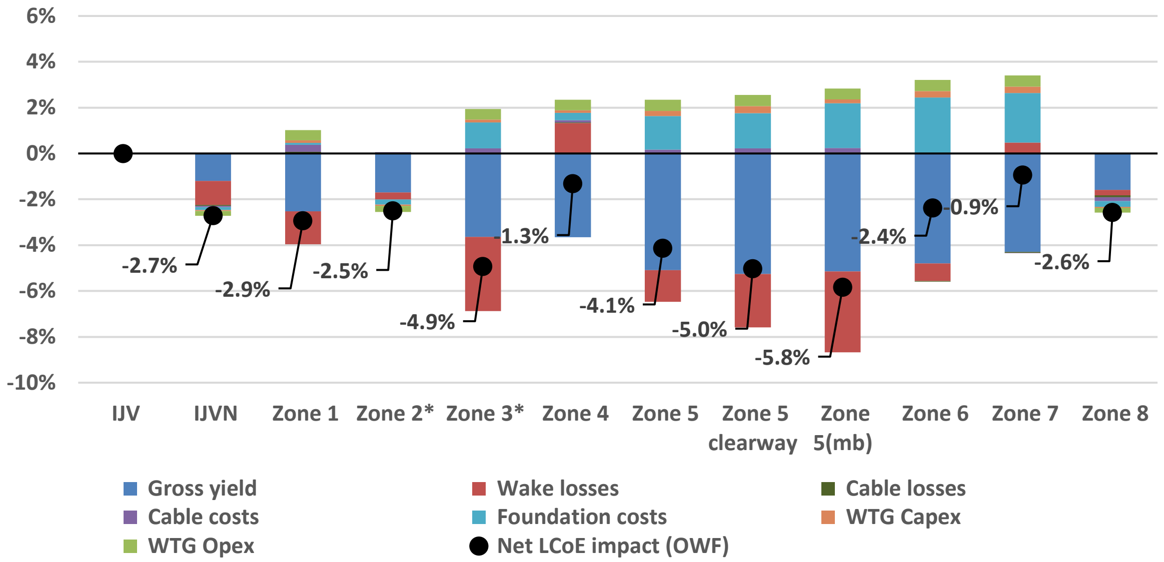

**Figure 70: Comparison of the OWF LCoE of the HVDC wind farm zones and IJmuiden Ver**

**Table 22: Comparison of the OWF LCoE of the HVDC wind farm zones and IJmuiden Ver**

| Zone | Net LCoE impact (OWF) | Cable costs | Foundation costs | WTG Capex | WTG Opex | Gross yield | Wake losses | Cable losses |
|---|---|---|---|---|---|---|---|---|
| **IJV** | - | - | - | - | - | - | - | - |
| **IJVN** | -2.7% | -0.1% | -0.1% | -0.0% | -0.2% | -1.2% | -1.0% | -0.0% |
| **Zone 1** | -2.9% | 0.3% | 0.1% | 0.1% | 0.5% | -2.5% | -1.4% | 0.1% |
| **Zone 2*** | -2.5% | 0.1% | -0.2% | -0.1% | -0.3% | -1.7% | -0.3% | 0.0% |
| **Zone 3*** | -4.9% | 0.2% | 1.1% | 0.1% | 0.5% | -3.6% | -3.2% | 0.0% |
| **Zone 4** | -1.3% | 0.1% | 0.3% | 0.1% | 0.5% | -3.7% | 1.3% | 0.0% |
| **Zone 5** | -4.1% | 0.1% | 1.5% | 0.2% | 0.5% | -5.1% | -1.4% | 0.0% |
| **Zone 5 clearway** | -5.0% | 0.2% | 1.5% | 0.3% | 0.5% | -5.3% | -2.3% | 0.0% |
| **Zone 5 (mb)** | -5.8% | 0.2% | 2.0% | 0.2% | 0.5% | -5.1% | -3.5% | 0.0% |
| **Zone 6** | -2.4% | 0.0% | 2.4% | 0.3% | 0.5% | -4.8% | -0.8% | -0.0% |
| **Zone 7** | -0.9% | -0.0% | 2.2% | 0.3% | 0.5% | -4.3% | 0.5% | -0.0% |
| **Zone 8** | -2.6% | -0.2% | -0.3% | -0.0% | -0.2% | -1.6% | -0.2% | -0.1% |

*Size, location and orientation of this zone is not adapted after Part I analysis.

### HVAC zones

In Figure 71 and Table 23 the OWF LCoE comparison results of the HVAC zones are shown compared to reference IJmuiden Ver.

The following main conclusions can be drawn on wind farm zone level for the HVAC zones:

- The HVAC zone HKNW has a -1.5% lower net OWF LCoE, while HKZW has a 1.6% higher net OWF LCoE than IJmuiden Ver. This difference between the two HVAC zones is mainly caused by the differences in gross yield and wake losses.
- The HVAC zones experience less wake losses than IJV due to their favourable shape and orientation with respect to the prevailing wind direction.
- The parameter “wind farm size costs” represents the relative high costs for the 700 MW HVAC wind farms compared to the 2 GW HVDC wind farms of IJV, due to economies of scale.

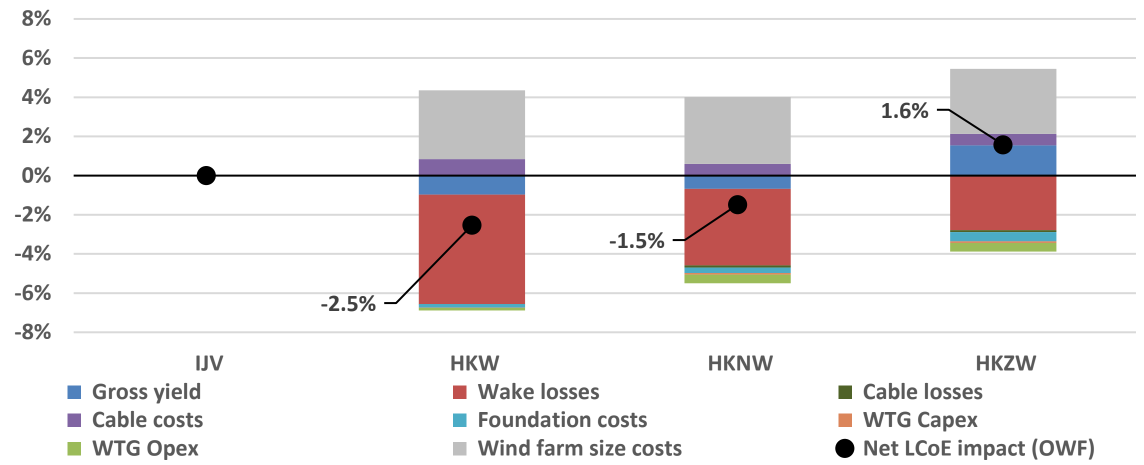

**Figure 71: Comparison of the OWF LCoE of the HVAC wind farm zones and IJmuiden Ver**

**Table 23: Comparison of the OWF LCoE of the HVAC wind farm zones and IJmuiden Ver**

| Zone | Net LCoE impact (OWF) | Cable costs | Foundation costs | WTG Capex | WTG Opex | Wind farm size costs | Gross yield | Wake losses | Cable losses |
|---|---|---|---|---|---|---|---|---|---|
| **IJV** | - | - | - | - | - | - | - | - | - |
| **HKW** | -2.5% | 0.8% | -0.2% | -0.0% | -0.1% | 3.5% | -1.0% | -5.6% | -0.0% |
| **HKNW** | -1.5% | 0.6% | -0.3% | -0.1% | -0.4% | 3.4% | -0.7% | -3.9% | -0.1% |
| **HKZW** | 1.6% | 0.6% | -0.5% | -0.1% | -0.4% | 3.3% | 1.6% | -2.8% | -0.1% |

## 11.3 Relative LCoE impact of the Grid Connection System (GCS)

In this paragraph the relative LCoE results of the GCS are described with a comparison between zones.

### HVDC zones

In Figure 72 and Table 24 the GCS LCoE comparison results of the HVDC zones are shown compared to reference IJmuiden Ver.

The following main conclusions can be drawn on wind farm zone level for the HVDC zones:

- The HVDC zones 1, 2, 4, 5, 5 clearway, 5 (mb) and 8 have a substantially lower net GCS LCoE (in the range between -3.6% and -14.5%) than the reference IJmuiden Ver, while Zone 3 has a comparable net LCoE (-0.9%) and the zones 6 and 7 a significantly higher net GCS LCoE than IJV (+2.9% and +6.4% respectively).
- The differences in net LCoE compared to IJV can mainly be explained by large variations in the export cable costs due to large differences in the length of the export cables (corresponding to the distance of the offshore substations to the onshore substation at the landing area multiplied by a landing area specific factor to account for obstacles and soil conditions in the optimal routing).
- The LCoE impact of variations in the other costs, such as surveying (incl. UXO), project management, insurance and Devex, and O&M costs are also considerable (up to +/- 2.4%), while the LCoE impact of variation in the platform costs, export cable losses and GCS non-availabilities are small (less than +/- 1.0%).

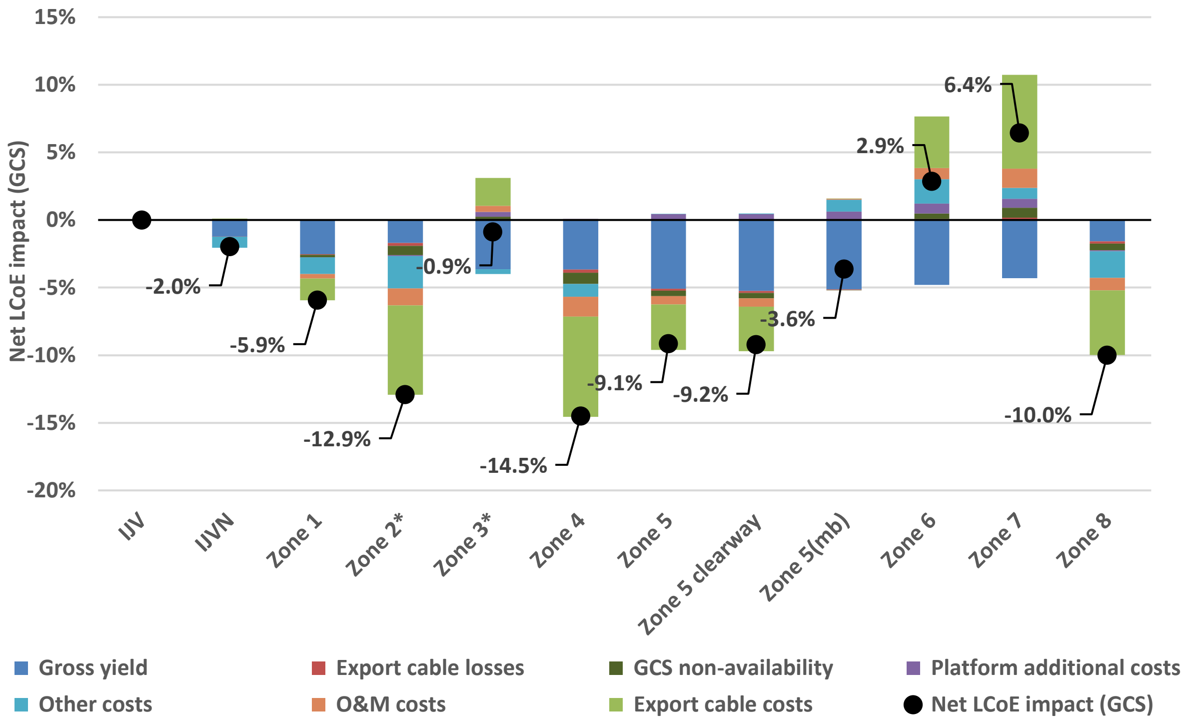

**Figure 72: Comparison of the GCS LCoE of the HVDC wind farm zones and IJmuiden Ver**

**Table 24: Comparison of the GCS LCoE of the HVDC wind farm zones and IJmuiden Ver**

| Zone | Net LCoE impact (GCS) | Platform costs | Other costs | O&M costs | Export cable costs | Gross yield | Export cable losses | GCS non-availability |
|---|---|---|---|---|---|---|---|---|
| **IJV** | - | - | - | - | - | - | - | - |
| **IJVN** | -2.0% | -0.0% | -0.8% | 0.0% | 0.1% | -1.2% | -0.0% | 0.0% |
| **Zone 1** | -5.9% | -0.0% | -1.2% | -0.3% | -1.6% | -2.5% | -0.1% | -0.2% |
| **Zone 2*** | -12.9% | -0.1% | -2.4% | -1.3% | -6.6% | -1.7% | -0.2% | -0.7% |
| **Zone 3*** | -0.9% | 0.4% | -0.3% | 0.4% | 2.1% | -3.6% | 0.0% | 0.2% |
| **Zone 4** | -14.5% | 0.1% | -1.0% | -1.5% | -7.4% | -3.7% | -0.2% | -0.8% |
| **Zone 5** | -9.1% | 0.4% | 0.0% | -0.6% | -3.4% | -5.1% | -0.1% | -0.4% |
| **Zone 5 clearway** | -9.2% | 0.4% | 0.0% | -0.6% | -3.3% | -5.3% | -0.1% | -0.4% |
| **Zone 5 (mb)** | -3.6% | 0.6% | 0.9% | 0.1% | 0.0% | -5.1% | -0.0% | -0.0% |
| **Zone 6** | 2.9% | 0.7% | 1.8% | 0.8% | 3.8% | -4.8% | 0.1% | 0.4% |
| **Zone 7** | 6.4% | 0.7% | 0.8% | 1.4% | 6.9% | -4.3% | 0.2% | 0.7% |
| **Zone 8** | -10.0% | -0.1% | -2.0% | -0.9% | -4.8% | -1.6% | -0.2% | -0.5% |

*Size, location and orientation of this zone is not adapted after Part I analysis.

