



# Cost Evaluation of North Sea Offshore Wind Post 2030

On behalf of the North Sea Wind Power Hub Consortium

4 February 2019

**Project** Cost Evaluation of North Sea Offshore Wind Post 2030  
**Client** North Sea Wind Power Hub Consortium

**Document**  
**Status** Final  
**Date** 4 February 2019  
**Reference** 112522/19-001.830

**Project code** 112522  
**Project Leader** K.A. Haans MSc  
**Project Director** M.T. Marshall MTech

**Author(s)** E.C.M. Ruijgrok PhD, E.J. van Druten MSc, B.H. Bulder MSc (ECN part of TNO)  
**Checked by** A.H.J. van Kuijk MSc  
**Approved by** K.A. Haans MSc

**Initials**



**Address** Witteveen+Bos Raadgevende ingenieurs B.V.  
Leeuwenbrug 8  
P.O. Box 233  
7400 AE Deventer  
The Netherlands  
+31 570 69 79 11  
[www.witteveenbos.com](http://www.witteveenbos.com)  
CoC 38020751

The Quality management system of Witteveen+Bos has been approved based on ISO 9001.

© Witteveen+Bos

No part of this document may be reproduced and/or published in any form, without prior written permission of Witteveen+Bos, and the NSWPH consortium, nor may it be used for any work other than that for which it was manufactured without such permission, unless otherwise agreed in writing. Witteveen+Bos, ECN part of TNO and the NSWPH consortium do not accept liability for damages or loss arising from application or use of any outcome of the content of this document.

## TABLE OF CONTENTS

<b>1</b>	<b>INTRODUCTION</b>	<b>20</b>
1.1	Background	20
1.2	Study purpose	21
1.3	Reading guide	21
<b>2</b>	<b>FINDING SPACE FOR OFFSHORE WIND ENERGY IN THE NORTH SEA</b>	<b>23</b>
2.1	Space consumption in the North Sea	23
2.2	Optimizing grid connection design by cooperation between countries	25
2.3	Cost drivers and optimal use of economies of scale	26
<b>3</b>	<b>STARTING POINTS</b>	<b>27</b>
3.1	Study scope	27
3.1.1	Methodological scope	27
3.1.2	Geographical and depth scope	28
3.1.3	Roll-out scope	29
3.1.4	Cost scope	29
3.2	Trends in of offshore wind energy production	30
3.3	Reference wind farm and grid connection for this study	32
3.4	Used input data	33
<b>4</b>	<b>LCOE-R MAPPING MODEL</b>	<b>35</b>
4.1	LCoE mapping	35
4.1.1	LCoE formula	35
4.1.2	OWF cost formulas	37
4.1.3	GCS cost formulas	39
4.1.4	LCoE uncertainty margins	41
4.1.5	LCoE maps	43
4.2	LCoE-R mapping	45
4.2.1	Spatial risk principles	45
4.2.2	LCoE-R calculations	48
4.2.3	LCoE-R maps	52

<b>5</b>	<b>IDENTIFYING POSSIBLE NEW OWF LOCATIONS</b>	<b>56</b>
5.1	Searching for new locations from different perspectives	56
5.1.1	Set with possible new locations based on low LCoE-R	56
5.1.2	Set with possible new locations excluding visibility from shore	57
5.1.3	Set with possible new locations excluding nature protected areas	58
5.2	Selection of a preferred set with possible new locations for grid roll-out	59
<b>6</b>	<b>GRID ROLL-OUT PATHWAYS</b>	<b>62</b>
6.1	Adding inter-OWF wake losses	62
6.2	Grid optimization and economies of scale	63
6.3	Identified roll-out pathways	65
6.3.1	Pathway 1: Enough hubs	66
6.3.2	Pathway 2: Large hubs	67
6.3.3	Capturing economies of scale	68
6.4	Selection of preferred grid roll-out pathway	69
<b>7</b>	<b>SENSITIVITY ANALYSES</b>	<b>70</b>
7.1	Sensitivity to wind farm power density	70
7.2	Sensitivity to no hubs	72
7.3	Sensitivity to including areas just outside nature areas	73
<b>8</b>	<b>MAIN RESULTS &amp; FOLLOW UP STUDIES</b>	<b>77</b>
8.1	Main results	77
8.1.1	Possible new OWF locations and their LCoEs	77
8.1.2	Roll-out pathways and their LCoE	78
8.1.3	Sensitivity analyses	78
8.2	Follow-up studies	79
8.2.1	More detailed investigation of spatial risks	79
8.2.2	Economies and diseconomies of scale	80
8.2.3	Include interconnection benefits	80
<b>9</b>	<b>REFERENCES</b>	<b>81</b>
	<a href="#">Last page</a>	82

## APPENDICES

		Number of pages
I	Trends in space use at the North Sea	10
II	Spatial cost calculation formulas	2
III	Detailed design of German shipping corridors	3



## LIST OF USED ABBREVIATIONS

- AC Alternating Current
- AC farm Offshore wind farm that is connected with an AC radial grid connection system
- AEP Annual Energy Production
- CapEx Capital Expenditure
- COP21 21st Conference of the Parties in Paris
- DC Direct Current
- DC farm Offshore wind farm that is connected with a DC radial grid connection system
- EEZ Exclusive Economic Zone
- GCS Grid Connection System
- GIS Geographic Information System
- GW Gigawatt
- H&S Hub and Spoke
- H&S farm Offshore wind farm that is connected with a H&S grid connection system
- LCoE Levelized Cost of Energy
- LCoE-R Levelized Cost of Energy including spatial Risk
- MW Megawatt
- MWh Megawatt hour
- NM Nautical Mile
- NSWPH North Sea Wind Power Hub
- O&M Operation and Maintenance
- OpEx Operational Expenditure
- OWF Offshore Wind Farm
- TWh Terawatt hour
- WSI Wind farm Sensitivity Index

## SUMMARY

### Decarbonizing electricity production

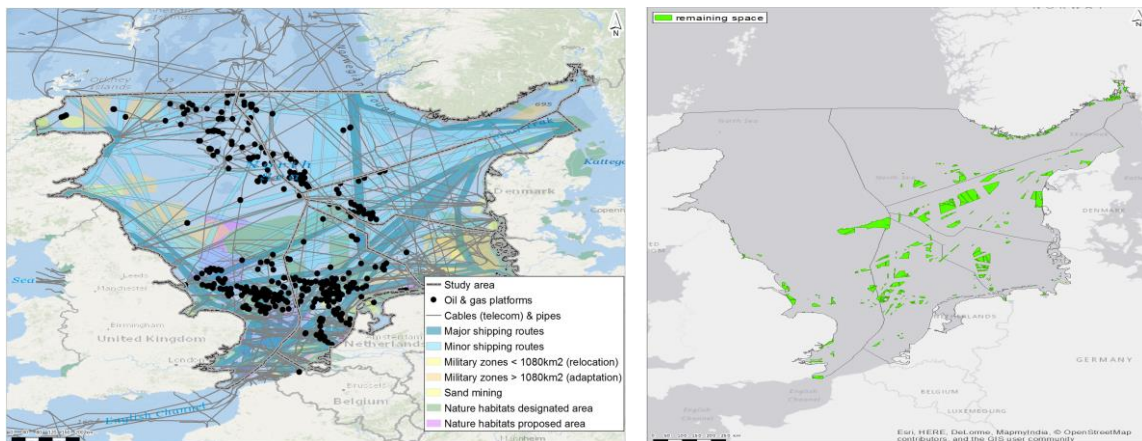
Meeting the climate change targets of the Paris Agreement is a challenge that involves deployment of large scale offshore wind energy production capacity. Recent estimates show that approximately 180 GW of offshore wind capacity is required in the North Sea to decarbonize the power sector of the North Sea Declaration countries<sup>1</sup>.

The North Sea countries<sup>2</sup> have planned new OWF capacity of 55 GW up to 2030 and 20 GW<sup>3</sup> after 2030. This study looks into the OWF locations post 2030. Taking into account the planned capacity up until 2030, an additional 110 GW is expected to be needed.

### Finding space for wind farms in a heavily used sea

The North Sea is used for many different purposes, such as shipping, military exercises, fisheries and sand mining. Figure S1 (left) shows the present space consumption of the various users of the North Sea. Figure S1 (right) shows the remaining suitable space (water depth  $\leq 55$  m) when excluding areas used by other functions.

Figure S1 Present space consumption (left); Remaining space (depth  $\leq 55$  m) when using an exclusionary approach (right)



On the basis of these maps it was calculated that only approximately 3 % of the suitable space<sup>4</sup> remains available for OWFs (14,000 km<sup>2</sup>), if all the used areas are excluded. The remaining space can host 47-84 GW, depending on the used power density<sup>5</sup>. This is less than the strived for 110 GW. It leads to the observation that a co-utilization approach will be necessary in the future<sup>6</sup>. The extent to which co-utilization will be needed highly depends on future developments such as the decommissioning of oil and gas platforms.

### Identifying possible new OWF locations with relatively low cost

Policy makers consider multiple criteria when identifying and selecting new offshore wind farm locations. These criteria include techno-economic considerations (such as water depth, wind speed, cost and subsidies),

<sup>1</sup> By Muller et al. (2017).

<sup>2</sup> Including Norway, the UK, the Netherlands and the North Sea EEZs of Denmark and Germany.

<sup>3</sup> When expressed in terms of the power density of 3.6 MW/km<sup>2</sup>, which is used in this study.

<sup>4</sup> Percentage of the study area, which is the North Sea with a depth  $\leq 55$  meter, minus the EEZ of Belgium and France.

<sup>5</sup> 3.6-6.4 MW/km<sup>2</sup>.

<sup>6</sup> In addition to or as an alternative to an exclusionary approach.



existing spatial claims, the natural environment and public concerns such as visibility. Considering these criteria, the objectives of this study are to:

- 1 identify possible new locations in the North Sea region where OWFs can be developed without excluding areas used by other functions beforehand;
- 2 calculate the levelized cost of energy (LCoE) of these locations;
- 3 take the risk of encountering other user functions into account by means of a first evaluation of the cost of co-utilization (LCoE-R), i.e. the cost of mutual adaptation of user functions and OWFs to each other's presence at sea;
- 4 design grid roll-out pathways to connect the identified new locations to the onshore grid that combine all available grid connection types (AC, DC and H&S);
- 5 discover connected OWF-clusters with a relatively low overall LCoE.

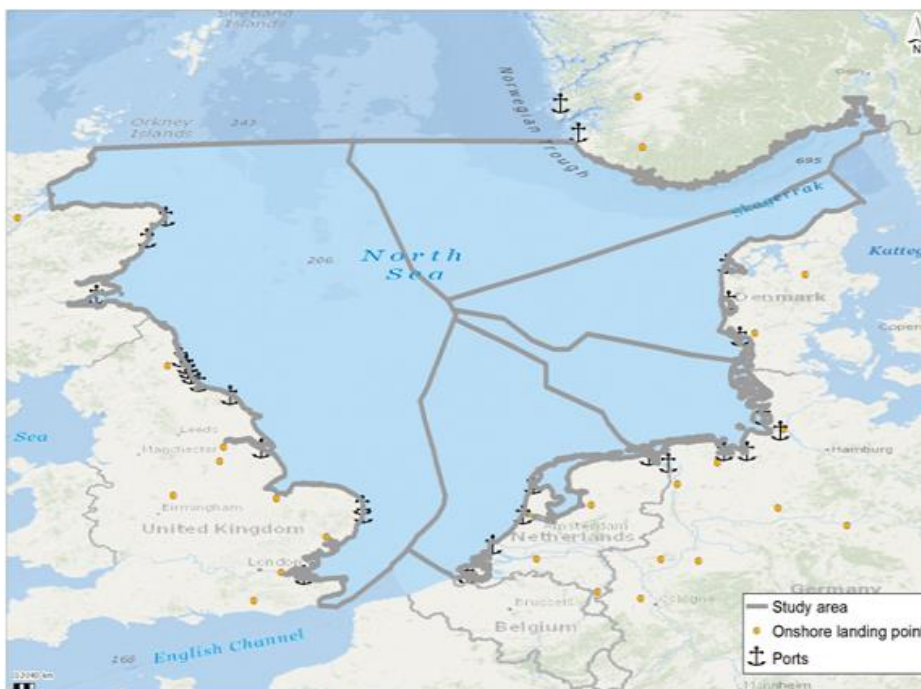
The study provides a basis from which the NSWPH consortium can contribute to the general discussion on North Sea spatial planning by providing insight into offshore wind energy production and transmission costs for different locations across the North Sea.

### Study scope and key assumptions

Figure S2 shows the geographical scope of the study search area. The search area includes the North Sea declaration countries Denmark, Germany, the Netherlands, Norway and the United Kingdom. Only areas with less than 55 m water depth are considered, so that monopiles can be applied.

Two important scoping decisions in this study are (1) the focus on transmission using electrical infrastructure, and (2) the implicit assumption that onshore grid connection points are able to host the capacity that is connected to it in the various grid roll-out pathways.