### HVAC zones

In Figure 73 and Table 25 the GCS LCoE comparison results of the HVAC zones are shown compared to reference IJmuiden Ver.

The following main conclusion can be drawn on wind farm zone level for the HVAC zones:

- The HVAC zones HKNW, HKZW and HKW have substantially lower net GCS LCoE than reference IJV due to the significantly lower "transmission type costs" which represent the difference in costs between HVAC and HVDC systems (see also paragraph 3.3).

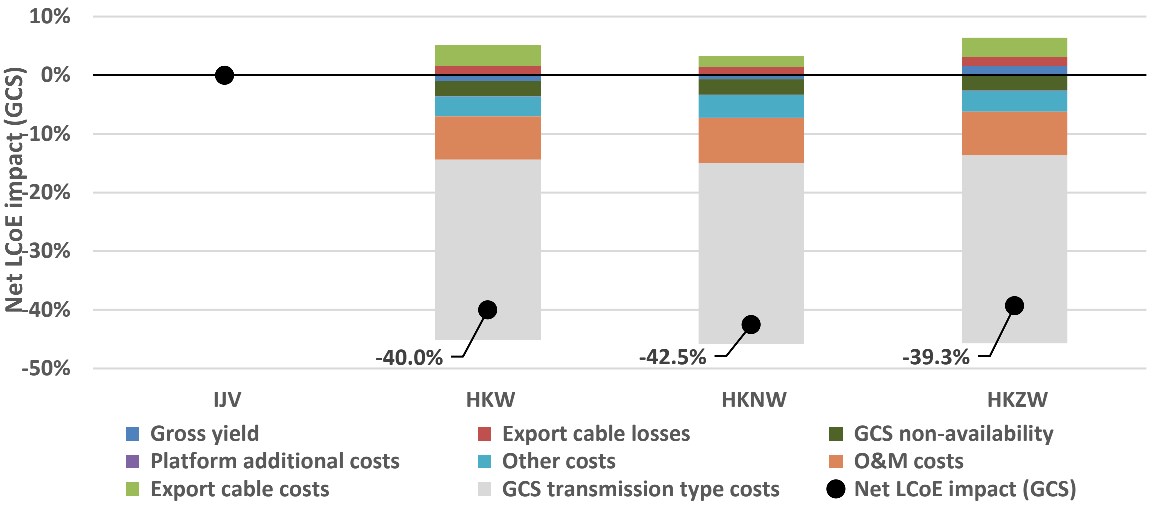

Figure 73: Comparison of the GCS LCoE of the HVAC wind farm zones and IJmuiden Ver

Table 25: Comparison of the GCS LCoE of the HVAC wind farm zones and IJmuiden Ver

| Zone | Net LCoE impact (GCS) | GCS transmission type costs | Platform additional costs | Other costs | O&M costs | Export cable costs | Gross yield | Export cable losses | GCS non-availability |
|---|---|---|---|---|---|---|---|---|---|
| **IJV** | - | - | - | - | - | - | - | - | - |
| **HKW** | -40.0% | -30.7% | -0.1% | -3.4% | -7.4% | 3.6% | -1.0% | 1.5% | -2.6% |
| **HKNW** | -42.5% | -30.9% | -0.1% | -3.8% | -7.7% | 1.9% | -0.7% | 1.4% | -2.6% |
| **HKZW** | -39.3% | -32.0% | -0.1% | -3.5% | -7.5% | 3.3% | 1.6% | 1.6% | -2.6% |

## 11.4 Landing area sensitivity of the GCS LCoE results

Table 26 shows the distance to the landing site per wind farm zone and the selected base case based on the shortest distance (for further explanation please see paragraph 3.3.1). Table 27 shows the relative LCoE of the grid connection compared to IJV A for the various landing sites.

The following main conclusions can be drawn with respect to the sensitivity of the GCS LCoE results by varying the export cable landing area of the HVDC sites:

- The alternative export cable landing areas Rijnmondgebied and Zeeland/West-Brabant for the sites of Zone 1, 2 and 3 result in worse LCoE results (+10% to +15%) than the base assumption of connecting to Noordzeekanaalgebied, due to longer cable lengths .
- For Zone 4 no alternative landing area is analysed.
- The alternative Noordzeekanaalgebied landing area for the sites of Zone 5, 5 clearway and 5 (mb) results in worse LCoE results (up to +10%) than the base assumption of connecting these sites to Eemshaven-Delfzijl.
- The largest increase up to +30% of the GCS LCoE difference with IJV can be seen for the Zone 6, Zone 7 and 8 sites when selecting the Rijnmondgebied or Zeeland/West-Brabant export cable landing area instead of Noordzeekanaalgebied or Eemshaven-Delfzijl.

**Figure 74: Overview of the offshore wind energy search areas (studied in Part II)**

**Table 26: Distances from the offshore substation of the wind farm sites to the landing areas**

| Site | DC/AC | Base Case | Distances (km) | | | |
|---|---|---|---|---|---|---|
| | | | NZK | RNM | Z/W | E-D |
| **IJV A** | DC | Z/W | - | - | 165.2 | - |
| **IJV B** | DC | RNM | 103.2 | 119.1 | 154.7 | - |
| **Zone 1 A** | DC | NZK | 135.6 | 156.9 | 191.5 | - |
| **Zone 1 B** | DC | NZK | 147.3 | 173.8 | 209.2 | - |
| **Zone 1 C** | DC | NZK | 152.2 | 181.8 | 217.7 | - |
| **Zone 2 A** | DC | NZK | 113.9 | 148.2 | 186.8 | - |
| **Zone 2 B** | DC | NZK | 100.3 | 138.0 | 177.9 | - |
| **Zone 2 C** | DC | NZK | 97.8 | 141.4 | 182.1 | - |
| **Zone 3 A** | DC | NZK | 175.3 | 219.1 | 257.8 | - |
| **Zone 4 A** | DC | E-D | - | - | - | 102.5 |
| **Zone 4 B** | DC | E-D | - | - | - | 96.4 |
| **Zone 4 C** | DC | E-D | - | - | - | 90.3 |
| **Zone 4 D** | DC | E-D | - | - | - | 85.6 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Zone 4 E** | DC | E-D | - | - | - | 82.3 |
| **Zone 5 A** | DC | E-D | 204.2 | - | - | 127.9 |
| **Zone 5 B** | DC | E-D | 212.5 | - | - | 121.0 |
| **Zone 5 clearway A** | DC | E-D | 209.5 | - | - | 129.0 |
| **Zone 5 clearway B** | DC | E-D | 213.0 | - | - | 120.6 |
| **Zone 5 (mb) A** | DC | E-D | 203.0 | - | - | 152.9 |
| **Zone 6 A** | DC | E-D | 195.6 | 247.5 | 287.2 | 182.3 |
| **Zone 6 B** | DC | E-D | 207.9 | 261.4 | 301.3 | 181.6 |
| **Zone 6 C** | DC | E-D | 220.8 | 275.9 | 315.8 | 181.7 |
| **Zone 6 D** | DC | E-D | 235.5 | 291.7 | 331.6 | 185.2 |
| **Zone 6 E** | DC | E-D | 253.1 | 310.3 | 350.2 | 191.8 |
| **Zone 7 A** | DC | NZK | 200.9 | 247.2 | 286.0 | 208.4 |
| **Zone 7 B** | DC | NZK | 209.5 | 256.6 | 295.3 | 211.1 |
| **Zone 7 C** | DC | NZK | 220.4 | 268.4 | 307.2 | 215.0 |
| **Zone 7 D** | DC | NZK | 232.8 | 281.6 | 320.4 | 220.0 |
| **Zone 8 A** | DC | NZK | 119.3 | 170.8 | 211.6 | - |

Table 27: Relative GCS LCoE impact of the wind farm sites compared to IJmuiden Ver A for different landing areas

| Site | DC/AC | | Relative LCoE compared to ref IJV A | | | |
|---|---|---|---|---|---|---|
| | | Base case | NZK | RNM | Z/W | E-D |
| **IJV A** | DC | 0% | | | 0% | |
| **IJV B** | DC | -8% | -15% | -8% | -2% | |
| **Zone 1 A** | DC | -11% | -11% | -3% | 2% | |
| **Zone 1 B** | DC | -10% | -10% | 0% | 5% | |
| **Zone 1 C** | DC | -9% | -9% | 2% | 7% | |
| **Zone 2 A** | DC | -15% | -15% | -5% | 1% | |
| **Zone 2 B** | DC | -18% | -18% | -7% | -1% | |
| **Zone 2 C** | DC | -18% | -18% | -6% | 1% | |
| **Zone 3 A** | DC | -5% | -5% | 10% | 14% | |
| **Zone 4 A** | DC | -16% | | | | -16% |
| **Zone 4 B** | DC | -17% | | | | -17% |
| **Zone 4 C** | DC | -19% | | | | -19% |
| **Zone 4 D** | DC | -20% | | | | -20% |
| **Zone 4 E** | DC | -21% | | | | -21% |
| **Zone 5 A** | DC | -12% | -2% | | | -12% |
| **Zone 5 B** | DC | -14% | -1% | | | -14% |
| **Zone 5 clearway A** | DC | -12% | -1% | | | -12% |
| **Zone 5 clearway B** | DC | -14% | -1% | | | -14% |
| **Zone 5 (mb) A** | DC | -8% | -2% | | | -8% |
| **Zone 6 A** | DC | 0% | -1% | 16% | 20% | 0% |
| **Zone 6 B** | DC | -1% | 1% | 19% | 23% | -1% |
| **Zone 6 C** | DC | -2% | 2% | 20% | 23% | -2% |
| **Zone 6 D** | DC | -2% | 4% | 22% | 26% | -2% |
| **Zone 6 E** | DC | -1% | 7% | 26% | 29% | -1% |
| **Zone 7 A** | DC | 0% | 0% | 16% | 20% | 4% |
| **Zone 7 B** | DC | 1% | 1% | 17% | 21% | 4% |
| **Zone 7 C** | DC | 3% | 3% | 20% | 23% | 5% |
| **Zone 7 D** | DC | 5% | 5% | 22% | 25% | 6% |
| **Zone 8 A** | DC | -14% | -14% | 0% | 6% | |

# 12 DISCUSSION

## 12.1 Limitations of current approach

The current study is based on a schematisation of reality. 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 or removed). 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 present approach is deemed suitable for the purpose of this study, which is to compare relative differences between zones and sites.

Two different turbine grid orientation methodologies were used for Part I and Part II and via a sensitivity analysis on IJmuiden Ver (noord) it was concluded that the impact of a southwest or south oriented grid orientation was limited. The conclusions of the other zones can be slightly different when using a different orientation of the turbine grid.

# 13 CONCLUSION

## 13.1 Conclusions

In this study, the Levelized Cost of Energy of a first selection of new search areas for potential wind farm zones after Roadmap 2030 is evaluated to support decisions on whether or not to further explore these search areas for possible future development of offshore wind farms and if so, if it is recommended to adjust the layouts from a cost perspective point of view. Hereto, the results for the search areas are compared to the results of zone IJmuiden Ver.

For each new search area, as well as the already designated wind farm zones IJmuiden Ver (noord), Hollandse Kust (noordwest), Hollandse Kust (zuidwest), IJmuiden Ver and Hollandse Kust (west), indicative wind farm layouts are designed. Next, the wind climate at each of the zones was assessed and used as basis for yield calculations. Costs were modelled for the offshore wind farm and the grid connection system. Finally, the overall LCoE, OWF LCoE and GCS LCoE is determined for each wind farm site individually and the impact of the main parameters is analysed.