Figure S2 Geographical scope of the study



### Reference wind farm

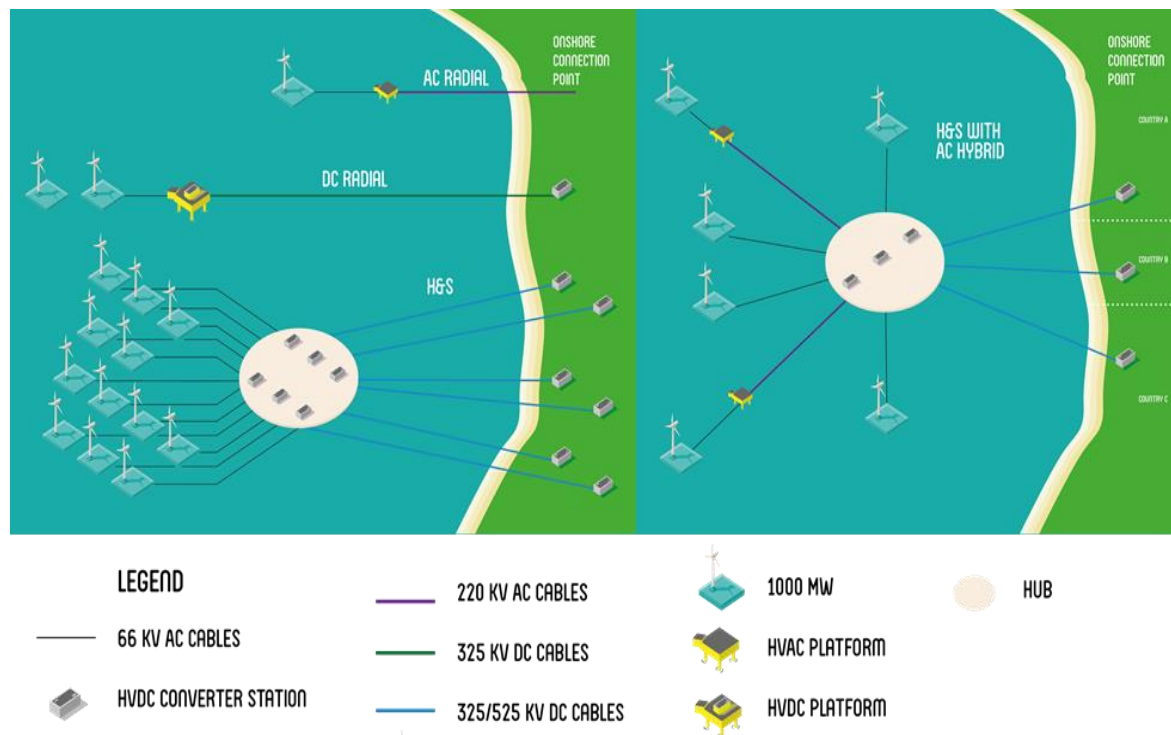
Considering the trend of increasing turbine size and wind farm size, this study uses a 1 GW reference farm for the future that contains 67 turbines (monopiles) of 15 MW. A power density of 3.6 MW/km<sup>2</sup> is used, based on the expectation of ECN part of TNO that this is an optimal future density with an eye on inter-OWF (i.e. OWF cluster) wake losses.

### Grid connection systems

Three different grid connection systems are used in this study: AC radial, DC radial and hub and spoke (H&S) (see figure S3). AC radial is used for farms nearshore (up to 80 km). DC radial is used for isolated farms far from shore (more than 80 km). H&S is applied to clusters of farms far from shore (more than 80 km).

The hubs of the H&S are located within OWF clusters in such a way that each hub can serve as many OWFs as possible. Farms at a distance up to 30 km of a hub are connected to the hub with 66 kV AC inter-array cables. In order to also connect farms at distances up to 80 km of a hub, an extra AC substation is used that is connected to the hub with 220 kV AC cables. The latter is called 'AC hybrid'.

Figure S3 Grid connection systems applied in study



### North Sea covering mapping tool

In this study a mapping tool is developed that calculates and visualises the levelized cost of energy of all grid cells<sup>7</sup> of the North Sea. The tool allows its user to draw new wind farms on the basis of this cost information and to connect them to existing onshore landing points with the grid connection systems AC radial, DC radial and/or the relatively new concept of H&S. Table S1 presents the data used in the mapping tool.

<sup>7</sup> The size of a grid cell is 1/48 degree in longitude and latitude, which is approximately 310 hectares..

Table S1 Data used for maps and formulas

Geographic maps	Cost/Yield Formulas
<ul style="list-style-type: none"> <li>- water depth, waves and wind speed</li> <li>- ports and existing onshore landing points<sup>8</sup></li> <li>- planned OFWs up to and after 2030</li> <li>- user functions, such as shipping routes, military zones, nature areas, sand mining sites etc.</li> </ul>	<ul style="list-style-type: none"> <li>- annual energy production and energy losses</li> <li>- capital and operational expenditure for each OWF asset component<sup>9</sup></li> <li>- capital and operational expenditure for each transmission asset component<sup>10</sup></li> <li>- the adaptation cost of encountering other user functions<sup>11</sup></li> </ul>

### LCoE and LCoE-R calculation

The mapping tool calculates the levelized cost of energy (LCoE) and the levelized cost of energy including spatial planning risk (LCoE-R) on the basis of a reference farm and three reference grid connection systems. The mapping tool calculates LCoEs for the future and therefore relies on assumptions regarding future technology and future economic conditions. This introduces uncertainty in the LCoE results. The uncertainty margins are estimated at approximately -30 % to +50 %. The uncertainty margin for H&S is slightly higher than for AC and DC radial, because it is a new GCS for which there are no experience numbers. Because the applied assumptions are based on expert judgement about component costs for the future, the resulting LCoE-values do not provide a basis for comparison with current bid prices or market values. The primary purpose of calculating LCoE is to provide a relative comparison of locations from a techno-economic perspective. Hence, all LCoE values provided in the report should be interpreted with this in mind.

It may be noted that this study focusses on the costs (LCoE) of producing wind energy and transmission to shore with different GCS concepts, and not on the benefits. Consequently, differences in benefits between the GCS concepts, such as the benefits resulting from interconnection functionality that only the H&S concept offers, are not valued in this study<sup>12</sup>.

Figure S4 illustrates the difference between the LCoE and LCoE-R maps for the H&S grid connection system. A comparison of both maps reveals that LCoE-R map has more green and light blue coloured areas at several locations nearshore. The green areas are sand mining areas. The spatial planning risk of sand mining turns out to be the risk that dominates spatial adaptation costs, reflecting the importance of sand as a key material for coastal defence and the built environment.

<sup>8</sup> Determined in the previous Urgency & Benefit study (Vree and Verkaik, 2017).

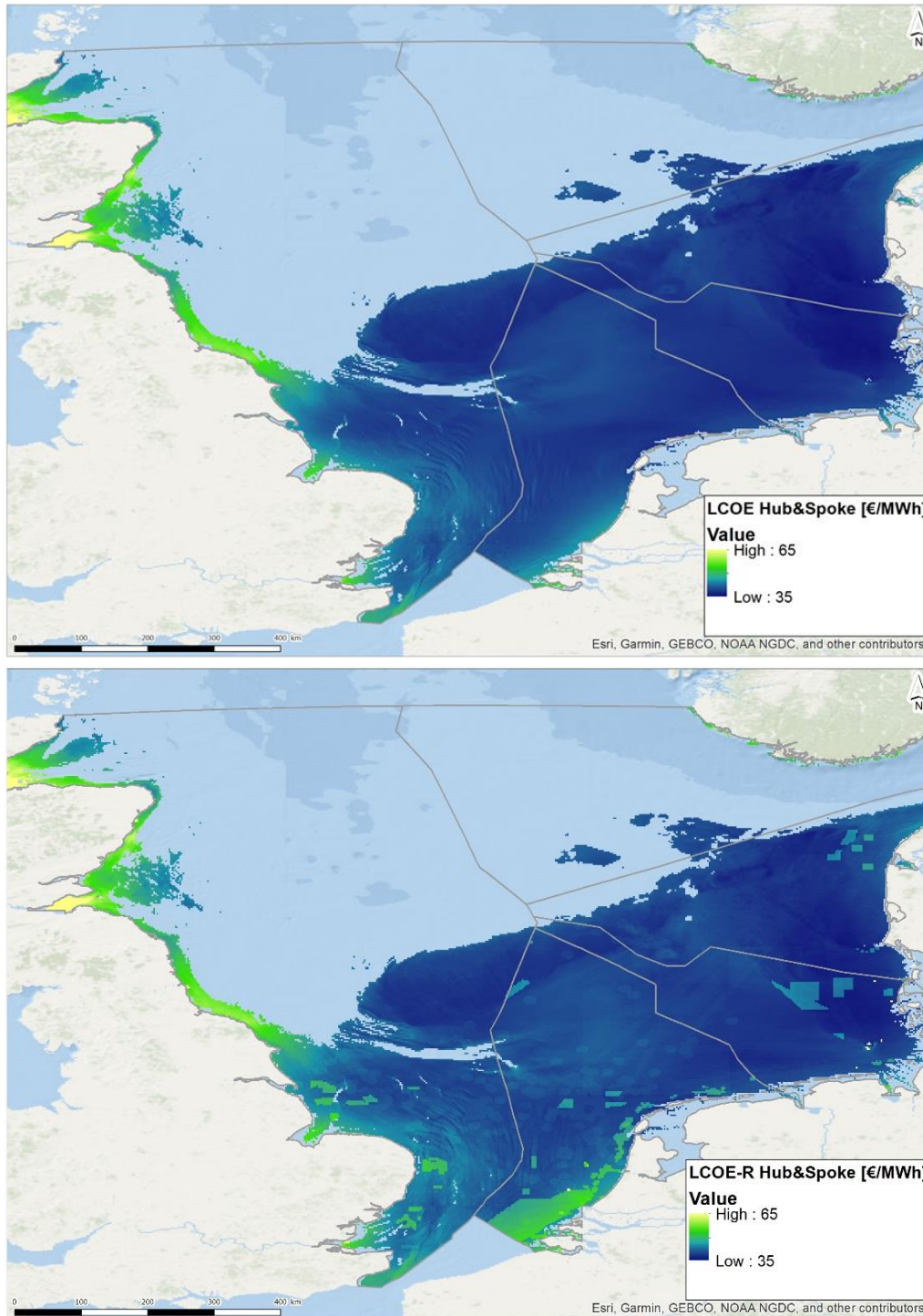
<sup>9</sup> OWF costs provided by ECN part of TNO.

<sup>10</sup> Transmission asset costs provided by NSWPH consortium.

<sup>11</sup> Derived from an earlier study on spatial planning cost (Hoefsloot et al., 2018).

<sup>12</sup> While different cost determining factors such as availability are accounted for.

Figure S4 LCoE (top) and LCoE-R (bottom) maps for the H&S grid connection system

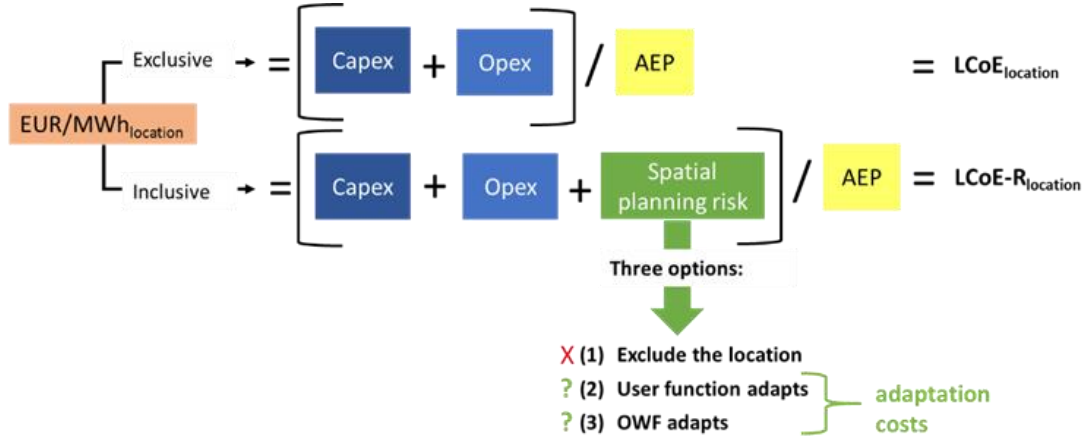


The LCoE is calculated on the basis of the capital and operational expenditure of the OWF and GCS and the annual energy production (see figure S4). Future onshore grid reinforcement costs are not included in the GCS expenditures<sup>13</sup>. As a first approximation for minimising grid integration cost, deeper inland connections have been considered. These connect offshore transmission cables to locations where available connection capacity is expected based on fossil fuel phase-out scenarios.

<sup>13</sup> These costs are deeply uncertain. Since the energy transition requires significant grid reinforcements anyhow, it is questionable whether these costs should be included in the LCoE of offshore wind. A special onshore grid connection study is required to determine these costs, which is outside the scope of this study.

In order to determine the yearly CapEx, the total CapEx over the lifespan of the OWF is divided by an annuity of 20. This annuity is based on a 30 year lifespan plus a discount rate of 2.9 %. The annual energy production corrected for both availability (96-97 %) and the energy losses (1.0-1.2 %) of the OWF and GCS.

Figure S5 LCoE and LCoE-R calculation



The LCoE-R is calculated in a similar way as the LCoE, but it also includes spatial planning risks (see figure S5). Instead of excluding locations that are already used by other functions, the risk of encountering other functions is expressed in terms of adaptation costs. This renders locations that are intensively used by other functions more expensive than those that are not.

Adaptation costs are determined in terms of the cost for adapting the wind farm to the user function or vice versa. For example, in nature areas the wind farms adapt by means of shutting down turbines when birds fly over and/or by applying 'Building with Nature' solutions e.g. scour protection that stimulates reef builder species. For minor shipping routes, the shipping function adapts by sailing around the wind farm, while for major routes, the farm layout is adapted by creating a shipping corridor through the farm. All these adaptations lead to costs which are roughly estimated and included in the LCoE-R maps. These estimates add to the uncertainty range of the LCoE-R and therefore accentuate the need to interpret the values from a relative comparison perspective and not their absolute value.

Though adaptation costs of multiple users at one location are included in the LCoE-R, the cumulative costs caused by the presence of multiple OWFs in the North Sea, i.e. of OWF clusters, are not accounted for<sup>14</sup>. The magnitude of these cumulative costs is not known at this time and difficult to estimate. It is therefore not possible to indicate the impact cumulative costs would have on the LCOE-R.

### Searching for possible new locations from different perspectives

On the basis of the LCoE-R maps possible new OWF locations were identified from three different perspectives:

- low LCoE-R;
- visibility from shore;
- nature conservation.

<sup>14</sup> In this study, the purpose was to let spatial adaptation cost influence the identification of new possible locations. Cumulative adaptation costs of OWF clusters can, however, only be calculated after the selection of a set of new locations.

Table S2 presents the key characteristics of the three sets of possible new locations and of the baseline farms that have been planned up to and after 2030. This table shows that the average LCoEs of the three sets of possible new locations range from 37 to 39 €/MWh, while the average LCoE-R is slightly higher and ranges from 38 to 40 €/MWh. The overall adaptation costs for OWF locations overlapping with existing functions can be calculated by the difference between the average LCoE and LCoE-R of the roll-out list and is approximately 0.6 €/MWh.

Table S2 Key features of the baseline and the three set with possible new locations

Set with possible new locations	Number of OWF	Surface (km <sup>2</sup> )	Capacity (3.6 MW/km <sup>2</sup> ) (GW)	LCoE (€/MWh)	LCoE-R (€/MWh)
Baseline up to 2030	99	13,000	55*	-	-
Baseline planned after 2030	24	5,000	20**	39	40
LCOE-R based set	113	31,000	110	37	38
Visibility based set	130	34,000	120	37	38
Nature based set	87	21,000	77	38	38
<b>OWF roll-out list after 2030 = Baseline planned after 2030 + LCOE-R based set</b>	<b>137</b>	<b>36,000</b>	<b>130</b>	<b>37</b>	<b>38</b>

\* The power density of these OWFs deviates from the power density of the reference farm which is 3.6 MW/km<sup>2</sup>.

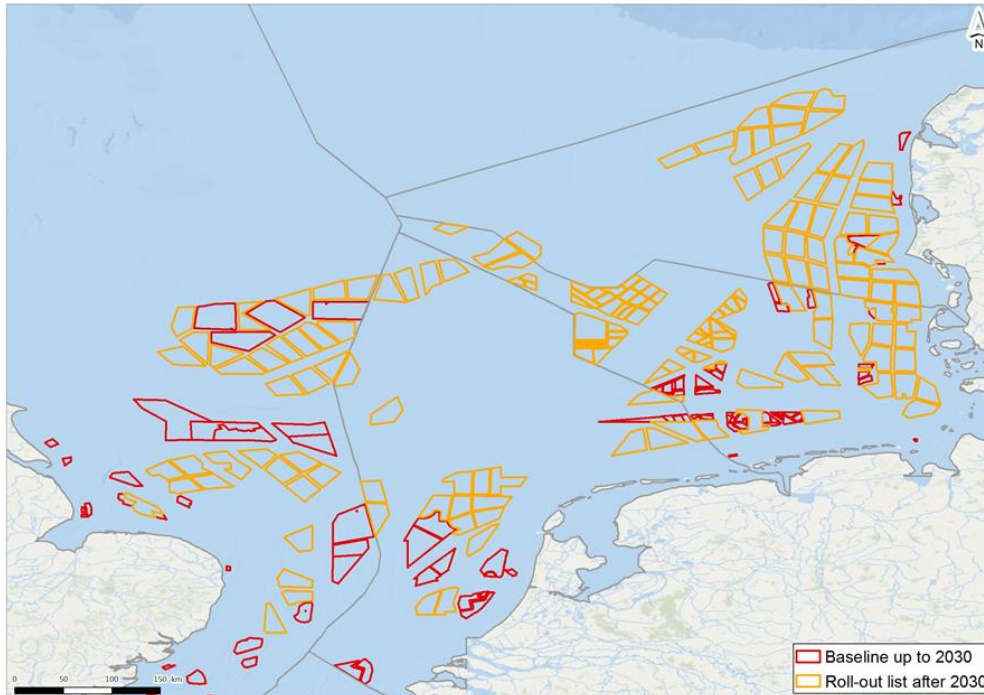
\*\* This capacity is recalculated for a power density of 3.6 MW/km<sup>2</sup>; see appendix 1, table 1.1.

Table S2 also reveals that the set with possible new locations that excludes nature areas has a lower capacity than strived for (77 GW instead of 110 GW<sup>15</sup>). A sensitivity analysis in this study looked at the impact on the overall LCoE by adding OWF locations to compensate for the insufficient capacity level of this set.

A more detailed inspection of the cost numbers disclosed that the LCoE-R based set is economically the most attractive one. Together with the planned baseline locations for the period after 2030 it was therefore selected as a roll-out list, for which grid roll-out pathways are designed. Figure S6 shows this roll-out list.

<sup>15</sup> An extra amount of 110 GW is expected to be needed after 2030 to meet the COP21 target to decarbonize the power sector of the North Sea Declaration countries.

Figure S6 Roll-out list



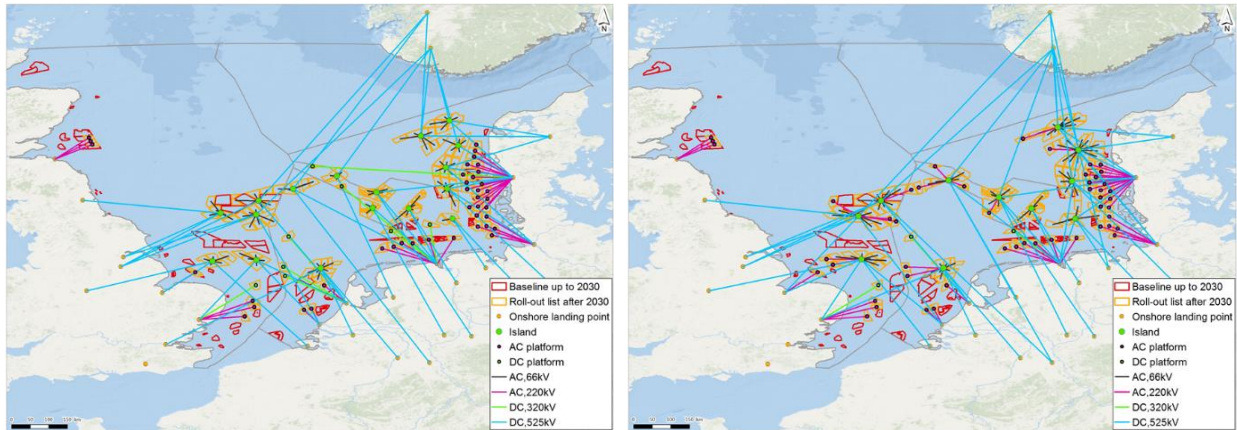
### Designing grid roll-out pathways

For the roll-out list of figure S6, two grid roll-out pathways were designed, following two different approaches:

- a simple roll-out approach, with enough hubs to connect all OWFs. This approach optimized the hub location, taking into account the 66 kV cable reach of 30 km. This roll-out path contains 17 hubs with a capacity ranging from 3 to 8 GW (see figure S7 left);
- a more complex roll-out approach, where the AC hybrid GCS was used to increase the connection reach of the hubs and enabling larger clusters. This roll-out path contains 11 hubs with a capacity of 4 to 14 GW (see figure S7 right).

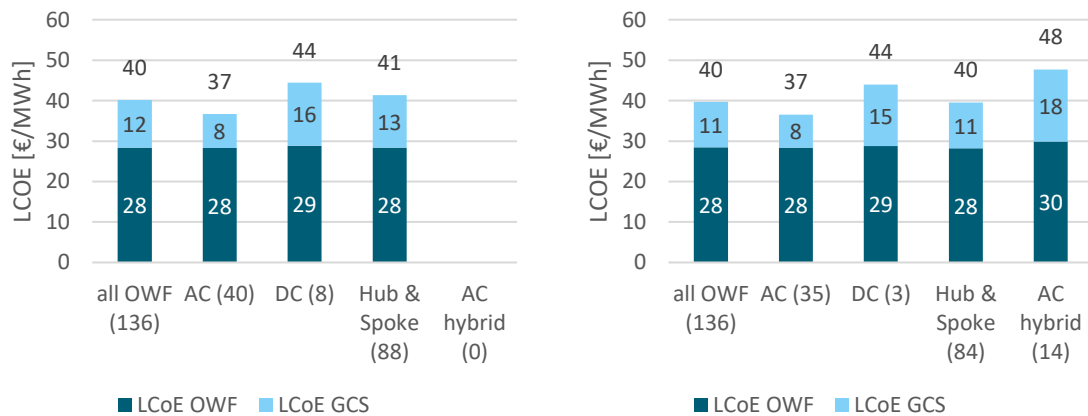
In both cases, near shore farms (35 to 40 farms) were predominantly connected by means of AC radial. A small number of isolated farms (3 to 8 farms) far from shore were connected by DC radial. All other farms (the majority) were connected by H&S, including the AC hybrid variant. Hubs were located in such a way that they could serve as many farms as possible. The hubs were connected to existing onshore landing points in multiple countries. During this grid design exercise for each hub a balance between serving multiple countries and limiting the cable cost was strived for.

Figure S7 Grid roll-out path ways with enough hubs (left) and large hubs (right)



For the two roll-out pathways of figure S7, the LCoE-R was not calculated. The purpose of the LCoE-R was merely to identify new locations, not to design grid roll-out pathways. Therefore only the LCoE of both roll-out pathways was calculated. This was done more accurately than the initial LCoE calculations of the three sets with possible new locations, because in the detailed grid design a more realistic clustering<sup>16</sup> and connection of the hubs was possible. Furthermore, two aspects were added to obtain more accuracy: inter-OWF wake losses and hub economies of scale. Inter-OWF wake losses were calculated on the basis of cluster size in the dominant wind direction. Hub economies of scale were accounted for by applying lower cost per MW for large hubs than for small hubs. The final state of the roll-out pathways was considered, since the sequencing of the OWFs and the roll-out pace were not considered in this exercise. Figure S8 shows the LCoE breakdown of both roll-out pathways.

Figure S8 LCoE breakdown of the roll-out pathways 'enough hubs' (left); 'large hubs' (right)



Both pathways result in a (rounded) average LCoE of all OWFs of 40 €/MWh. A more detailed inspection of the average of both pathways reveals that the 'large hubs' pathway has a LCoE that is 0.4 EUR/MW lower than the 'enough hubs' pathway. This means that there could be modest economies of scale to be gained by reducing the number and increasing the size of hubs. The LCoE breakdown also reveals that farms connected with 'AC hybrid' have relatively high GCS costs, but they reduce the GCS costs for a large number of H&S farms and consequently also the overall LCoE of the roll-out pathway<sup>17</sup>.

<sup>16</sup> Instead of assuming all hubs have the reference size of 12 GW, which was done to identify sets of possible new locations.

<sup>17</sup> There will be a tipping point at which the cost advantage of further increasing hub size is outbalanced by the extra costs of expensive AC hybrid farms.



## Sensitivity analyses

In this study three sensitivity analyses were carried out:

- Sensitivity Analysis 1: Higher power density of OWFs;
- Sensitivity Analysis 2: Using only AC and DC radial GCS to connect OWFs;
- Sensitivity Analysis 3: Selecting locations just outside nature areas.