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

**Part I: OWF LCoE analysis of initial layouts for offshore wind energy search areas**

1. The OWF LCoE varies considerably between the wind farm zones (with -0.6% to -4.6% difference compared to the reference IJmuiden Ver) and between the wind farm sites (with +1.2% to -4.5% difference compared to the reference IJmuiden Ver A).
2. The effect of yield is dominant over variations in cost, as the OWF LCoE is in general lowest for the wind farm zones with the lowest wake losses. The differences in wake effects can be explained by the size, the shape and the orientation of the wind farm zones, as the power density was kept at 10 MW/km$^2$ for each zone.
3. All wind farm zones in the new search areas are, compared to IJmuiden Ver, attractive from a cost perspective point of view and qualify for further assessment.
4. The average gross yields are substantially higher for the wind farm zones in the northern large new search areas (Zone 5,5 (mb), 6 and 7) than for IJmuiden Ver but this is largely offset by the higher wake effects, higher foundation costs and higher WTG installation and maintenance cost; there is however a large variation between the sites in these zones, so selecting only the most attractive sites or allocating the sites in a more effective way (taking the impact of the size, shape and orientation into account) will result in a lower average LCoE for these wind farm zones.
5. From the sensitivity analysis the conclusion can be drawn that for all wind farm zones a decrease in LCoE between -4%-point and -5.5%-point is to be expected with a density of 6 MW/km2¬ instead of 10 MW / km2 (except for Zone 3, which consists of only 1 site and therefore experiences limited wake losses already).

**Part II: LCoE analysis (overall, OWF, GCS) of adapted search areas layouts, IJVN, HKNW and HKZW**

1. All HVDC zones have a net overall LCoE (OWF + GCS) lower than the reference IJmuiden Ver, except for Zone 7 which has an overall LCoE of 2.3% higher than IJmuiden Ver due to the relatively high GCS and OWF costs. From a cost point of view Zone 7 is therefore less attractive than IJmuiden Ver and the other HVDC zones for further assessment.
2. The HVAC zones HKNW and HKZW are very attractive for further assessment, as they have a net overall LCoE (OWF + GCS) significantly lower than the reference HVDC zone IJmuiden Ver (-16.1% and -12.7% resp.) due to the relatively low GCS costs of a HVAC GCS compared to a HVDC GCS.

3. All HVDC and HVAC wind farm zones have a net OWF LCoE lower than the reference zone IJmuiden Ver, except for HKZW (+1.6%). Differences in wake losses are the dominant factor that influences the LCoE of the OWF and are predominately determined by big differences in orientation of the zones (towards the prevailing wind direction), size and shape of the zones. Differences in gross yield (caused by differences in wind climate) and cost of foundation (due to depth differences) are secondary factors that influence OWF LCoE. The impact of differences in WTG Capex and Opex, IA cable costs and IA cable losses is limited.
4. The HVDC and HVAC zones that are situated relatively close to shore (Zone 1, 2, 4, 5, 5 clearway, 5 (mb), 8, HKNW, HKZW) have a substantially lower net GCS LCoE than the reference IJmuiden Ver, while the zones furthest away from shore are the most expensive to connect (Zone 3, 6 and 7). Differences in net GCS LCoE compared to IJmuiden Ver are mainly caused by large variations in the export cable costs and transmission type costs (HVAC only). The LCoE impact of variations in the other costs (Surveying (incl. UXO), project management, insurance and Devex) and O&M costs are also considerable, while the LCoE impact of differences in the platform costs, export cable losses and GCS non-availabilities are small.
5. The choice of export landing area has a significant impact on the GCS LCoE results. Deviating from the current base assumption that the sites will be connected to the closest landing area increases the GCS LCoE of the sites compared to the reference IJmuiden Ver A with +10% to +30%.

## 13.2 Recommendations

In this study the search areas and unused parts of the existing wind farm zones were filled from the boundary closest to shore to keep the export cable costs as low as possible and therewith also the GCS and overall LCoE results. This chosen filling strategy is not optimal for the OWF LCoE of the zones. Conclusions would be slightly different with a different filling strategy, but since all zones have a lower OWF LCoE compared to the reference IJmuiden Ver (which was one of the targets when defining the layouts of the zones and sites) the overall conclusions for the OWF LCoE results will not change. In a follow-up study of optimizing the search areas without taking the GCS into account it is recommended to apply a different filling strategy, e.g. to fill from SW to NE.

The requirement of a fixed power density for all zones means that there will remain parts of the search areas and zones unused. This gives room for improvement of the LCoE, because the LCoE would be lower in case the full areas were used, as was proven by the density sensitivity of Part I. The present approach is deemed suitable for the purpose of this study, which is to compare relative differences between sites, keeping a similar density. In a follow-up study we recommend to investigate if full usage of the search areas and IJVN, HKNW, HKZW zones is possible and what the effect of the density decrease is on the LCoE results.

The wake effects are modelled using the N.O. Jensen wake model, which is the accepted industry standard for wake loss calculations. This model is known to be an oversimplified version of reality, most likely underestimating wake losses significantly. However, for the comparative purpose of this study, this is still considered to be acceptable. 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. However, Tractebel's HKW wind resource assessment study [5], supervised by BLIX and Pondera, has recently suggested that external wake losses from neighbouring wind farms could be higher than calculated using the N.O. Jensen wake model. More research is necessary to study accumulation of wake effects due to clustering of offshore wind farms.

This study modelled the energy yield of wind farm zones in new search areas individually to allow comparison between wind farm zones and sites. The impact of neighbouring existing or planned wind farms of Roadmap 2030 were included in the scope but the interaction effects between the wind farm zones in the new search areas not, nor is any effect of (planned) wind farms in bordering countries. An increase in wake losses is obvious when neighbouring wind farm zones are assigned in the new Roadmap. The interaction effects of existing offshore wind farms (such as OWEZ) and planned offshore wind farms (such as Hollandse Kust (noord)) on the wind farm zones in new search areas were included in the calculations.

# Reference List

1. BLIX Consultancy (2018) *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* https://www.rvo.nl/sites/default/files/2018/12/20181114_BLIX_RVO_LCOE_HKW_TNW_IJV_F.pdf
2. BLIX Consultancy (2020) *Study into Levelized Cost of Energy of variants for wind farm site boundaries of Hollandse Kust (west)* (2020)
   In the process of being published by RVO.
3. TenneT TSO (2020) *Deliverable 1.3: Synthesis of available studies on offshore meshed HVDC grids.* PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks.
4. Navigant. (2019) *Connecting Offshore Wind Farms.*
5. Tractebel (2020) *Wind Resource Assessment Hollandse Kust (west) Wind Farm Zone* (https://offshorewind.rvo.nl/file/download/55040678/03+Presentation+held+during+WRA+Webinar+on+October+8th%2C+2020)