*Sensitivity Analysis 1* addressed the following key question: *What happens to the LCoE if a higher wind farm power density is applied?* In order to answer this question, a test location in the German Zone 4 was redesigned with two higher power densities than the reference density of 3.6 MW/km<sup>2</sup>: 6.4 and 14.4 MW/km<sup>2</sup>. Subsequently, the LCoE of this location was recalculated for each power density, while taking into account two opposing aspects:

- diseconomies of scale of wake loss: higher power densities induce higher wake losses;
- economies of scale of hub size: more GW on a hubs lowers the costs per GW.

The results of this exercise suggest that hub economies of scale, based on sandy island hubs, seem to surpass wake loss diseconomies of scale. The results also indicate that there is an optimal power density between 6 and 14 MW/km<sup>2</sup> and that above this optimum the impact of wakes losses on LCoE becomes dominant. This means that using a reference OWF with a higher power density (higher than 3.6 MW/km<sup>2</sup>), may further reduce the LCoE while at the same time reducing the space consumption of offshore wind farms, thereby simultaneously reducing the risk of spatial planning conflicts. Further wake loss simulations inside large clusters are required to find the optimal power density.

*Sensitivity Analysis 2* posed the key question: *‘What if all newly identified locations are connected with just AC radial or DC radial and no hubs are applied?’* In order to answer this question all H&S farms of the roll-out list were changed into DC farms, while the AC farms remained the same. Subsequently, the average LCoE of the roll-out list was recalculated.

The results of this exercise reveal that solely relying on AC and DC radial GCS, increases the LCoE with approximately 2.2 €/MWh. Multiplied with the annual energy production of the roll-out list<sup>18</sup>, this amounts to approximately 1,300 M€/year for the 30 years lifetime of the OWFs. This means that the H&S concept can save society a significant amount of costs.

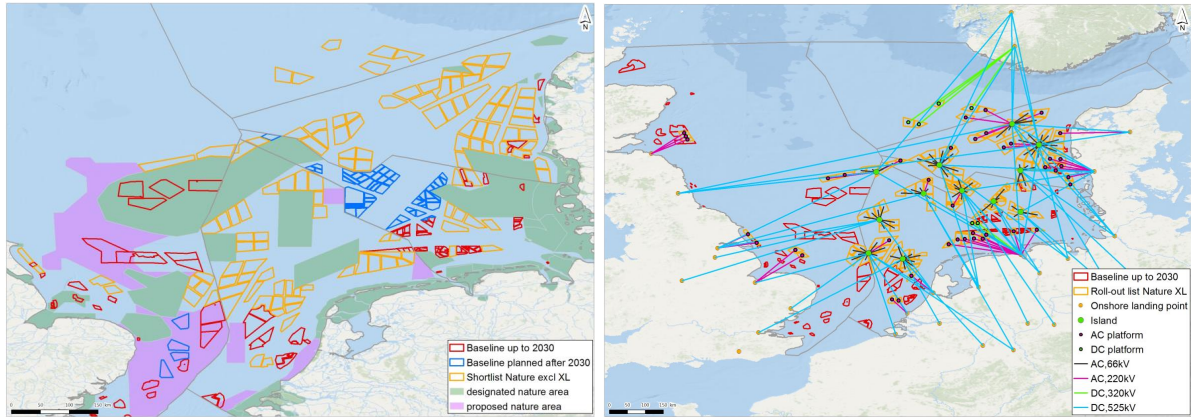
*Sensitivity Analysis 3* focussed on the key question: *‘What will happen to the LCoE if locations just outside nature areas are selected instead of locations inside nature areas?’* The set with possible new locations that excludes nature areas was used to answer this question. This set did not contain any OWFs inside nature areas and as a result its capacity was not sufficient to meet the COP21 target. To compensate this insufficiency, locations just outside nature areas were added (see figure S9). Subsequently, the overall LCoE of the expanded set was calculated.

This exercise reveals that adding extra nature adjacent areas to realize sufficient capacity, increases the LCoE with 1.1 €/MWh. From this one can conclude that it is possible to find sufficient capacity outside of nature conservation areas, but the additional costs to accommodate an exclusionary approach for nature conservations areas, are not negligible. Using an exclusionary approach may require moving OWFs to deeper waters. It may limit the exploitation of economies of scale due to more scattered OWF locations. Policy makers therefore need to carefully weigh the aforementioned costs: are these significant enough to co-utilize nature conservation areas in the development of OWFs? There may also be ecosystem benefits of co-utilization which are not considered in this study.

---

<sup>18</sup> This is approximately 600 TWh/year.

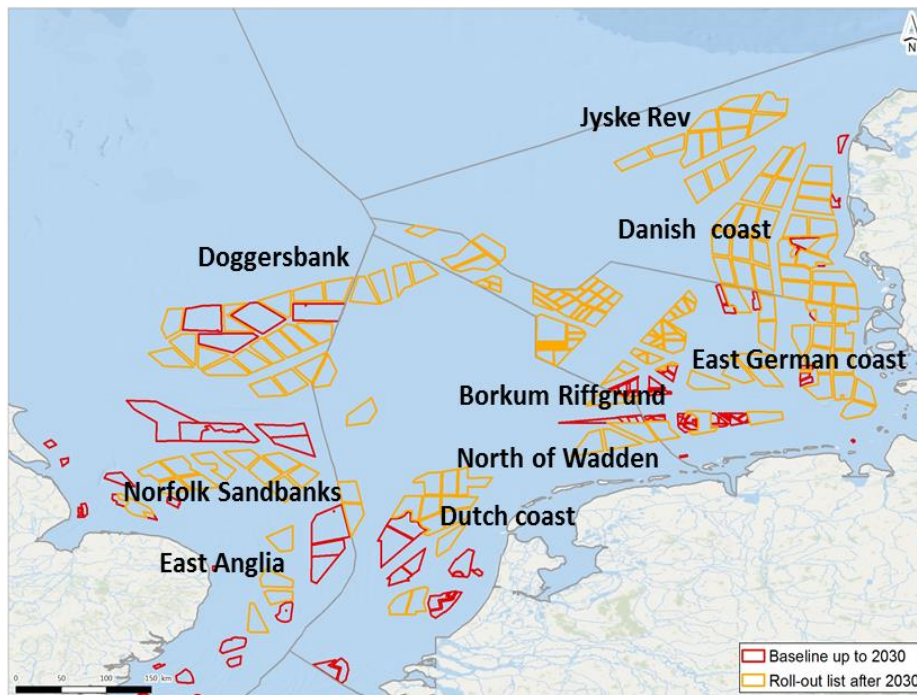
Figure S9 Expanded Nature based set with possible new locations (left) and its roll-out pathway with large hubs (right)



### Main findings

In this study 113 possible new locations were identified with a total capacity of 110 GW<sup>19</sup>. Together with the already planned baseline farms, this adds up to a total roll-out list of 130 GW after 2030. The new locations were found in all parts of the North Sea except for the central part of the Dutch EEZ (see figure S10). They were identified on the basis of relatively low cost per MWh (LCoE-R) and by not excluding any locations that are already used by other functions.

Figure S10 Identified possible new OWF locations range (orange polygons)<sup>20</sup>



<sup>19</sup> The expected extra capacity needed to meet the COP21 target to decarbonize the power sector of the North Sea Declaration countries.

<sup>20</sup> The OWF areas depicted in this figure provide a point of departure to stimulate discussion among various stakeholders. The shape and location of the polygons do not represent any specific policy recommendation.

The levelized cost of energy of individual new locations ranges from 33 to 45 €/MWh<sup>21</sup>. This includes both OWF and GCS costs. Relatively attractive locations in terms of cost were found at Borkum Riffgrund (36 €/MWh), facing the Danish coast (37 €/MWh), the Dutch coast (38 €/MWh), at East Anglia, the Eastern German coast, the Jyske Rev plus to the North of the Wadden (39 €/MWh), at the North Norfolk sandbanks (41 €/MWh) and also at the Doggersbank (42 €/MWh)<sup>22</sup>. It is noted here that the LCoEs are numbers for the future that cannot be compared with current LCoEs. These are first order estimates with a significant uncertainty range. As a result more detailed analysis should be conducted before specific areas can be considered for OWF development.

When inspecting the LCoEs of the individual locations, it is revealed that the baseline farms are at the expensive side of the spectrum. They increase the average LCoE of the total roll-out list. It is also revealed that relatively expensive AC hybrid farms reduce the average LCoE of the total roll-out list. This is primarily due to economies of scale in relation to the hub size.

## Conclusions

A conclusion that can be drawn from this study is that one can find the most economically attractive OWF locations in shallow waters. The LCoE has a strong positive correlation with water depth. From a LCoE perspective, the deep central part of the Dutch EEZ therefore seems less attractive. High energy yields resulting from higher wind speeds make the Danish EEZ around Jyske Rev extra attractive. Another conclusion is that the H&S concept can make far offshore locations nearly as attractive as nearshore locations due to the economies of scale that this concept offers. For an attractive hub location not only wind conditions and water depth are important, but also sufficient space around this hub to connect many wind farms. Not having an exclusionary approach on spatial use can facilitate this, thereby enabling economies of scale.

---

<sup>21</sup> These are numbers for the future (year 2030 and beyond). They are not comparable with today's numbers, because they are based on assumptions concerning future technology and future economic conditions.

<sup>22</sup> This ranking shows that Doggersbank does not have the lowest LCoE, although it seems very attractive on the LCoE colour map. This is caused by the assumption that the UK baseline farms at the Doggersbank will not be connected via H&S, which limits the economies of scale of surrounding hubs.

# 1

## INTRODUCTION

This study provides a basis from which the NSWPH consortium can contribute to the general discussion on North Sea spatial planning of offshore wind energy after the year 2030, by providing insight into offshore wind farm and transmission costs for different locations across the North Sea. In the following paragraphs the background and purpose of conducting this study are briefly described. Finally, a reading guide for this report is presented.

### 1.1 Background

Meeting the climate change targets of the Paris Agreement is a challenge that involves deployment of large scale offshore wind energy production capacity. Recent estimates show that approximately 180 GW of offshore wind capacity is required in the North Sea to decarbonize the power sector of the North Sea Declaration countries.

This raises the question of which locations are attractive for development of offshore wind farms (OWFs). Policy makers consider multiple criteria when planning new offshore wind farm locations. These criteria range from techno-economic considerations (such as water depth, wind resource, cost and subsidies), existing space use (such as sand mining, shipping, military exercise and fisheries), the natural environment, and public concerns such as visibility.

So far offshore wind farm locations have been selected by their proximity to shore and by excluding areas used by other functions as much as possible. When the least intensively used locations are occupied by offshore wind farms in the future, the co-use of locations and mutual adaptation of wind farms and other user functions, needs to be considered.

So far, the majority of offshore wind farms are close to shore (less than 80 km from shore) and built with alternating current (AC), because that is the most cost effective solution. OWFs that are further away (roughly more than 80 km from shore) are traditionally connected either with an AC booster station or with a direct current (DC) connection. In Germany, the latest offshore connection (Borwin 3) is installed approximately 160 km from shore and utilizes HVDC converter platforms. The Borwin 3 connection is expected to go operational in 2019. These connections are, however, relatively expensive solutions. In order to realise affordable offshore wind energy new ways to connect 'far from shore' locations, such as the hub and spoke (H&S) concept need to be considered.

## 1.2 Study purpose

The purpose of this study is to identify new OWF locations post 2030 while considering cost drivers of offshore wind farm and offshore transmission assets development. This study aims to bring an economic perspective and has the following objectives:

- 1 identification of possible new locations in the North Sea region, where OWFs can be developed, without excluding areas used by other functions beforehand;
- 2 calculating the levelized cost of energy (LCoE) of these locations, while taking the adaptation cost of encountering other user functions into account (LCoE-R);
- 3 providing a first evaluation of the cost of co-utilization of space i.e. cost of adaptation;
- 4 designing conceptual roll-out pathways to connect the identified new locations to the onshore grid that combine all available grid connection systems (AC, DC and H&S);
- 5 discovering connected OWF-clusters with a relatively low overall LCoE.