# Appendix A: Wind climate of all wind farm zones at 140 m hub height

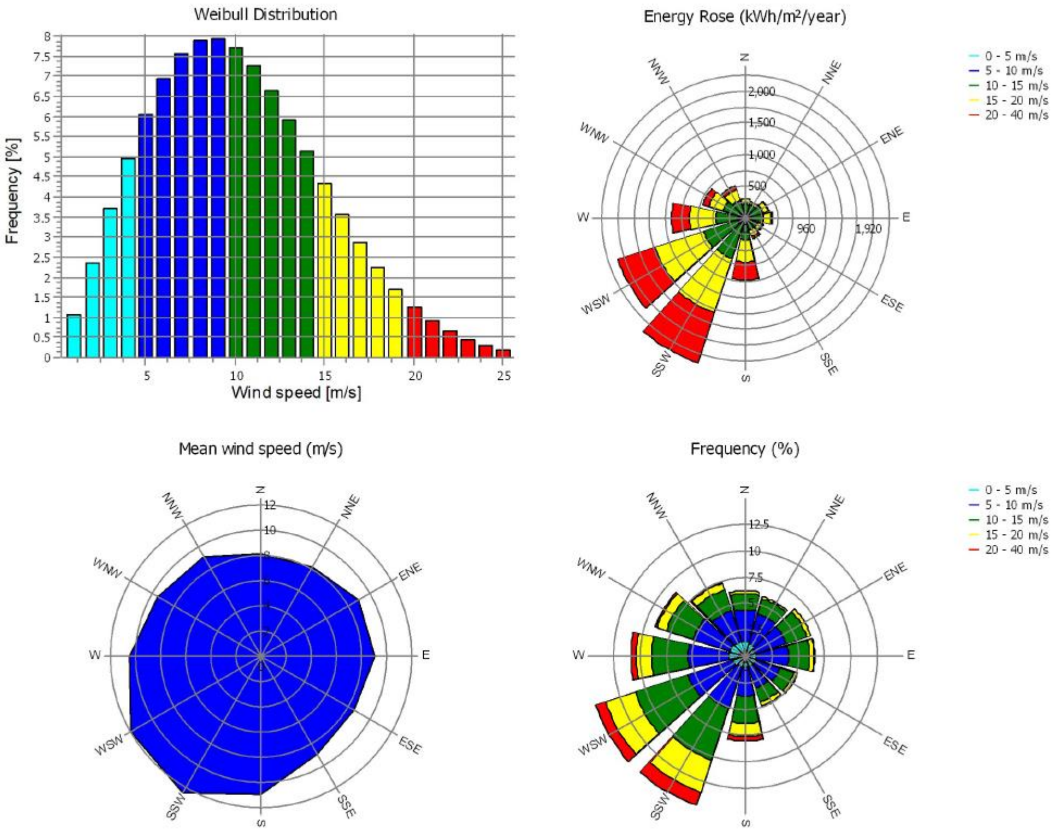

**Figure 75: Wind climate at WFZ IJmuiden Ver at 140 m hub height**

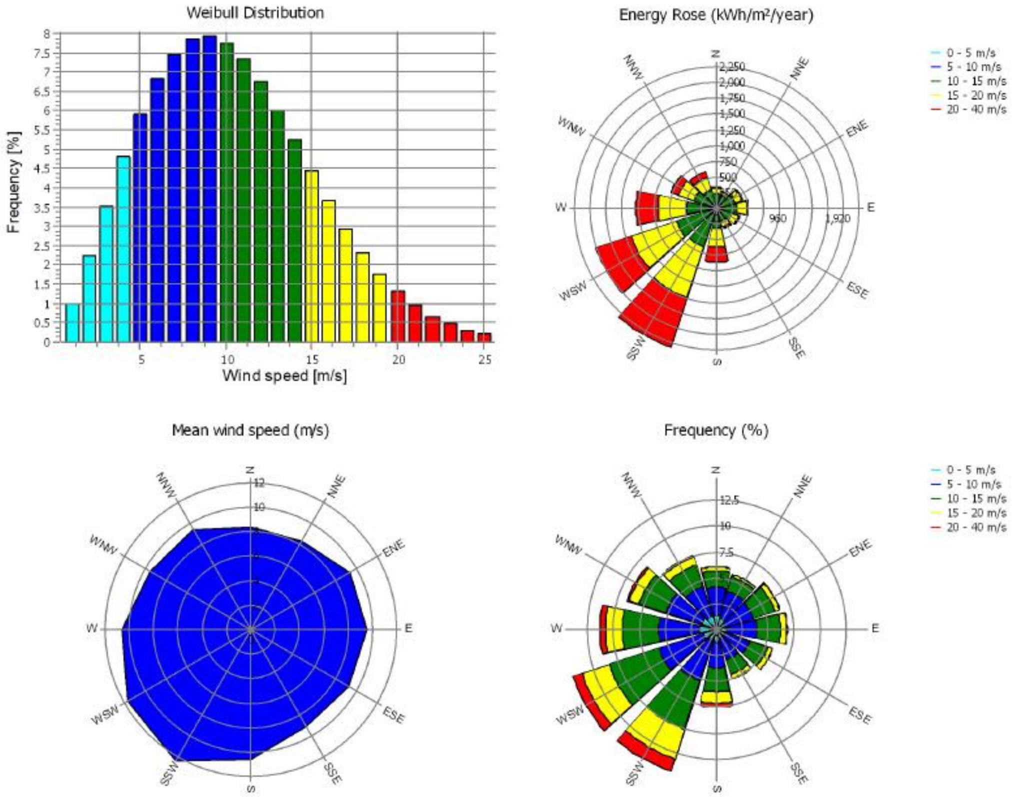

Figure 76: Wind climate at Zone 1 at 140 m hub height

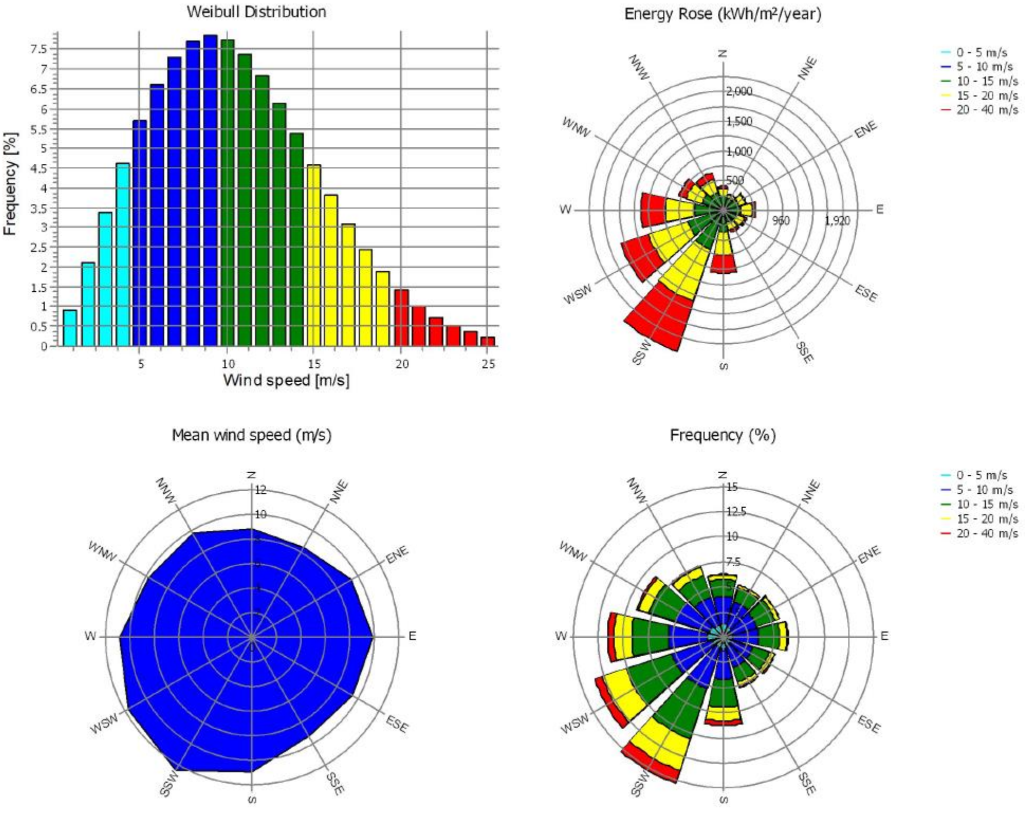

Figure 77: Wind climate at Zone 2 at 140 m hub height

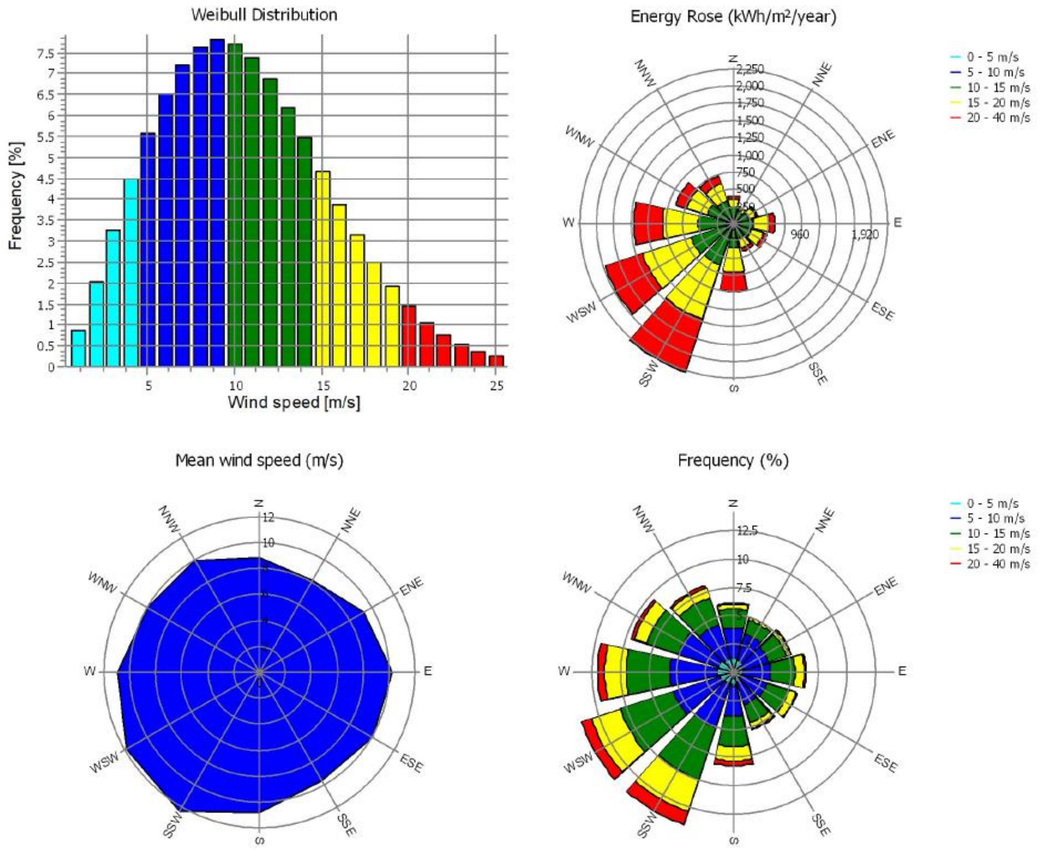

Figure 78: Wind climate at Zone 3 at 140 m hub height

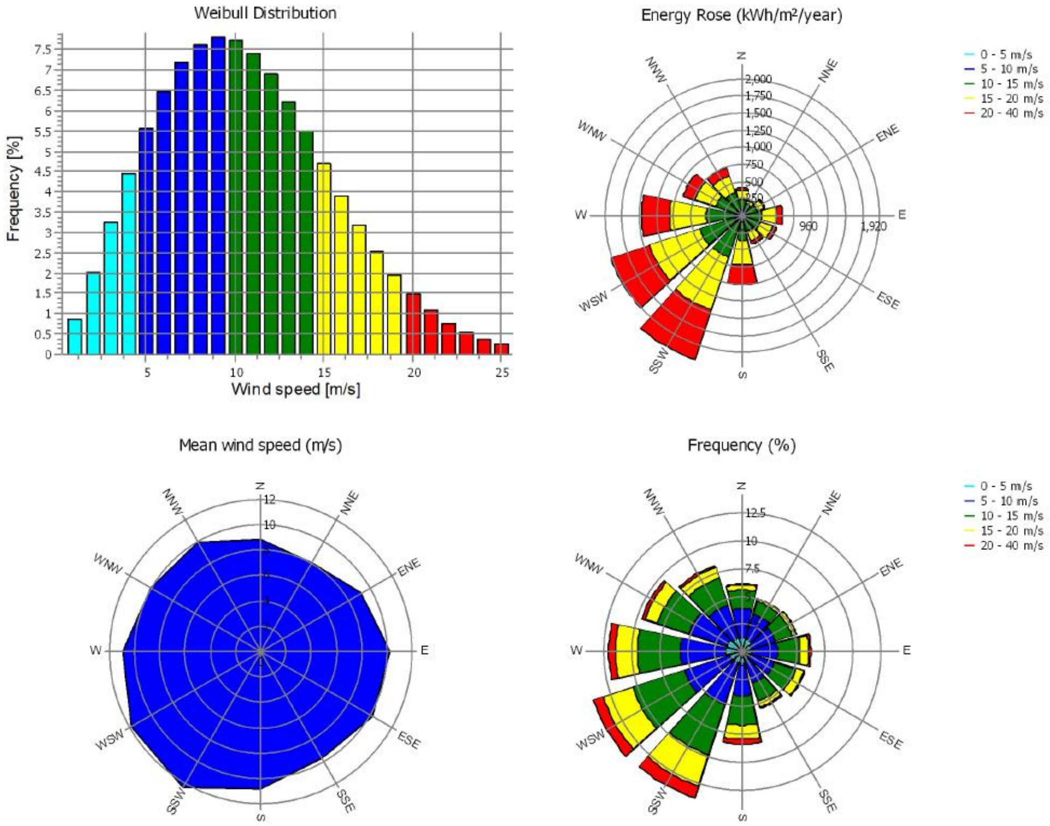

Figure 79: Wind climate at Zone 4 at 140 m hub height

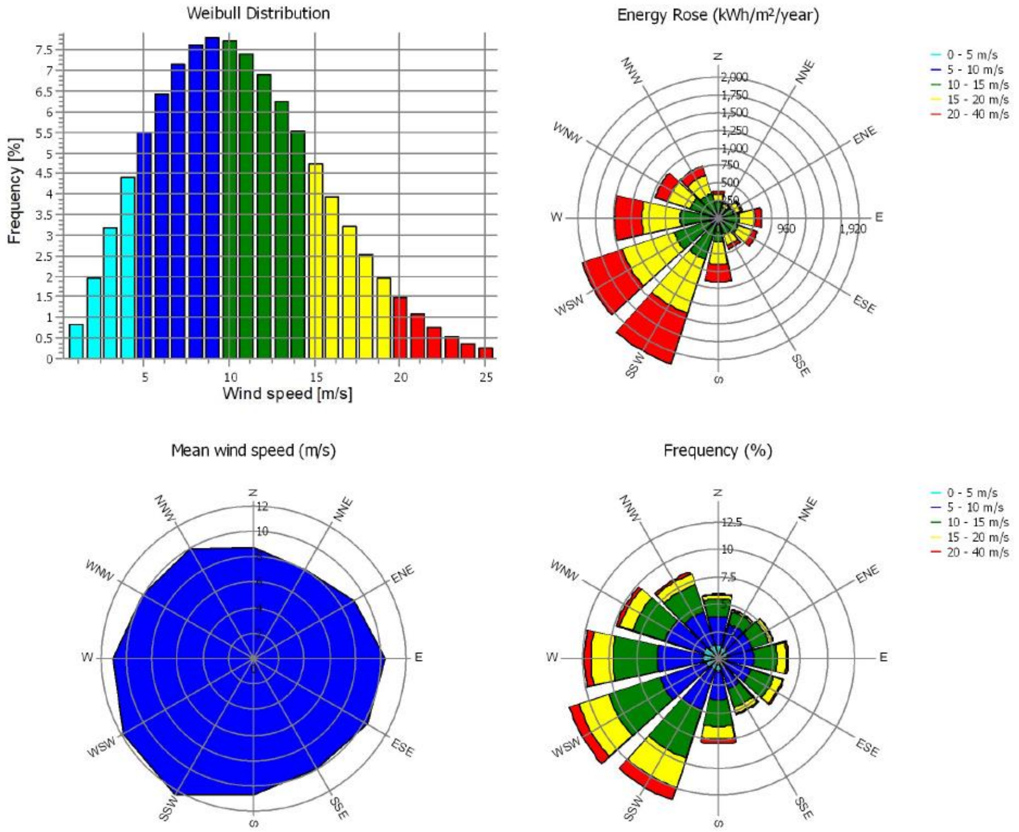

Figure 80: Wind climate at Zone 5 at 140 m hub height

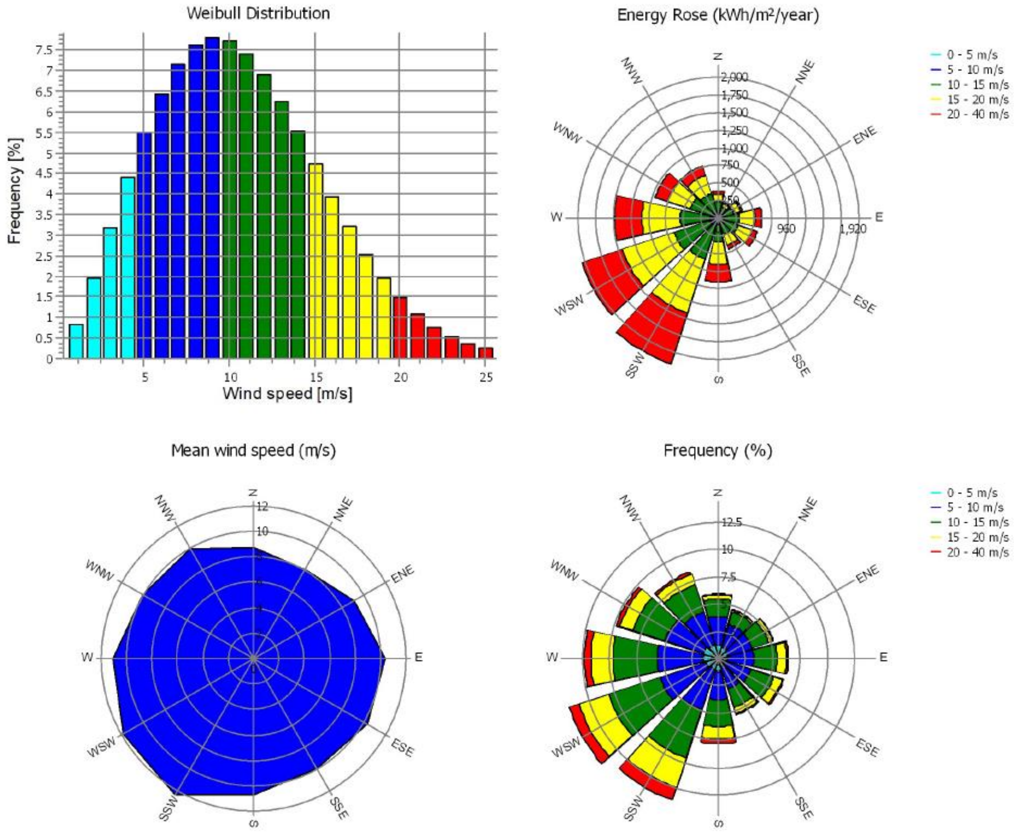

Figure 81: Wind climate at Zone 6 at 140 m hub height

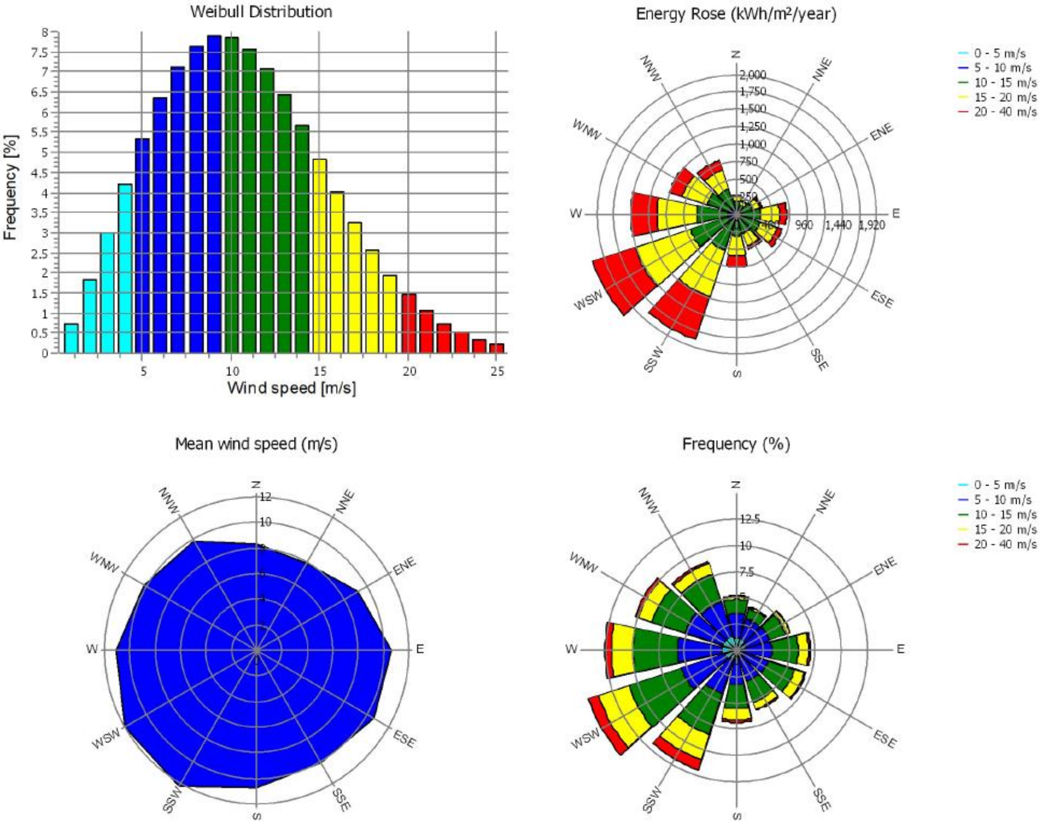

**Figure 82: Wind climate at Zone 7 at 140 m hub height**

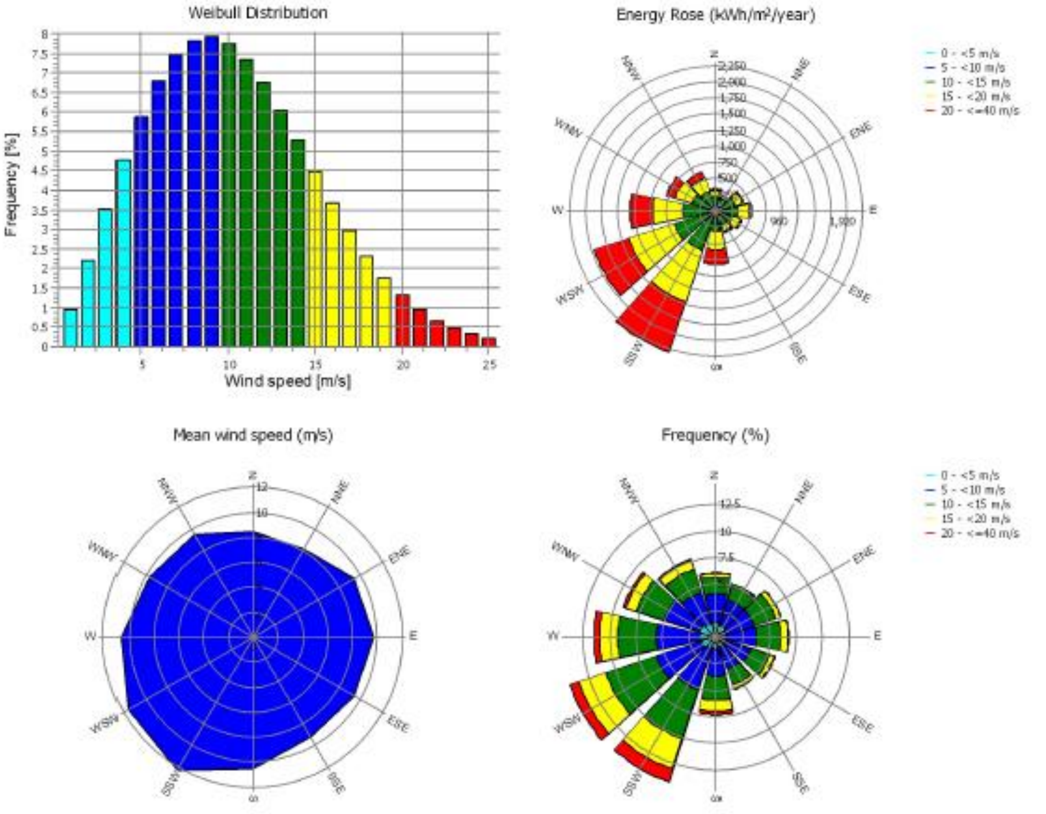

**Figure 83: Wind climate at Zone 8 at 140 m hub height**

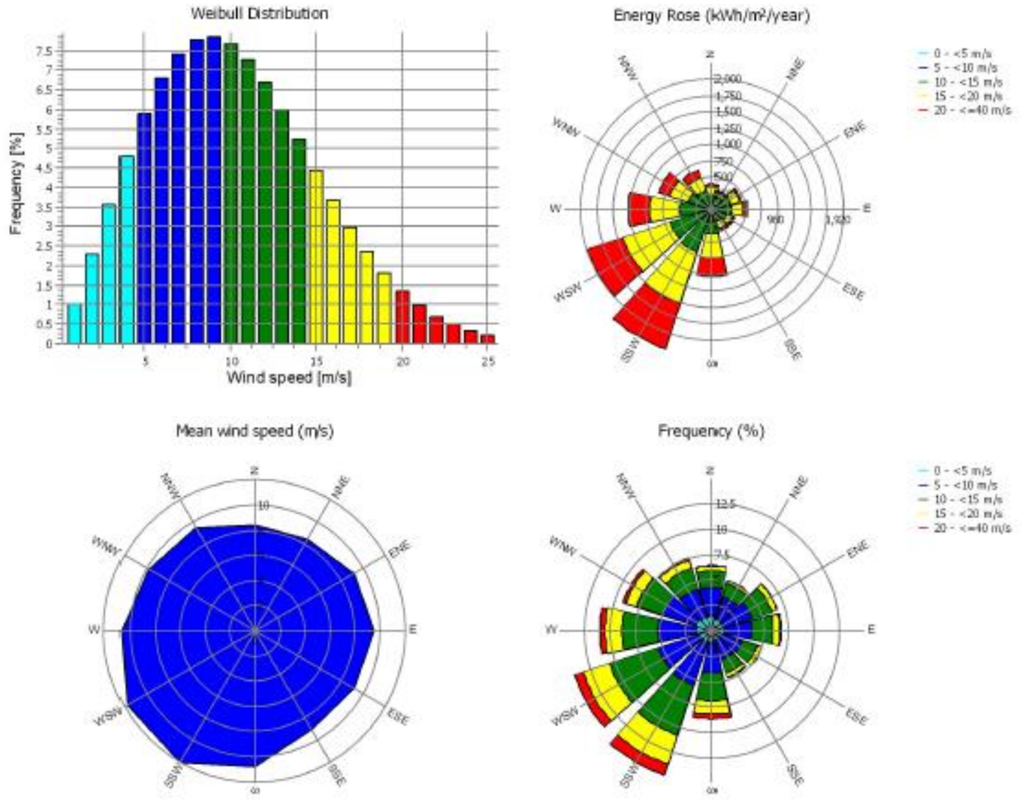

Figure 84: Wind climate at IJVN at 140 m hub height

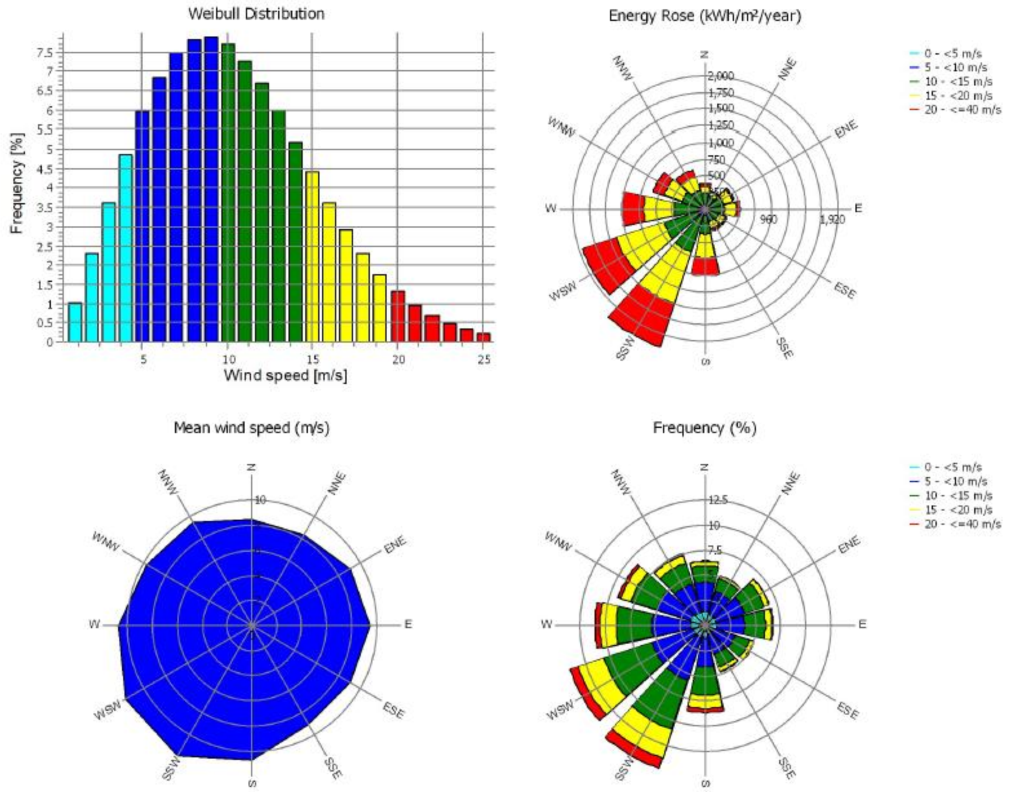

Figure 85: Wind climate at HKW at 140 m hub height

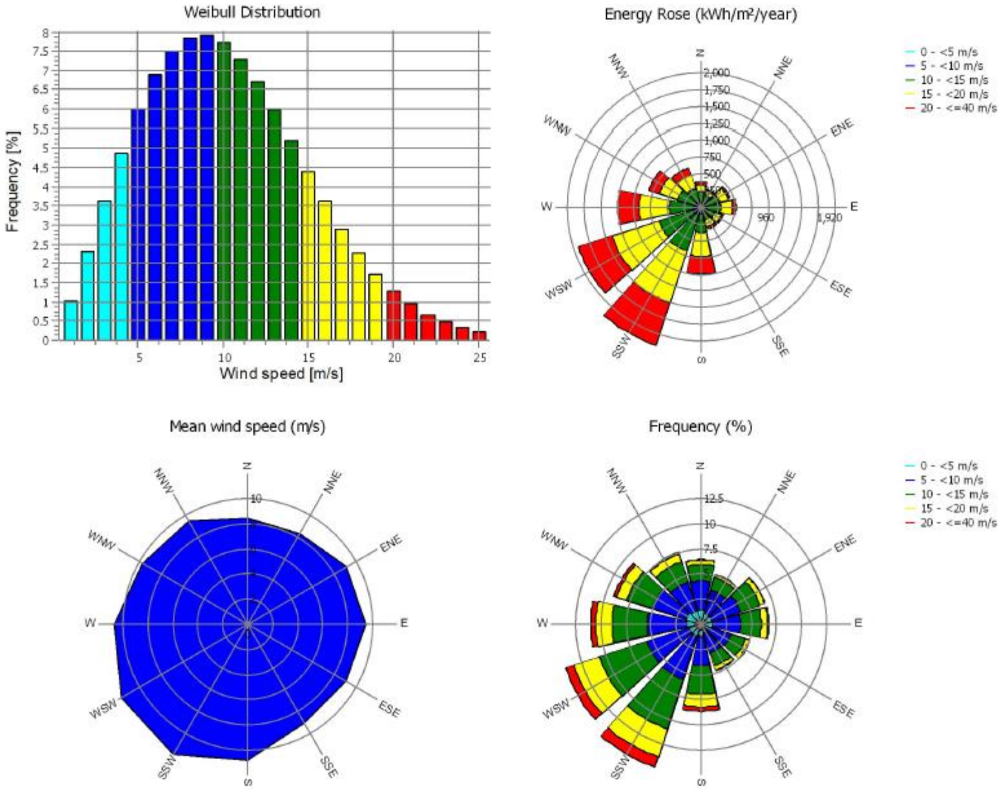

**Figure 86: Wind climate at HKNW at 140 m hub height**

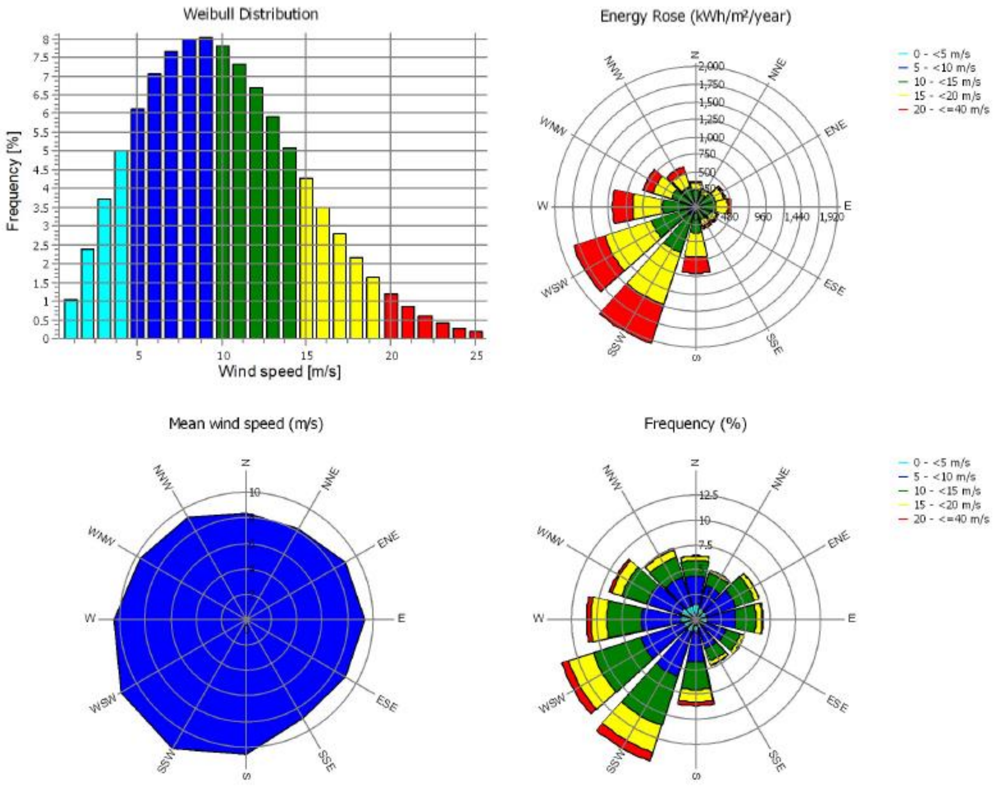

**Figure 87: Wind climate at HKZW at 140 m hub height**

# Appendix B: LCoE comparison between sites

In this appendix the relative LCoE results of Part II are described with a comparison between sites.

## Relative overall LCoE impact

### HVDC sites

In Figure 88 and Table 28, the overall LCoE comparison results for the HVDC sites are shown compared to reference IJmuiden Ver A.