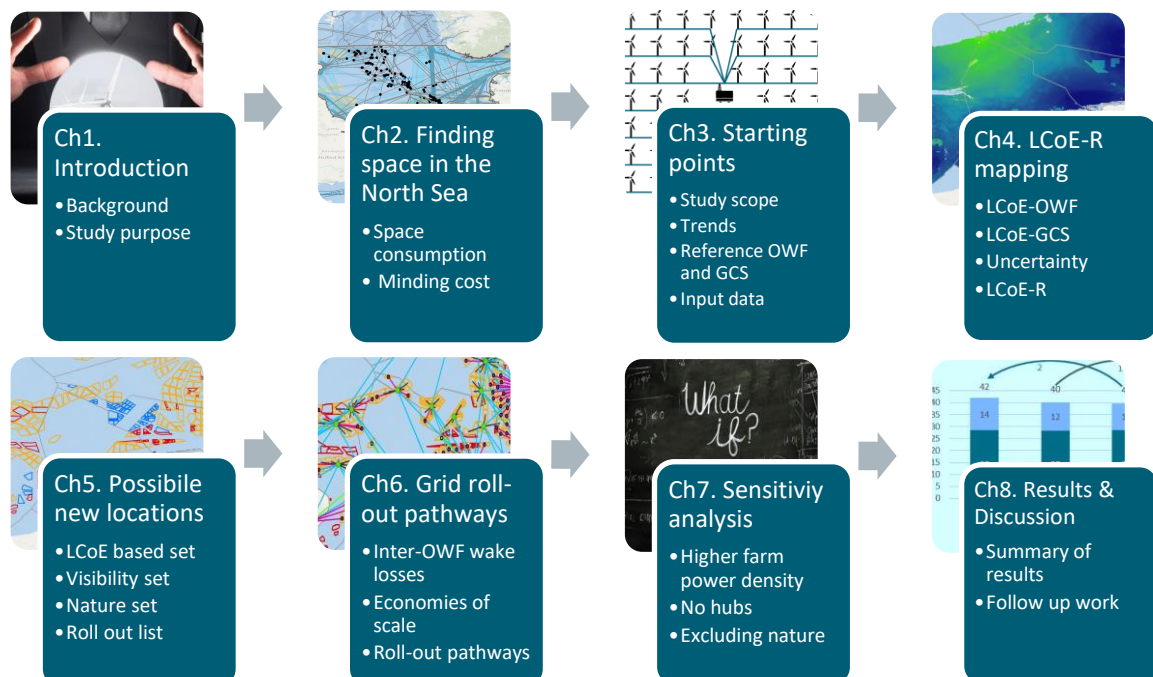
In order to meet these objectives a North Sea covering LCoE-mapping model is built in this study. This model calculates the LCoE and LCoE-R of all locations, i.e. grid cells of the North Sea region, and allows the user to draw wind farms on the basis of this information and to connect them to existing onshore landing points with the grid connection systems AC, DC and/or H&S.

The study also provides a basis from which the NSWPH consortium can contribute to the general discussion of North Sea spatial planning by providing insight into offshore transmission costs for different locations across the North Sea.

## 1.3 Reading guide

To make it easy to navigate the report, figure 1.1 presents a reading guide. This guide shows the structure of the report, which follows the working steps of this spatial study.

Figure 1.1 Structure of this spatial study report



In chapter 2 the two main reasons to search for new OWF locations are elaborated upon:

- the concern whether the amount of space consumed by various sea users leaves enough space for large scale offshore wind deployment;
- the goal to optimize the offshore transmission assets in order to limit the cost of energy production.

In chapter 3 the starting points of this study are presented. The study scope is explained and the trends in offshore wind energy production are described. These trends provide the basis of the lay out of the reference wind farm that is used all through the study. Finally, an overview of key input data used in this study is presented.

In chapter 4 the North Sea covering LCoE-R mapping model is presented that was built to identify possible new OWF locations and to connect them to the onshore grid. Overviews are provided on the used GIS data, calculation formulas, economic input parameters and their uncertainty margins.

In chapter 5 possible new locations for OWFs are determined by means of the LCoE-mapping model. This model generates LCoE-R colour maps that show where economically attractive areas are situated. In these areas new OWFs are drawn from three different search perspectives: low LCoE-R, visibility from shore and nature conservation. Subsequently, the three sets with possible new locations are compared on the amount of GW that they contain, their average LCoE and LCoE-R and their space consumption. On the basis of these characteristics a preferred set is selected.

In chapter 6 two different grid roll-out pathways are designed for the preferred set of possible new locations. Firstly, relevant wake losses are assigned to each OWF. Secondly, all OWFs are connected to the onshore grid with a relevant connection type: AC for farms near the shore, DC for isolated farms far from shore and H&S for farms in clusters far from shore. After connecting the farms to the grid, their grid connection cost are calculated and added up to their OWF cost. Finally, LCoEs are calculated for individual OWF locations and for set of possible new locations. It may be noted that in this chapter LCoE is used, and not LCoE-R. For the purpose of this study the R-component is only relevant to identify locations, not for grid design. This chapter results in two different roll-out pathways for the set with possible new locations: one with simply enough hubs to connect every farm and one with less hubs (but larger) in order to improve the overall LCoE. The difference in LCoE between the two pathways suggests that there are modest economies of scale to be gained by increasing the hub size. This is tested for the three pilot areas. On the basis of these tests, a preferred i.e. optimized roll-out pathway is selected.

In chapter 7 three sensitivity analyses are carried out considering the results of the previous chapter. The first analysis pertains to capturing economies of scale by increasing farm power density in combination with large hubs. In the second analysis it was checked how the LCoE is impacted if the H&S connection is not used and all identified OWFs were to be connected with AC or with DC only. In the third analysis, it is checked what happens to the LCoE when extra OWFs adjacent to nature areas are added as possible new locations so that the amount of GW deployed is aligned with the Paris target without building in nature areas.

Finally, in chapter 8 the key study results are briefly summarized and suggestions for follow up work are made.

# 2

## FINDING SPACE FOR OFFSHORE WIND ENERGY IN THE NORTH SEA

Meeting the climate change targets of the Paris Agreement (COP 21) is a challenge that involves large scale offshore wind energy production. Recent estimates of the amount of offshore wind capacity that is needed in the North Sea by the year 2045 to meet these targets, indicate that approximately 180 GW needs to be deployed<sup>1</sup>. Because the North Sea is used for many different purposes, such as military exercises, fisheries and sand mining, this raises the question of where space can be found for offshore wind energy production. In paragraph 2.1 the present space consumption of the North Sea is therefore investigated.

Appointment of OWF locations by policy makers is generally done by careful evaluation and extensive engagement with all stakeholders to ensure a decision which balances multiple interests. This study focuses primarily on the cost perspective of OWF locations. Once an area has been appointed, the grid connection design needs to be addressed: a design in which every country connects its own OWFs radially back to its own nearest onshore landing points in an incremental manner (National Incremental Roll Out or NIRO) or a design in which countries co-operate and share connections in an International Coordinated Roll Out (ICRO). In paragraph 2.2 the possibilities to and advantages of sharing grid connections are briefly described.

An important aspect of decarbonizing the economy and meeting the Paris agreement is affordability: minding the cost of energy. This raises the question of how the cost offshore wind energy production can be limited. In paragraph 2.3 the idea of smartly making use of economies of scale in offshore grid development is introduced. This can potentially reduce the cost of offshore wind energy production.

### 2.1 Space consumption in the North Sea

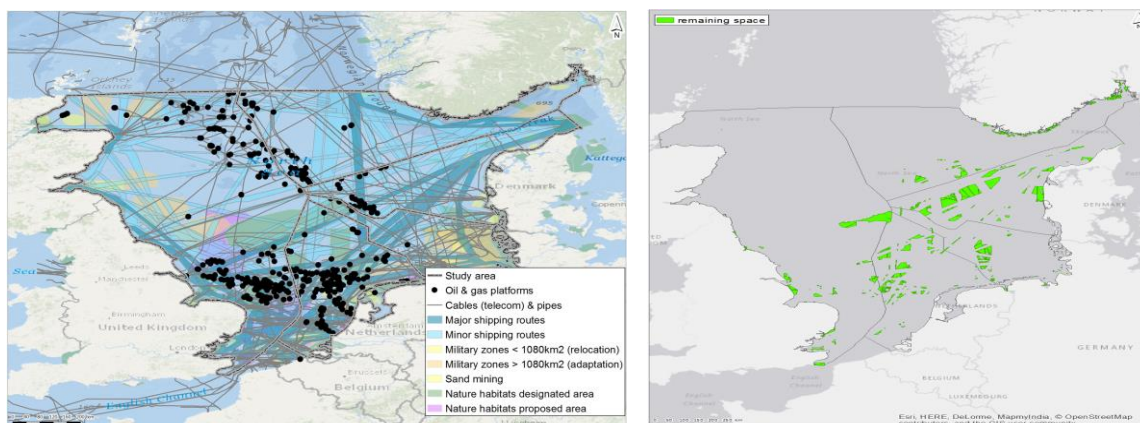
The North Sea may consist of a vast area, but it is not an empty space. In fact, projecting the present space consumption of the various North Sea users into one map, reveals that this sea is heavily used. The left side of figure 2.1 shows where different uses take place<sup>2</sup>. The right side reveals where suitable space (with a depth  $\leq 55$  m) can be found for offshore wind energy when areas are excluded that are already being used by other functions.

---

<sup>1</sup> See Muller et.al., (2017).

<sup>2</sup> Fishery and bird areas are not shown in the left side map, as they are everywhere. The Central Oyster grounds are shown in the left side map, but are not excluded in the right side map, as this nature area does not have a N2000 status, though it is search area for sea bottom protection.

Figure 2.1 Overview of the present space used in the North Sea [left], remaining space (depth < 55 m) [right]



Source: LCoE-R mapping model developed in this study

Figure 2.1 shows that not much space remains to develop offshore wind farms if used areas are excluded. Considering the estimated 180 GW of required installed offshore wind power generation capacity to meet the COP21 target, it was checked whether there is enough space left accommodate such a deployment.

Table 2.1 shows the results of this check. It starts with the parts of the study area<sup>1</sup> with a depth less than 55 m, because deeper areas are not expected to be suitable for bottom mounted wind turbines<sup>2</sup>. Subsequently, the space consumption of each user function (second column) is subtracted from the space use of the previous user function(s), resulting in the remaining space (third column) and how much that remainder is in percentage of the study area. It may be noted that the spatial claims of the user functions sometimes overlap. This is accounted for in the calculation of the remaining space, by only removing a used area once.

Table 2.1 Space consumption and remaining space for OWF

Space use of the North Sea	Space consumption (km <sup>2</sup> )	Remaining space (km <sup>2</sup> )	% of study area	Amount of GW that fits in the remaining space	
				3.6 MW/km <sup>2</sup> (reference farm)	6.4 MW/km <sup>2</sup> (common density****)
Study area (part of the North Sea*)		430,000	100 %	1,600	2,800
Deep areas (> 55 m)	210,000	220,000	52 %	800	1,400
Military zones	30,000	190,000	45 %	700	1,200
Nature areas	69,000	120,000	29 %	450	800
Shipping lanes	85,000	40,000	9 %	140	250
Helicopter zones oil and gas platforms	3,700	36,000	8 %	130	230
Cables & pipes**	3,400	32,000	7 %	120	210
Sand mining	680	32,000	7 %	110	200
Fishery (only heavily trawled***)	2,900	29,000	7 %	100	190
Sea birds (only very sensitive areas****)	15,000	14,000	3 %	49	87
Baseline OWFs up to 2030	470	13,000	3 %	47	84

\* see paragraph 3.1.2; \*\*500 m on both sides; \*\*\*more than two times a year; \*\*\*\* red areas in figure I.4 in Appendix I

\*\*\*\* not for German OWFs, those have higher densities

Source: LCoE-R mapping model developed in this study

<sup>1</sup> See geographical scope in chapter 3.1.

<sup>2</sup> Water deeper than 55 m requires floating turbines, which are currently significantly more expensive than bottom-mounted turbines. It is expected that this will still be the case around the year 2030.



Table 2.1 shows that the present North Sea user functions only leave 3 % of the space free for wind energy. Depending on the wind power density that OWFs may have, this provides space for 47 to 84 GW. Figure 2.1 (right side) shows that the remaining space contains many small fragmented patches that could be considered too small and unattractive for OWF development. This means that in practice the remaining useable space could be even less than 3 %, as larger OWFs are typically considered more attractive to OWF developers. Furthermore, this implies that excluding areas with existing space use, could make it difficult to realise the target of 180 GW of offshore wind.

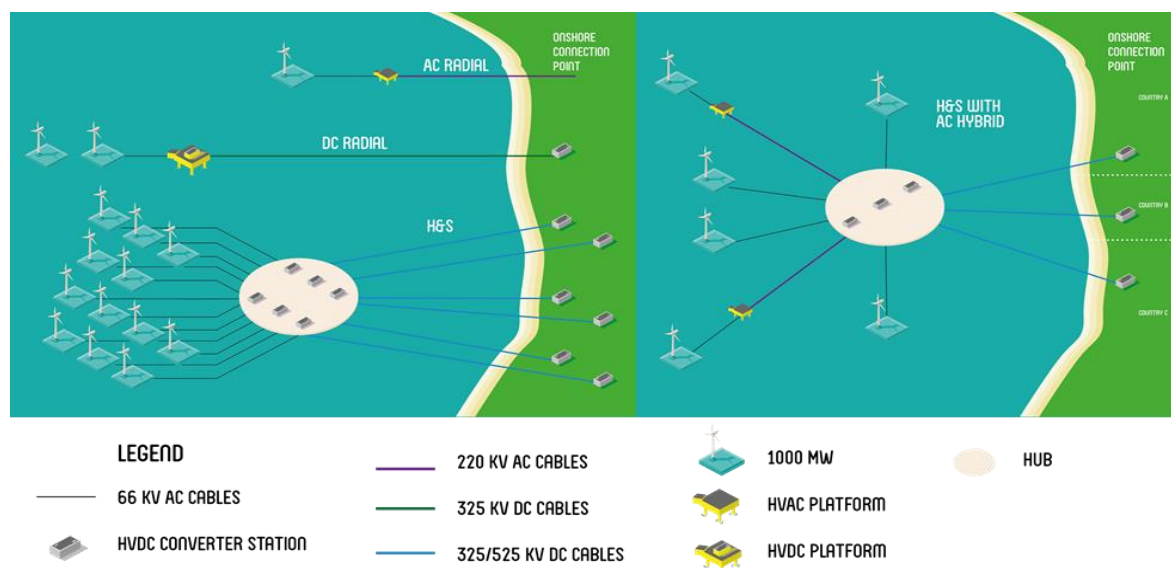
In this study locations with existing space claims are therefore not excluded when identifying possible new locations for OWFs. Instead of excluding locations, the cost of encountering user functions are accounted for in the identification procedure of possible new locations.