The following main conclusions can be drawn on wind farm site level for the HVDC sites:

- All HVDC sites have a net overall LCoE (OWF + GCS) equal to or lower than the reference IJmuiden Ver A except for three sites of Zone 7, namely 7 B, 7 C and 7 D. These three sites have relatively high GCS and OWF costs and low net yield compared to the other sites.
- For the zones 4, 6, and 7 there is a large difference up to 3.5% in net overall LCoE between the sites within one zone compared to IJmuiden Ver, mainly caused by differences in yield and GCS costs between the sites.

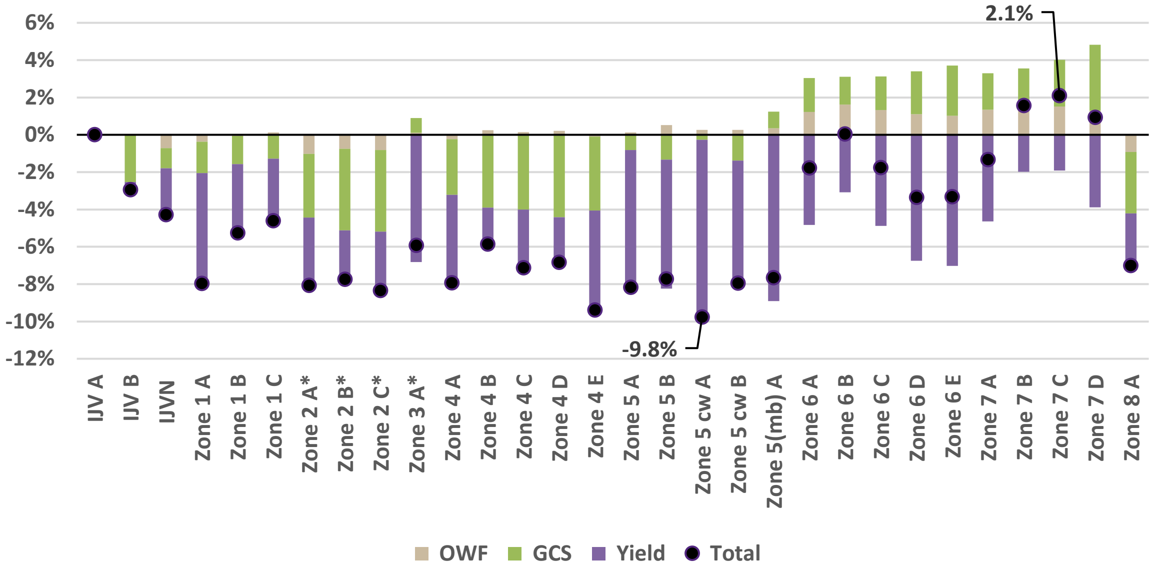

Figure 88: Comparison of the overall LCoE of the HVDC wind farm sites and IJmuiden Ver A

Table 28: Comparison of the overall LCoE of the HVDC wind farm sites and IJmuiden Ver A

| Site | Net LCoE impact | OWF | GCS | Yield |
|---|---|---|---|---|
| **IJV A** | - | - | - | - |
| **IJV B** | -2.9% | -0.0% | -2.5% | -0.4% |
| **IJVN** | -4.3% | -0.7% | -1.1% | -2.5% |
| **Zone 1 A** | -8.0% | -0.4% | -1.7% | -5.9% |
| **Zone 1 B** | -5.3% | -0.1% | -1.5% | -3.7% |
| **Zone 1 C** | -4.6% | 0.1% | -1.3% | -3.4% |
| **Zone 2 A*** | -8.1% | -1.0% | -3.4% | -3.7% |
| **Zone 2 B*** | -7.7% | -0.7% | -4.4% | -2.6% |
| **Zone 2 C*** | -8.3% | -0.8% | -4.4% | -3.2% |
| **Zone 3 A*** | -5.9% | 0.1% | 0.8% | -6.8% |
| **Zone 4 A** | -7.9% | -0.2% | -3.0% | -4.7% |
| **Zone 4 B** | -5.9% | 0.2% | -3.9% | -2.2% |

| | | | | |
|---|---|---|---|---|
| **Zone 4 C** | -7.1% | 0.1% | -4.0% | -3.3% |
| **Zone 4 D** | -6.8% | 0.2% | -4.4% | -2.6% |