## 2.2 Optimizing grid connection design by cooperation between countries

Meeting the climate targets of COP21 requires developing new OWF locations, but it also demands the roll-out of an offshore power transmission grid that delivers generated power to the onshore grid. There are three possible grid connection systems (GCS) to connect OWFs to the onshore grid. The first two are currently used in OWF development, while the third GCS is a new concept that is proposed by the NSWPH consortium:

- 1 AC radial: this GCS uses alternating current technology. The AC-cable cost and energy transport losses are relatively high per kilometre, but the relatively low cost of AC-platforms, make this is the least expensive connection type for wind farms nearshore.
- 2 DC radial: this GCS uses direct current technology. DC-cables have lower costs and lower energy transport losses per kilometre than AC-cables, but their expensive DC-platforms, render this the least expensive connection type for OWFs far from shore and for isolated OWF areas that cannot be clustered and connected to a hub.
- 3 Hub and spoke (H&S) is a relatively new GCS that uses a central hub, possibly in the form of an artificial island, where AC-electricity from a cluster of surrounding OWFs (up to 30 km) is gathered, converted to DC-electricity and then transported to multiple countries via DC-cables (spokes). Farms further away (up to 80 km) can also be connected, but they require an extra AC-substation: this is called AC hybrid as it combines the AC and H&S concept. Although the hub is an expensive component, the H&S concept can be less expensive for OWFs far from shore than the DC-system, because it does not require multiple expensive DC-platforms. On top of this there is potential for capturing economies of scale by connecting as much GW as possible to the hub.

Figure 2.2 Grid connection systems used in this study: AC radial, DC radial and H&S (left), AC hybrid variant of H&S (right)



When looking for new OWF locations after 2030, the focus shifts from nearshore to further offshore since the available nearshore locations in various countries will be to a large extent occupied by then. So far, only AC and DC connections have been applied to OWFs in the North Sea. Considering the potential cost advantage that the H&S GCS has to offer for locations far from shore, all three connections types are applied and compared in this study.

## 2.3 Cost drivers and optimal use of economies of scale

Striving to reduce the societal cost of offshore wind energy development will increase the likelihood that the Paris (COP21) targets are achieved. Identifying OWF locations with low cost per megawatt hour (MWh) due to various techno-economic factors such as shallow water (low building cost) and/or high wind speed (high energy production), is a key factor. Smart use of economies of scale in grid connection is also a relevant factor. This is particularly the case for the H&S connection type. Although this study focuses on the cost factors of OWF location, spatial planning as a whole needs to balance cost information with several other tangible and intangible criteria.

The H&S concept contains hubs, possibly in the form of artificial islands. Previous studies have found that there are economies of scale in building such a hub in the form of sandy islands: larger islands are relatively more cost effective than small islands (Klomp et al., 2017). Large hub islands serving many turbines may have lower grid connection cost per megawatt hour produced than small hub islands serving few turbines.

If serving many turbines per hub reduces the cost, it seems logical to reduce cost by simply increasing farm power density. Unfortunately, increasing farm power density also increases wake losses (Bulder et al., 2018): both wake losses within and between wind farms may increase. In other words: large power densities tend to have diseconomies of scale.

To attempt to save societal cost, this study pays special attention to the trade-off between economies and diseconomies of scale of the combination of hub size and power density (see chapter 7).

# 3

## STARTING POINTS

In this chapter the starting points of this spatial study are presented. Firstly, the study scope is described. Subsequently, relevant trends in offshore wind energy production are investigated in order to define a reference wind farm and reference grid connection systems which are used throughout this study.

### 3.1 Study scope

The purpose of this study is to find possible new OWF locations for after 2030 and investigate LCoE cost drivers. Given the vast amount of space in the North Sea that is already claimed by various user functions (see chapter 2.1), the scope of this study is not to exclude areas used by other functions, but to discover new attractive locations by keeping all options open.

#### 3.1.1 Methodological scope

How can possible new OWF locations be identified on the basis of their levelized cost of energy (LCoE) without excluding areas used by other functions on the one hand, but without ignoring the cost risks that these uses entail from the perspective of both off shore wind farms and other users?

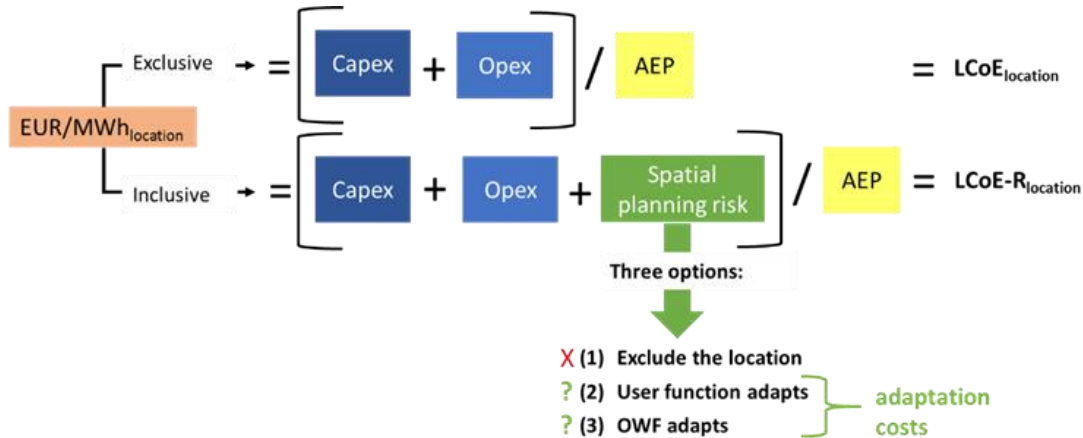
The LCoE of a location (i.e. each grid cell of the North Sea) is determined by dividing the sum of the capital and operational cost by the annual energy production at that location. To account for differences in spatial planning risk between locations, spatial planning costs are also determined. By including these costs in the levelized cost of energy, one can account for spatial planning risks (i.e. the adaptation cost of co-utilization) without excluding locations and thereby create a LCoE-R. In this study spatial planning costs are therefore determined for every possible location in the North Sea. Figure 3.1 illustrates that methodological scope of this study it to calculate both the LCoE and the LCoE-R.

This figure also shows that spatial planning risks can be determined in two different ways:

- the costs of the user function adapting itself to the new situation with offshore wind energy production;
- the costs of the OWF adapting itself to the user function's presence at sea.

In principle, it is possible to determine the risk of each spatial user function both ways and then select the option that produces the lowest risk value. In this study, however, a pragmatic choice is made for each function (see chapter 4.2.1) in order to prevent unnecessary calculations.

Figure 3.1 LCOE and LCOE-R calculation



### Including the cost of multiple use, but excluding the cost of cumulation

The LCOE-R is calculated in order to influence the identification of possible new OWF location.

The adaptation cost of/for each user function is mapped and these cost maps are added up to determine the LCOE-R of a location. This means that locations with multiple user functions are bound to have higher cost than those with only one user function.

Adaptation costs may increase when the number of OWFs in the North Sea becomes larger. For example, the cost of minor shipping routes to adapt to OWFs will be smaller when there are only few OWFs on the route compared to when there are many. With just few OWFs the detour distance will be relatively small, but with many it will be larger. There may not be a linear relation between the adaptation costs and the number of OWFs. In other words: the cumulative adaptation costs of OWF clusters may be larger than the sum of the adaptation costs of individual farms.

In this study cumulative adaptation cost are not determined. This would require a separate study per user function, that is beyond the scope of this study. The results of such studies can only be applied after possible new locations have been selected<sup>1</sup>, while the purpose of the LCOE-R calculation is to include adaptation cost during the selection process of new locations.

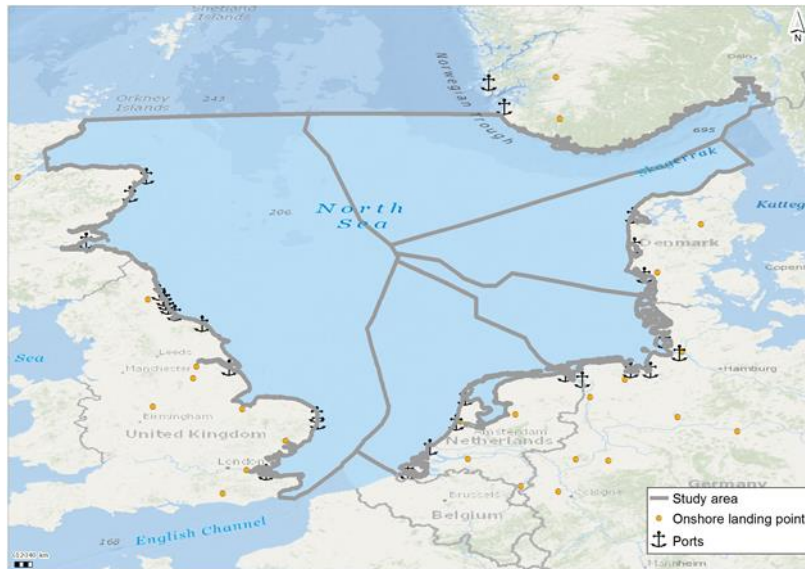
### 3.1.2 Geographical and depth scope

The focus of this spatial study is the central part of the North Sea, with a water depth of less than 55 m. A depth of less than 55 m is used since is a technical requirement of bottom mounted turbines and only this type of turbines is considered (see paragraph 3.3).

Figure 3.2 shows that the study area for which the LCOE and LCOE-R are calculated, follows the boundaries of the North Sea and encompasses an area of 430,000 km<sup>2</sup>. The Belgium and France EEZ areas, and thus the English Channel, are excluded. The Skagerrak Strait is also excluded. Although it is possible to build wind farms in these remote areas, it does not seem straightforward to connect OWFs in those locations to hubs which are in the central North Sea.

<sup>1</sup> In order to determine cumulative costs, one needs to know where OWF clusters are situated.

Figure 3.2 Geographical scope of the study



### 3.1.3 Roll-out scope

This study also aims to identify both attractive new OWF locations and attractive grid roll-out pathways for after 2030. The main purpose of this study is to identify possible locations and not to determine the final wind energy capacity of the North Sea. Therefore the designed roll-out pathways may differ in terms of:

- wind farm locations and their grid connection system;
- the total amount of GW that is realized.

### 3.1.4 Cost scope

For both individual locations and for roll-out pathways both the LCoE and LCoE-R are calculated. The scope of these calculations is to include costs that are distinctive for both location choice and grid roll-out path. Cost components, such as onshore grid reinforcement, energy storage and Power to Gas, are very uncertain and similar for locations and grid roll-out and are therefore not included (in LCoE). As a first approximation for minimising grid integration cost, deeper inland connections have been considered which connect offshore transmission cables to locations where available connection capacity is expected based on fossil fuel phase-out scenarios.

However, spatial planning costs that are too small to have an impact on location choice and/or grid roll-out, are always included (in LCoE-R) for the sake of respecting other sea users interests. A spatial planning cost that may be small in relation to the cost of energy production, may be large in relation to the economic value of the relevant spatial user function. These spatial planning costs are specified in chapter 4.2.2.

It may be noted that some aspects are not taken into account within the LCoE analysis due to their data needs and the expectation that these aspects have little or no impact on the comparison of locations across the North Sea. For example, decommissioning costs, blade degradation and wind hysteresis have not been included in the LCoE calculation. The impact on the LCoE was considered similar across OWFs areas across the North Sea. In paragraph 4.1.4 these omissions are discussed in relation to the uncertainty margins of the LCoEs calculated in this study.

### Spatial risk without process costs

It should be noted here that the spatial costs do not include the extra process costs that are likely to occur whenever a wind farm meets another user function e.g. project delays or additional costs for permitting. Even if there is no conflict, stakeholders will fend for their interests and there will be communication cost on part of the wind farm developers and on part of the stakeholders i.e. user functions and on part of the involved governments.

Though the process cost could be significant, their magnitude cannot easily be determined and included in the spatial cost calculations. It would entail finding out how much extra procedure time is spent (e.g. on law suits and negotiations) each time a wind farm has engage with another user function. This does not fit within the scope and timeframe of this study. It is recognized that the spatial planning cost could be underestimated due to excluding process cost. Since the cost of all user functions are underestimated, this will not significantly influence the relative difference between user functions. It will however influence the absolute magnitude of the spatial planning cost and thus particularly the LCoE-R of locations with multiple users.