| **Zone 4 E** | -9.4% | -0.1% | -4.0% | -5.3% |
| **Zone 5 A** | -8.2% | 0.1% | -0.8% | -7.5% |
| **Zone 5 B** | -7.7% | 0.5% | -1.3% | -6.9% |
| **Zone 5 cw A** | -9.8% | 0.3% | -0.3% | -9.8% |
| **Zone 5 cw B** | -7.9% | 0.3% | -1.4% | -6.8% |
| **Zone 5 (mb) A** | -7.7% | 0.3% | 0.9% | -8.9% |
| **Zone 6 A** | -1.8% | 1.2% | 1.8% | -4.8% |
| **Zone 6 B** | 0.0% | 1.6% | 1.5% | -3.1% |
| **Zone 6 C** | -1.8% | 1.3% | 1.8% | -4.9% |
| **Zone 6 D** | -3.4% | 1.1% | 2.3% | -6.7% |
| **Zone 6 E** | -3.3% | 1.0% | 2.7% | -7.0% |
| **Zone 7 A** | -1.3% | 1.3% | 2.0% | -4.6% |
| **Zone 7 B** | 1.6% | 1.6% | 1.9% | -2.0% |
| **Zone 7 C** | 2.1% | 1.5% | 2.5% | -1.9% |
| **Zone 7 D** | 0.9% | 1.3% | 3.5% | -3.9% |
| **Zone 8 A** | -7.0% | -0.9% | -3.3% | -2.8% |

*Size, location and orientation of this site is not adapted after Part I analysis.

### HVAC sites

In Figure 89 and Table 29, the overall LCoE comparison results for the HVAC sites are shown compared to reference IJmuiden Ver A.

The following main conclusions can be drawn on wind farm site level for the HVAC sites:

- All HVAC sites have a net overall LCoE (OWF + GCS) significantly lower than the reference HVDC site IJmuiden Ver A due to their relatively low GCS costs.
- The differences in net overall LCoE between the sites within one zone compared to IJmuiden Ver are small, mainly caused by differences in yield and GCS costs between the sites.
- The lower yield of wind farm site HKZW B results in a net overall LCoE higher than the sites of HKW and HKNW, but with -13,7% still significantly lower than IJV A.