Another possible source of underestimation of spatial planning costs is that the cumulative cost of spatial claims (i.e. of co-utilization) of the total OWF deployment is not part of the scope of this study.

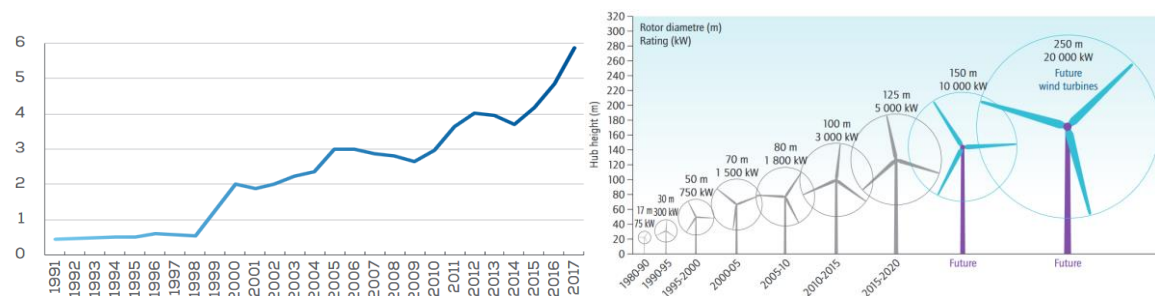
## 3.2 Trends in of offshore wind energy production

In order to determine the future wind farm lay out and future grid connection for the year 2030 trends in turbine size, wind farms size, power density and grid connection are investigated.

### Turbine size

Figure 3.3 shows the developments in turbine size. The trend is a rapidly increasing turbine size.

Figure 3.3 Yearly average of newly-installed offshore wind turbine rated capacity (MW)



Source: Remy et al., 2018 (left) and IEA, 2013 (right)

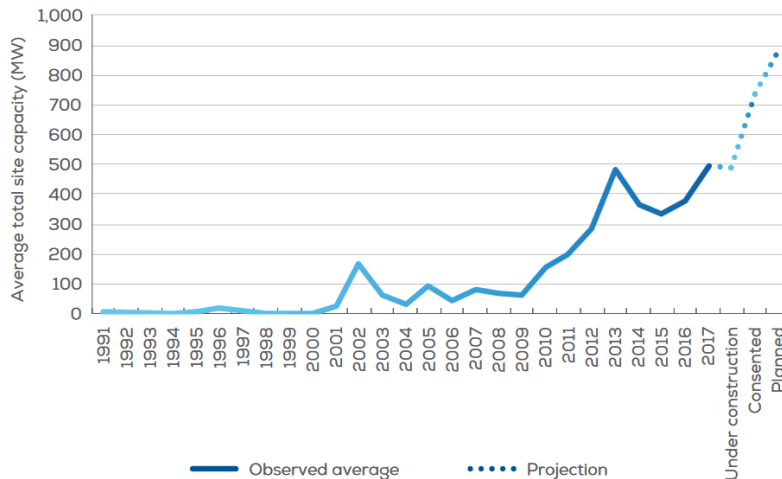
Given these trends, a fixed bottom mounted turbine size of 15 MW (monopile, with a rotor diameter of 250 m and a hub height of 155 m seems realistic for after 2030<sup>1</sup>.

### Wind farm size

Figure 3.4 shows the development of the average size of offshore wind farms: the trend is an increasing farm size up to 1 GW.

<sup>1</sup> Expert judgement by ECN part of TNO for this study (2018).

Figure 3.4 Average size of OWF projects (MW) commissioned per year



Source: Remy et al., 2018

Considering these developments, future OWFs are expected to have a capacity of 1 GW by the year 2030.

### Farm power density

Current power densities vary among existing OWFs in the North Sea and range from approximately 4 to 14 MW/km<sup>2</sup> (Bulder et al. 2018)<sup>1</sup>. A decrease in farm power density is expected because larger spacing between turbines reduces the wake effects (i.e. turbines ‘stealing’ each other’s wind<sup>2</sup>) that occur inside wind farms and in clusters of wind farms (Bulder et al., 2018).

Based on the expected optimal farm power density by ECN part of TNO for the year 2030, a reference power density of 3.6 MW/km<sup>2</sup> is used in this study.

### Grid reinforcement

Large scale offshore wind energy production is likely to require onshore grid reinforcement due to increasing demand-supply distances and increasing peak loads.

The distance between electricity demand centres and supply will probably grow. Power plants near energy demand centres will likely be replaced by wind and solar farms that are located offshore and in rural areas. In rural areas the local grid cannot handle the energy supply of wind and solar farms. As a consequence, offshore transmission system operators need to construct new offshore grids to bring energy ashore. They may also need to reinforce onshore connection points and the onshore power grid.

Peak loads may increase for two reasons:

- heating of buildings, mobility and industrial production will be electrified;
- base load power plants are replaced by intermittent renewable sources, which require more installed capacity (MW) for the same amount of energy production (MWh).

Increasing peak loads will likely require electricity grid reinforcement, but both hydrogen conversion and energy storage can lower the need for this reinforcement. By 2030 hydrogen could play a role in heating, mobility and industry, possibly resulting in less electrification. When applied to wind and solar farms, hydrogen conversion and energy storage could flatten renewable energy sources’ intermittent nature and thereby reduce the need for grid reinforcement.

<sup>1</sup> PBL’s report “The Future of the North Sea” (Matthijssen, J., E. Dammers and H. Elzenga, 2018) uses a power density of 6 MW/km<sup>2</sup>, whereas the Wind Europe’s “Unleashing offshore wind potential” (Hundleby, G. and K. Freeman, 2017) uses a power density of 5.4 MW/km<sup>2</sup>.

<sup>2</sup> Wind farms are “blocked” by other wind farms and become dependent on a vertical flux of wind energy from higher layers.

Given these developments it is expected that large scale offshore wind energy production will lead to extra costs to reinforce the onshore grid. The required magnitude of these reinforcements is deeply unknown and not easy to predict. It would require a special prediction study. Such a prediction study does not fit within the scope and timespan of this study. Consequently, grid reinforcement costs are not included in the LCoE calculations in this study.

### 3.3 Reference wind farm and grid connection for this study

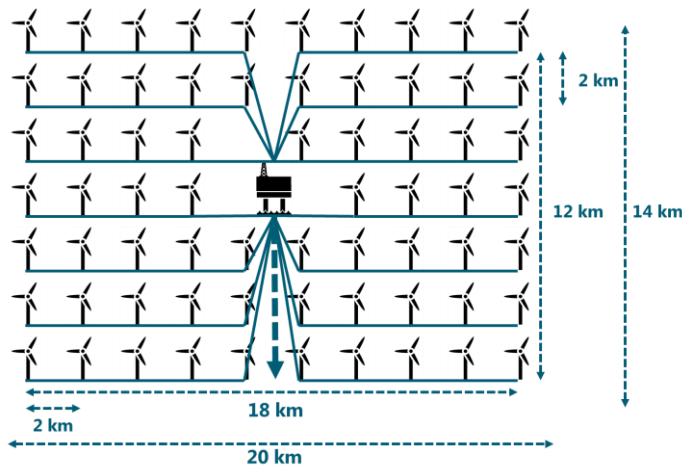
#### Reference wind farm for this study

Based on the previously described trends, table 3.1 summarizes the characteristics of the reference wind farm that is used throughout this study. Figure 3.5 shows a sketch of the wind farm layout.

Table 3.1 Reference wind farm characteristics

Element	Units	Reference
turbine nominal power	MW	15
rotor diameter (D)	m	250
hub height	m	155
turbine type	-	fixed bottom mounted monopile
turbine spacing	km	$8 \cdot D = 2$
farm power density	MW/km <sup>2</sup>	3.6
number of wind turbines	-	67
reference farm nominal power	GW	1

Figure 3.5 Sketch of the lay out of the reference farm





### Reference grid connection systems for this study

For the offshore grid connection, the following starting points are used throughout this study:

- transmission of power generated by the OWFs is through the use of electrical infrastructure only;
- three electrical GCSs are used: AC radial, DC radial and hub and spoke (H&S) are the three reference grid connection systems considered in this study;
- only existing onshore grid connection points are used (see figure 3.6, left top)<sup>1</sup>;
- onshore grid reinforcements are not accounted in the reference grid connection.

Figure 2.2 in chapter 2.2 provides a sketch of the three reference grid connection systems that are used in this study.

## 3.4 Used input data

In this study several data sources are used. These concern OWF-locations that have already been planned up to the year 2030 by the North Sea countries' governments, i.e. The baseline parks, maps with onshore landing points, port, water depth, wind speed, waves and maps with the different space uses at the North Sea such as fisheries and shipping. Table 3.2 provides an overview of the key data used and their sources. Figure 3.6 shows the key maps that were used as starting points.

Table 3.2 Key input data

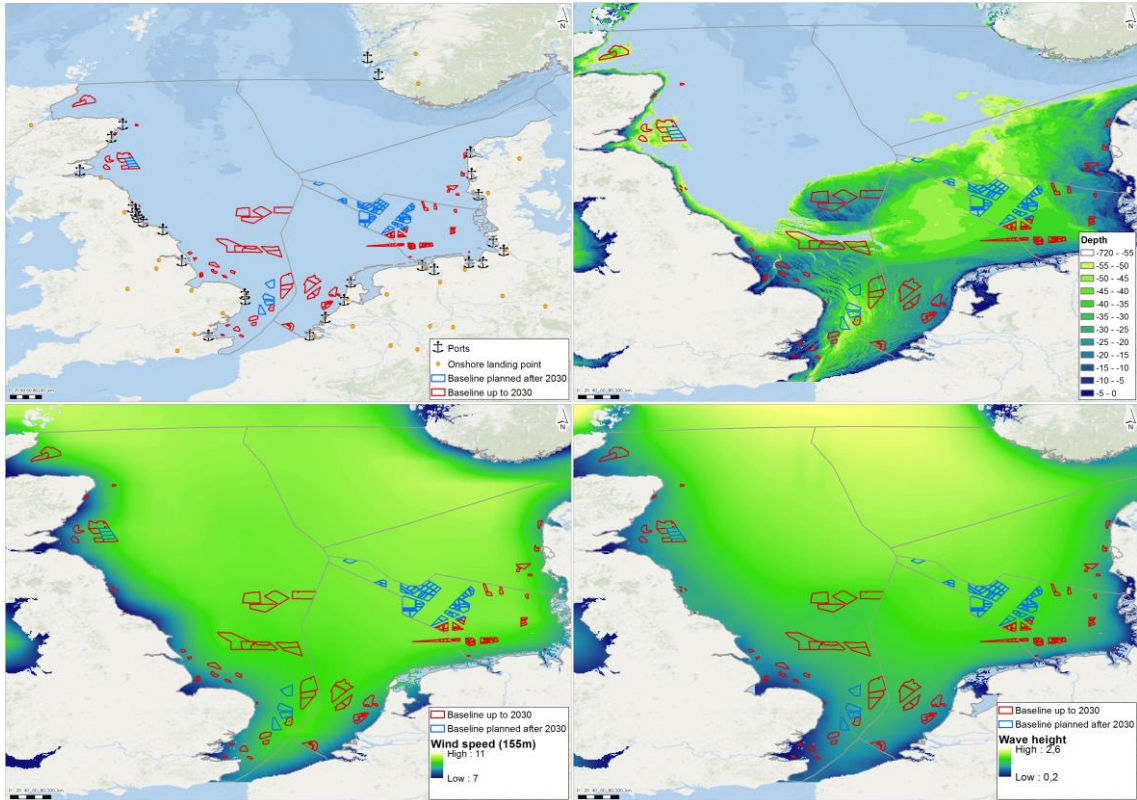
Input	Source
baseline OWF	Vree and Verkaik, (2017), NSWPH consortium, The Crown Estate UK
onshore landing points	Vree and Verkaik, (2017)
ports	ports.com
depth	EMODnet-bathymetry.eu
windspeed at hub height (155 m)	NOAA NCEP Climate Forecast System Reanalysis (CFSR)
windspeed at 10 m	NOAA Wavewatch III
waves	NOAA Wavewatch III
cost information OWF	ECN part of TNO cost modelling with simulations for operation and maintenance, for substructure and for energy yield and wake losse
cost information GCS	experience numbers provided by the NSWPH consortium <sup>2</sup>
cost information sandy hub islands	Klomp et al., (2014)
space use by other functions	Imares maps (Jongbloed et al., 2014)

Chapter 4 provides the key economic parameters used as starting points. For most spatial user functions GIS maps generated by IMARES (Jongbloed et al., 2014) are used: this source is chosen because it is North Sea covering and the maps- particularly the maps for nature and shipping- are tailor made for offshore wind studies. Appendix I presents the space use maps that were used in this study. In this appendix it is also described if and how the space use was updated for the year 2030 by investigating trends.