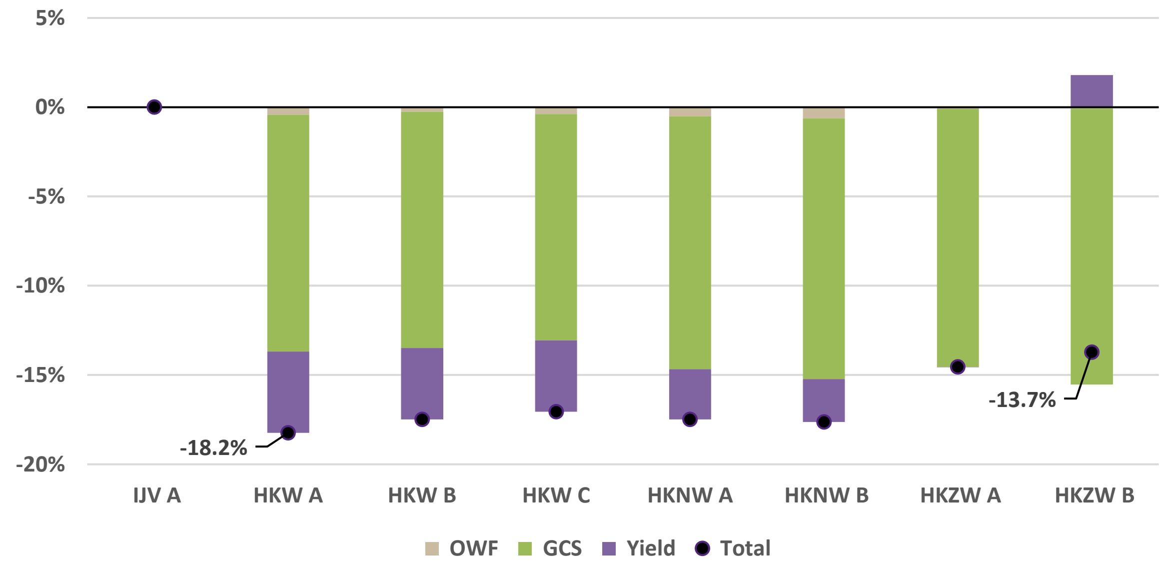

Figure 89: Comparison of the overall LCoE of the HVAC wind farm sites and IJmuiden Ver A

Table 29: Comparison of the overall LCoE of the HVAC wind farm sites and IJmuiden Ver A

| Site | Net LCOE impact | OWF | GCS | Yield |
|---|---|---|---|---|
| **IJV A** | - | - | - | - |
| **HKW A** | -18.2% | -0.4% | -13.3% | -4.5% |
| **HKW B** | -17.5% | -0.3% | -13.2% | -4.0% |
| **HKW C** | -17.1% | -0.4% | -12.7% | -4.0% |
| **HKNW A** | -17.5% | -0.5% | -14.2% | -2.8% |
| **HKNW B** | -17.6% | -0.6% | -14.6% | -2.4% |
| **HKZW A** | -14.5% | -0.1% | -14.4% | -0.0% |
| **HKZW B** | -13.7% | -0.1% | -15.4% | 1.8% |

## Relative LCoE impact of the Offshore Wind Farm (OWF)

### HVDC sites

In Figure 90 and Table 30 the OWF LCoE comparison results of the HVDC sites are shown compared to reference IJmuiden Ver A.

The following main conclusions can be drawn on wind farm site level for the HVDC sites:

- All HVDC sites in the new search areas have a net OWF LCoE equal to or lower than the reference IJmuiden Ver A except for the three sites Zone 4 B, Zone 7 B and Zone 7 C. In all three of these sites the wake losses are higher than at WFZ IJV.
- At zone 6 there is a large difference up to 4.0% in net OWF LCoE between the sites compared to IJmuiden Ver, mainly caused by differences in gross yield and wake losses between the sites.

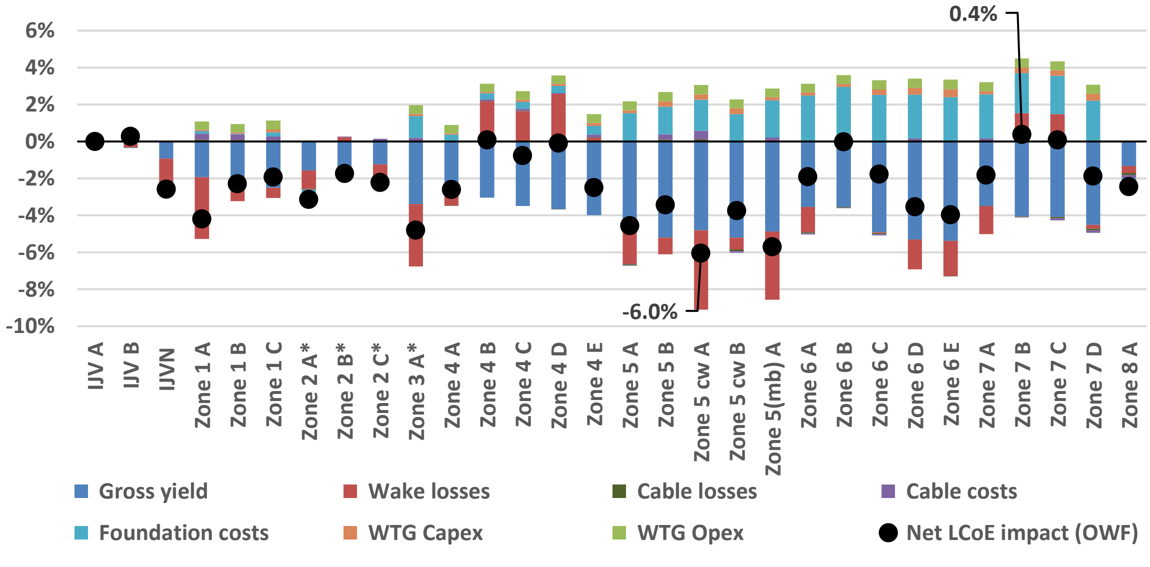

Figure 90: Comparison of the OWF LCoE of the HVDC wind farm sites and IJmuiden Ver A

Table 30: Comparison of the OWF LCoE of the HVDC wind farm sites and IJmuiden Ver A

| Site | Net LCoE impact (OWF) | Cable costs | Foundation costs | WTG Capex | WTG Opex | Gross yield | Wake losses | Cable losses |
|---|---|---|---|---|---|---|---|---|
| **IJV A** | - | - | - | - | - | - | -0.0% | - |
| **IJV B** | 0.3% | -0.0% | 0.1% | - | - | 0.5% | -0.3% | -0.0% |
| **IJVN** | -2.6% | -0.1% | -0.1% | -0.0% | -0.2% | -0.9% | -1.2% | -0.1% |
| **Zone 1 A** | -4.2% | 0.3% | 0.1% | 0.1% | 0.4% | -1.9% | -3.3% | 0.1% |
| **Zone 1 B** | -2.3% | 0.3% | 0.0% | 0.1% | 0.4% | -2.3% | -0.9% | 0.1% |
| **Zone 1 C** | -1.9% | 0.2% | 0.2% | 0.2% | 0.5% | -2.5% | -0.5% | 0.0% |
| **Zone 2 A*** | -3.1% | -0.0% | -0.3% | -0.0% | -0.2% | -1.6% | -1.0% | -0.0% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Zone 2 B*** | -1.7% | 0.0% | -0.2% | -0.0% | -0.2% | -1.5% | 0.2% | -0.0% |
| **Zone 2 C*** | -2.2% | 0.1% | -0.1% | -0.1% | -0.4% | -1.2% | -0.6% | 0.0% |
| **Zone 3 A*** | -4.8% | 0.2% | 1.2% | 0.1% | 0.5% | -3.4% | -3.4% | 0.0% |
| **Zone 4 A** | -2.6% | 0.0% | 0.4% | 0.1% | 0.4% | -2.8% | -0.7% | -0.0% |
| **Zone 4 B** | 0.1% | 0.1% | 0.3% | 0.1% | 0.4% | -3.0% | 2.2% | 0.0% |
| **Zone 4 C** | -0.8% | 0.1% | 0.4% | 0.1% | 0.5% | -3.5% | 1.6% | 0.0% |
| **Zone 4 D** | -0.1% | 0.0% | 0.4% | 0.1% | 0.5% | -3.7% | 2.6% | -0.0% |
| **Zone 4 E** | -2.5% | 0.2% | 0.5% | 0.2% | 0.5% | -4.0% | 0.2% | 0.0% |
| **Zone 5 A** | -4.6% | -0.0% | 1.5% | 0.2% | 0.5% | -4.5% | -2.2% | -0.1% |
| **Zone 5 B** | -3.4% | 0.3% | 1.5% | 0.3% | 0.5% | -5.2% | -0.9% | 0.1% |
| **Zone 5 cw A** | -6.0% | 0.5% | 1.7% | 0.3% | 0.5% | -4.8% | -4.3% | 0.1% |
| **Zone 5 cw B** | -3.7% | -0.1% | 1.5% | 0.3% | 0.5% | -5.2% | -0.7% | -0.1% |
| **Zone 5 (mb) A** | -5.7% | 0.2% | 2.0% | 0.2% | 0.5% | -4.9% | -3.7% | 0.0% |
| **Zone 6 A** | -1.9% | -0.1% | 2.5% | 0.2% | 0.5% | -3.5% | -1.4% | -0.1% |
| **Zone 6 B** | -0.0% | -0.0% | 2.6% | 0.2% | 0.5% | -3.5% | 0.4% | -0.0% |
| **Zone 6 C** | -1.8% | -0.1% | 2.5% | 0.3% | 0.5% | -4.9% | -0.1% | -0.1% |
| **Zone 6 D** | -3.5% | 0.2% | 2.4% | 0.4% | 0.5% | -5.3% | -1.6% | 0.0% |
| **Zone 6 E** | -4.0% | 0.0% | 2.4% | 0.4% | 0.5% | -5.4% | -1.9% | -0.0% |
| **Zone 7 A** | -1.8% | 0.2% | 2.4% | 0.2% | 0.5% | -3.5% | -1.5% | 0.0% |
| **Zone 7 B** | 0.4% | -0.0% | 2.2% | 0.3% | 0.5% | -4.0% | 1.8% | -0.0% |
| **Zone 7 C** | 0.1% | -0.1% | 2.1% | 0.3% | 0.5% | -4.1% | 1.8% | -0.1% |
| **Zone 7 D** | -1.9% | -0.1% | 2.2% | 0.4% | 0.5% | -4.5% | 0.2% | -0.1% |
| **Zone 8 A** | -2.4% | -0.2% | -0.2% | -0.0% | -0.2% | -1.3% | -0.4% | -0.1% |

*Size, location and orientation of this site is not adapted after Part I analysis.

### HVAC sites

In Figure 91 and Table 31 the OWF LCoE comparison results of the HVAC sites are shown compared to reference IJmuiden Ver A.

The following main conclusions can be drawn on wind farm site level for the HVAC sites:

- The OWF LCoE of the HVAC sites of HKNW are -1.2 to -1.5% lower than the reference HVDC site IJmuiden Ver A, while the sites of HKZW are +1.0% to +2.4% higher than IJV.
- The largest mutual differences between the sites can be seen in gross yield and wake losses.

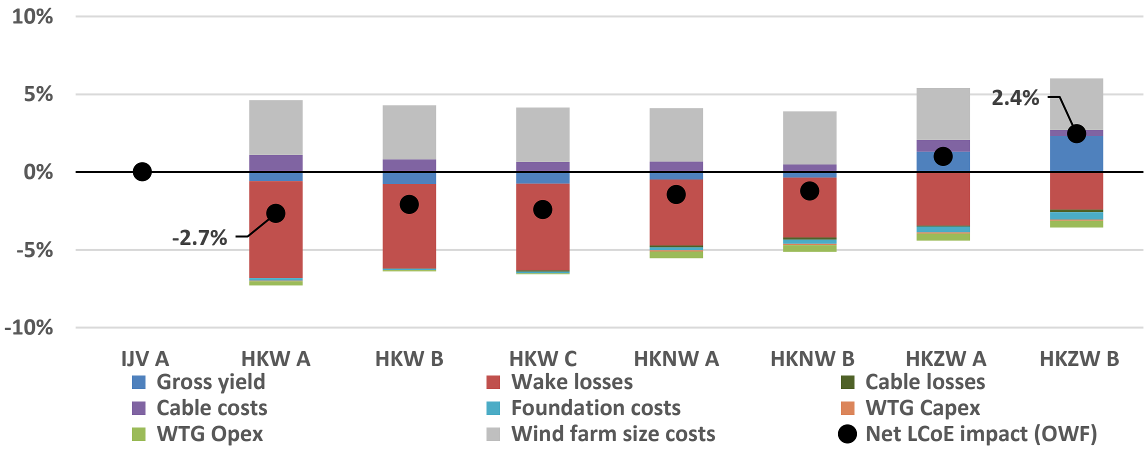

Figure 91: Comparison of the OWF LCoE of the HVAC wind farm sites and IJmuiden Ver A

Table 31: Comparison of the OWF LCoE of the HVAC wind farm sites and IJmuiden Ver A

| Site | Net LCoE impact (OWF) | Cable costs | Foundation costs | WTG Capex | WTG Opex | Wind farm size costs | Gross yield | Wake losses | Cable losses |
|---|---|---|---|---|---|---|---|---|---|
| **IJV A** | - | - | - | - | - | - | - | - | - |
| **HKW A** | -2.7% | 1.0% | -0.2% | -0.0% | -0.3% | 3.5% | -0.6% | -6.2% | 0.1% |
| **HKW B** | -2.1% | 0.8% | -0.1% | - | -0.1% | 3.5% | -0.8% | -5.4% | -0.0% |
| **HKW C** | -2.4% | 0.6% | -0.1% | - | -0.1% | 3.5% | -0.7% | -5.6% | -0.1% |
| **HKNW A** | -1.5% | 0.7% | -0.2% | -0.1% | -0.4% | 3.4% | -0.5% | -4.2% | -0.1% |
| **HKNW B** | -1.2% | 0.5% | -0.3% | -0.1% | -0.4% | 3.4% | -0.4% | -3.9% | -0.1% |
| **HKZW A** | 1.0% | 0.8% | -0.4% | -0.1% | -0.4% | 3.3% | 1.3% | -3.4% | -0.1% |
| **HKZW B** | 2.4% | 0.4% | -0.5% | -0.1% | -0.4% | 3.3% | 2.3% | -2.4% | -0.2% |

## Relative LCoE impact of the Grid Connection System (GCS)

### HVDC sites

In Figure 92 and Table 32 the GCS LCoE comparison results of the HVDC sites are shown compared to reference IJmuiden Ver A.

The following main conclusion can be drawn on wind farm site level for the HVDC sites:

- All HVDC sites have a net OWF LCoE lower than the reference IJmuiden Ver A except for all four sites of Zone 7. These sites are located further offshore and therefore have significantly higher export cable costs compared to the other sites.

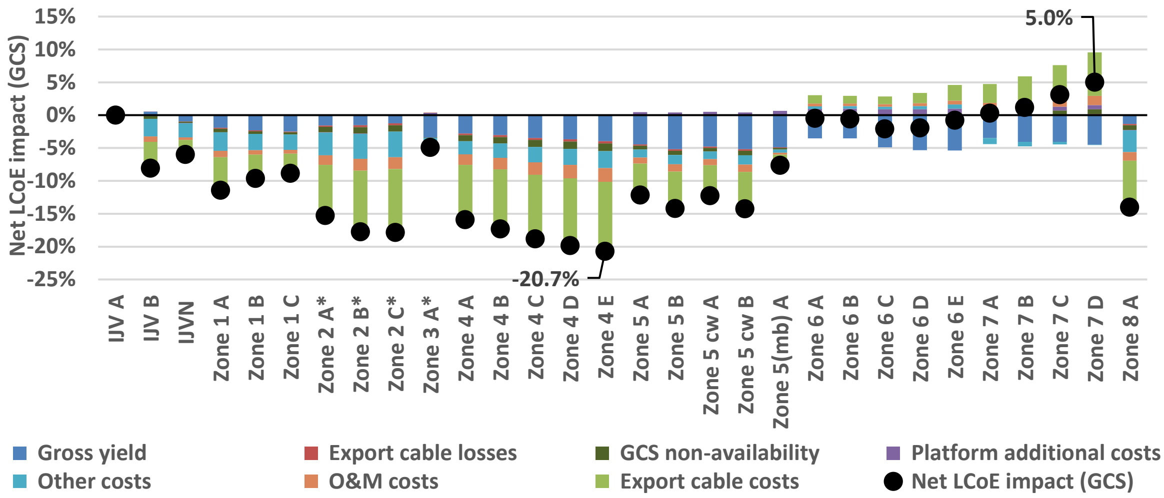

Figure 92: Comparison of the GCS LCoE of the HVDC wind farm sites and IJmuiden Ver A

Table 32: Comparison of the GCS LCoE of the HVDC wind farm sites and IJmuiden Ver A

| Site | Net LCoE impact (GCS) | Platform costs | Other costs | O&M costs | Export cable costs | Gross yield | Export cable losses | GCS non-availability |
|---|---|---|---|---|---|---|---|---|
| **IJV A** | - | - | - | - | - | - | - | - |
| **IJV B** | -8.1% | 0.0% | -2.7% | -0.8% | -4.6% | 0.5% | -0.1% | -0.5% |
| **IJVN** | -6.0% | -0.0% | -2.2% | -0.4% | -2.2% | -0.9% | -0.1% | -0.2% |
| **Zone 1 A** | -11.4% | 0.0% | -2.8% | -0.9% | -5.1% | -1.9% | -0.2% | -0.5% |
| **Zone 1 B** | -9.6% | -0.0% | -2.5% | -0.7% | -3.6% | -2.3% | -0.1% | -0.4% |
| **Zone 1 C** | -8.9% | 0.0% | -2.4% | -0.6% | -3.0% | -2.5% | -0.1% | -0.3% |
| **Zone 2 A*** | -15.3% | -0.1% | -3.4% | -1.5% | -7.7% | -1.6% | -0.2% | -0.8% |
| **Zone 2 B*** | -17.7% | -0.1% | -3.8% | -1.8% | -9.3% | -1.5% | -0.3% | -1.0% |
| **Zone 2 C*** | -17.9% | 0.0% | -3.9% | -1.8% | -9.7% | -1.2% | -0.3% | -1.0% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Zone 3 A*** | -4.9% | 0.4% | -1.7% | 0.0% | -0.2% | -3.4% | -0.0% | -0.0% |
| **Zone 4 A** | -15.9% | 0.1% | -2.0% | -1.6% | -8.5% | -2.8% | -0.3% | -0.9% |
| **Zone 4 B** | -17.3% | 0.1% | -2.2% | -1.8% | -9.2% | -3.0% | -0.3% | -1.0% |
| **Zone 4 C** | -18.8% | 0.1% | -2.3% | -1.9% | -9.8% | -3.5% | -0.3% | -1.1% |
| **Zone 4 D** | -19.9% | 0.1% | -2.5% | -2.0% | -10.4% | -3.7% | -0.3% | -1.1% |
| **Zone 4 E** | -20.7% | 0.1% | -2.6% | -2.1% | -10.7% | -4.0% | -0.3% | -1.2% |
| **Zone 5 A** | -12.2% | 0.5% | -1.2% | -0.9% | -5.3% | -4.5% | -0.2% | -0.6% |
| **Zone 5 B** | -14.2% | 0.4% | -1.4% | -1.1% | -6.0% | -5.2% | -0.2% | -0.7% |
| **Zone 5 cw A** | -12.3% | 0.5% | -1.2% | -0.9% | -5.1% | -4.8% | -0.2% | -0.6% |
| **Zone 5 cw B** | -14.3% | 0.4% | -1.4% | -1.1% | -6.1% | -5.2% | -0.2% | -0.7% |
| **Zone 5 (mb) A** | -7.7% | 0.6% | -0.5% | -0.3% | -2.3% | -4.9% | -0.1% | -0.3% |
| **Zone 6 A** | -0.5% | 0.8% | 0.4% | 0.4% | 1.3% | -3.5% | 0.0% | 0.1% |
| **Zone 6 B** | -0.6% | 0.9% | 0.4% | 0.4% | 1.2% | -3.5% | 0.0% | 0.1% |
| **Zone 6 C** | -2.1% | 0.8% | 0.4% | 0.4% | 1.2% | -4.9% | 0.0% | 0.1% |
| **Zone 6 D** | -1.9% | 0.7% | 0.5% | 0.4% | 1.6% | -5.3% | 0.0% | 0.2% |
| **Zone 6 E** | -0.8% | 0.7% | 0.7% | 0.6% | 2.4% | -5.4% | 0.0% | 0.3% |
| **Zone 7 A** | 0.3% | 0.8% | -0.9% | 0.7% | 2.9% | -3.5% | 0.1% | 0.3% |
| **Zone 7 B** | 1.2% | 0.7% | -0.7% | 0.9% | 3.9% | -4.0% | 0.1% | 0.4% |
| **Zone 7 C** | 3.1% | 0.6% | -0.4% | 1.1% | 5.2% | -4.1% | 0.1% | 0.6% |
| **Zone 7 D** | 5.0% | 0.6% | -0.1% | 1.4% | 6.6% | -4.5% | 0.2% | 0.7% |
| **Zone 8 A** | -14.0% | -0.1% | -3.3% | -1.3% | -7.1% | -1.3% | -0.2% | -0.7% |

*Size, location and orientation of this site is not adapted after Part I analysis.

## HVAC sites

In Figure 93 and Table 33 the GCS LCoE comparison results of the HVAC sites are shown compared to reference IJmuiden Ver A.

The following main conclusions can be drawn on wind farm site level for the HVAC sites:

- The HVAC sites of HKNW, HKZW and HKW have substantially lower net GCS LCoE than reference IJV due to the significantly lower "transmission type costs" which represent the difference in costs between HVAC and HVDC systems (see also paragraph 3.3).

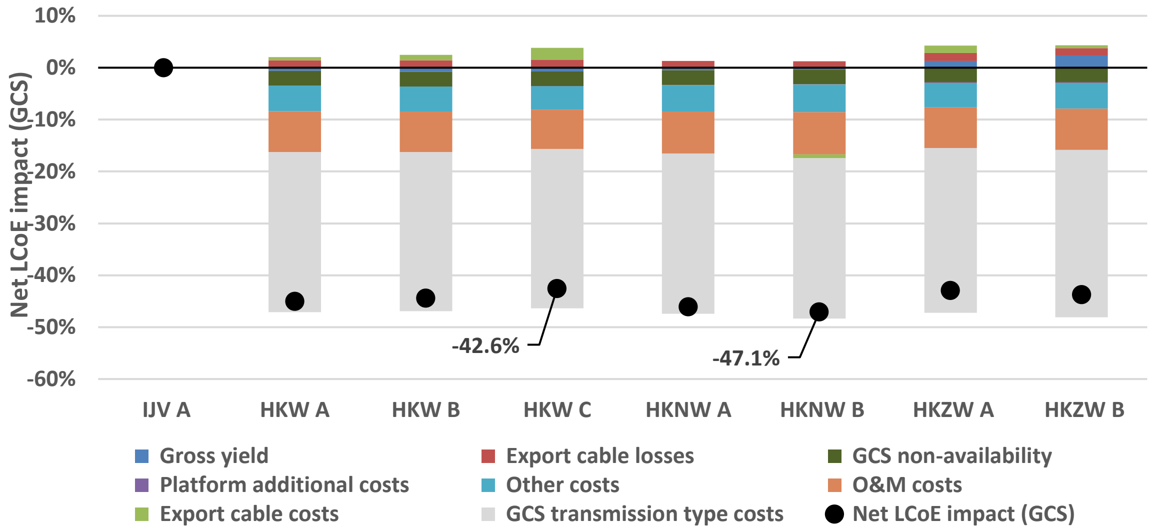

Figure 93: Comparison of the GCS LCoE of the HVAC wind farm sites and IJmuiden Ver A

**Table 33: Comparison of the GCS LCoE of the HVAC wind farm sites and IJmuiden Ver A**

| Site | Net LCoE impact (GCS) | Platform costs | Other costs | O&M costs | Export cable costs | GCS transmission type costs | Gross yield | Export cable losses | GCS non-availability |
|---|---|---|---|---|---|---|---|---|---|
| **IJV A** | - | - | - | - | - | - | - | - | - |
| **HKW A** | -45.1% | -0.0% | -4.9% | -7.9% | 0.6% | -30.8% | -0.6% | 1.4% | -2.8% |
| **HKW B** | -44.4% | -0.0% | -4.8% | -7.8% | 1.1% | -30.7% | -0.8% | 1.4% | -2.8% |
| **HKW C** | -42.6% | -0.0% | -4.5% | -7.6% | 2.2% | -30.7% | -0.7% | 1.6% | -2.8% |
| **HKNW A** | -46.1% | -0.0% | -5.1% | -8.1% | -0.1% | -30.8% | -0.5% | 1.3% | -2.9% |
| **HKNW B** | -47.1% | -0.1% | -5.3% | -8.2% | -0.7% | -30.9% | -0.4% | 1.3% | -2.9% |
| **HKZW A** | -43.0% | -0.1% | -4.7% | -7.8% | 1.4% | -31.8% | 1.3% | 1.5% | -2.8% |
| **HKZW B** | -43.8% | -0.1% | -4.9% | -8.0% | 0.6% | -32.2% | 2.3% | 1.5% | -2.8% |