<sup>1</sup> The onshore grid connection points were derived from a study by Vree and Verkaik (2017), which forecasted the future available hosting capacity of these onshore grid connection points based on the expected phasing-out of fossil fuelled power generation.

<sup>2</sup> These cost estimates are based on internal cost estimates by TenneT and Energinet.

Figure 3.6 Ports, landing points (left top), depth (right top), wind speed (left bottom), wave height (right bottom)



Source: LCoE-R mapping model developed in this study

# 4

## LCOE-R MAPPING MODEL

In this chapter new potential OWF locations are identified on the basis of North Sea covering LCoE and LCoE-R maps. First, the key principles and calculation formulas of the LCoE and LCoE-R maps are explained. Subsequently, the resulting LCoE and LCoE-R maps are presented and finally potential new locations are identified by means of these maps.

### 4.1 LCoE mapping

In this study, a grid based North Sea covering LCoE mapping model was built, inspired by Gerrits (2017), as a tool for identifying new OWF locations for the period after 2030. This mapping model consists of basic maps, with a resolution of 1/48 degree in longitude and latitude, such as water depth, wave height and wind speed, which determine costs and yields of an OWF. The model contains calculation formulas for all wind farm cost components, for energy yields and for all grid connection cost components of the three considered GCSs (AC radial, DC radial and H&S).

#### 4.1.1 LCoE formula

The levelized cost of energy (LCoE) is calculated on the basis of a reference OWF of 1 GW. This means that for every grid cell in the North Sea, the total cost to build and operate the reference wind farm there are estimated. In order to estimate these total costs, cost formulas that predict the cost on the basis of metocean conditions (such as water depth and wind speed), were developed for all OWF components (such as turbines and intra array cables) and for all GCS components (such as cables to land and transformer substations).

The **LCoE** calculation is based on the formula shown below. This formula considers:

- the annuity factor ***a*** of 20 years;
- the capital expenditure **CapEx**, for which there is a cost formula for investment for every component;
- the yearly operational expenditure **OpEx** which were either a fixed yearly value or a percentage of CapEx;
- the Annual Energy Production **AEP**, which is effected by:
  - availability of the OWF and the GCS;
  - energy losses per OWF and GCS component.

$$LCoE = \frac{\left(\frac{CapEx}{a} + OpEx\right)}{AEP}$$

#### Annuity (***a***)

The annuity (***a***) is used to determine a yearly value for CapEx. It depends on the discount rate and the depreciation period. A real discount rate of 2.9 % and a depreciation period of 30 years are used in this study, resulting in an annuity of approximately 20 years. Table 4.1 shows these assumptions.

Table 4.1 Economic assumptions\*

Component	Assumption
nominal discount rate (R)	4.4 %
inflation rate (i)	1.5 %
real discount rate ( $r = \frac{(1+R)}{(1+i)} - 1$ )	2.9 %
depreciation period	30 years
annuity ( $a = \frac{1-(1+r)^{-n}}{r}$ )	20 years

\* Based on international study results commissioned by the NSWPH consortium

### Annual Energy Production (AEP)

The AEP is calculated for the 1 GW reference farm layout on the basis of a wind farm power curve created by ECN part of TNO. This curve includes internal drive train efficiency losses and detailed wake losses that were calculated with *FarmFlow*. In the mapping phase of this study, i.e. The identification phase of potential new OWF locations, neighbouring wind farms are not taken into account. In the grid roll-out phase of this study, however, neighbouring farms are accounted for by an additional inter-OWF wake loss factor. Wind speed probability distributions are assumed to vary by direction sector. They are scaled according to the mean wind speed at hub height and Weibull distribution shape factor in order to create probabilities for each combination of wind speed and wind direction. Figure 4.1 shows resulting the lookup table for AEP before losses.

Before the AEP can be entered into the LCoE formula, it needs to be corrected for electrical energy losses and availability. The availability of the OWF is between 96.3 % and 96.5 % depending on maintenance times, which in turn depends on wave height, wind speed and distance to port. The GCS availability for AC, DC and H&S is respectively 98.6 %, 96.4 % and 99.0 % of the year. The electrical losses consist of a fixed percentage for transformer losses and a loss per km export cable. Especially the latter is higher for AC (150 kW/km) than for DC (45 kW/km).

Figure 4.1 Annual Energy Production (AEP) lookup table before energy losses

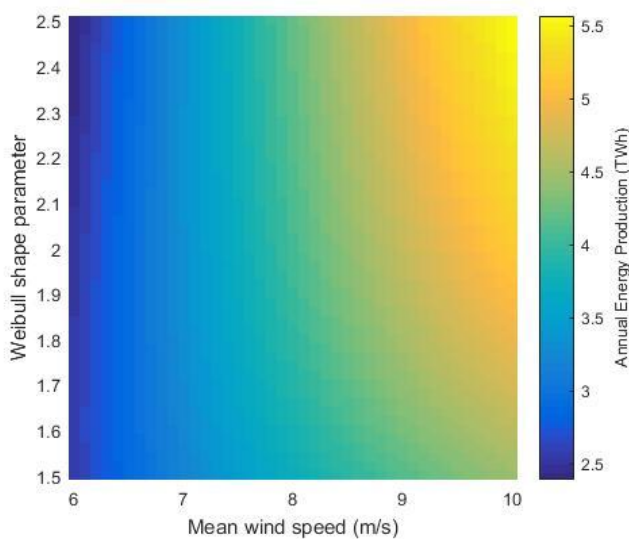
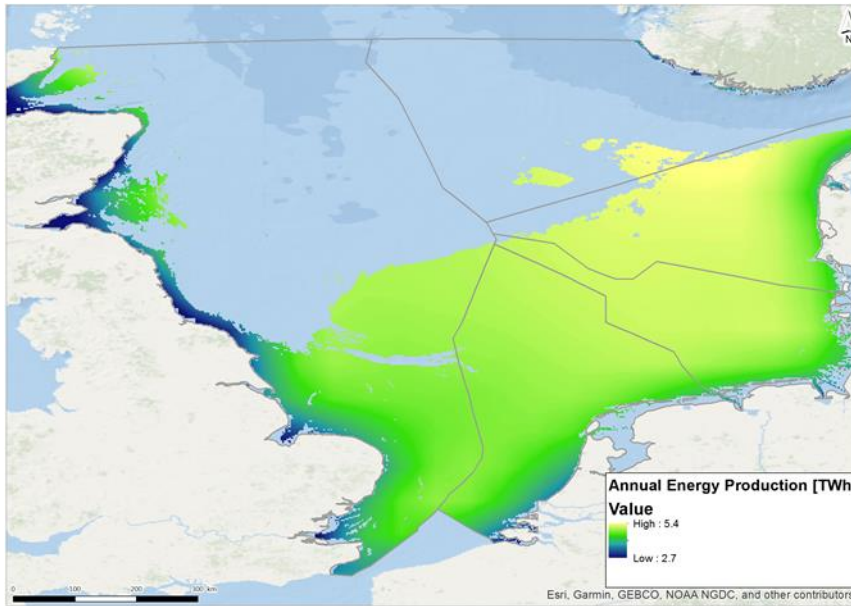


Figure 4.2 shows the annual energy production map of the study area. This map is the result of filling out the AEP lookup table for every grid cell and correcting the resulting value for energy losses. Energy yields are

relatively high in north eastern part of the sea. The colour legend of figure 4.2 reveals that the annual energy production ranges from 2.7 to 5.4 TWh per year. This corresponds with a capacity factor of 30 to 62 %.

Figure 4.2 Annual energy production map of the North Sea

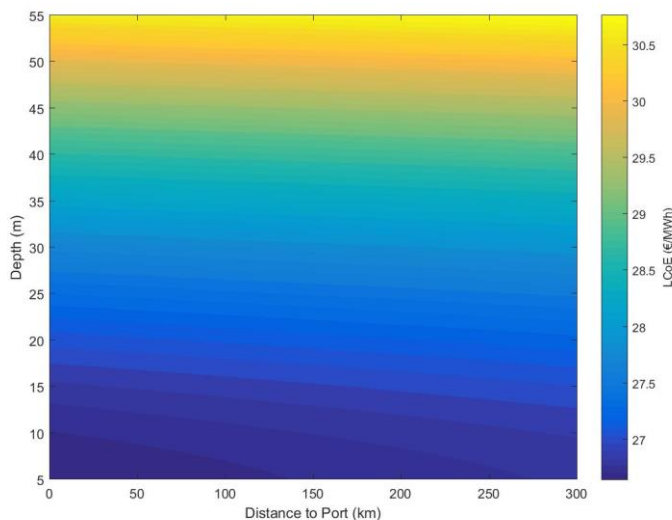


Source: LCoE-R mapping model developed in this study

#### 4.1.2 OWF cost formulas

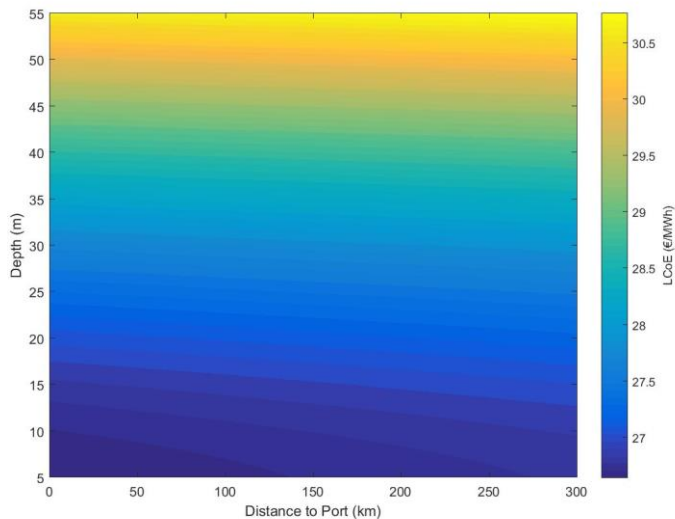
ECN part of TNO has developed formulas for this study to estimate the capital and operational expenditures of the different OWF components. The CapEx components are wind turbine, substructure, intra array cables project development and installation. The OpEx consists of operation and maintenance. The cost formulas of these components were entered into the LCoE formula. The results of this exercise can be summarized in the form of lookup tables. Figure 4.3 shows these look up tables for radial AC or DC and figure 4.4 for H&S<sup>1</sup>.

Figure 4.3 LCoE OWF look up table for radial AC or DC



<sup>1</sup> For both lookup tables a reference AEP of 5 TWh was used. In the mapping tool the location specific AEP is used.

Figure 4.4 LCoE OWF in case of H&S



### Wind turbine

The costs of the reference turbine are determined by calculating each component of the nacelle and blades using ECN part of TNOs cost modelling tools and knowledge. This resulted in 14 M€ per 15 MW turbine.

### Substructure

The costs of the substructure underneath the turbine are determined on the basis of the required mass of the tower, transition piece and monopile foundation for the 15 MW reference turbine. The cost equation is fitted to the data run for several water depths in a formula for substructure cost based on water depth. This formula ranges from 5.1 M€ at 5 m water depth and 10 M€ at 55 m depth.

### Intra-array cable

The intra-array cables are calculated based on a full electrical engineering design of cable requirements. This resulted in 180 km of 66 kV intra-array cables within the reference wind farm that cost 40 M€.

### Project development

The project development costs are assumed to be in total 100 M€ for a 1 GW wind farm and include all costs up to the start of construction. This is based on extrapolation experience with smaller wind farms. For 300-500 MW wind farms, the total costs amounted to 60 M€.

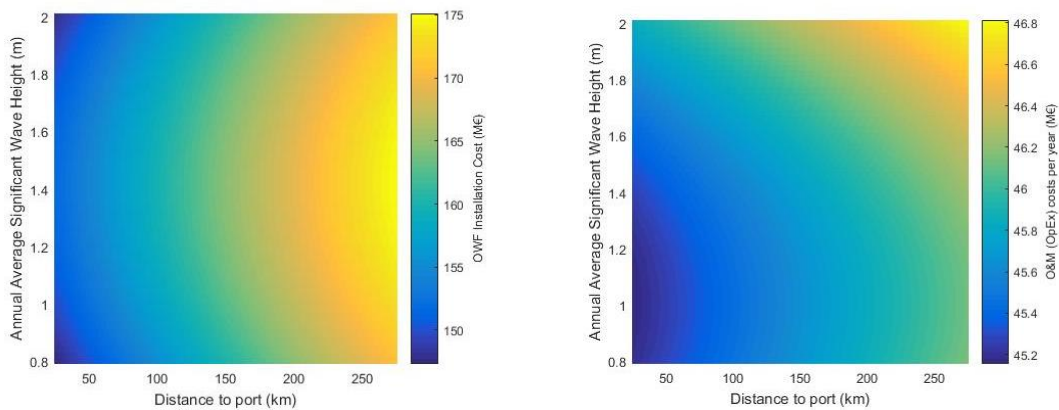
### Installation

Installation of the wind turbines and inter-array cables are calculated by means of simulations using the ECN part of TNO *model Install*. All vessels and components are assumed to depart from a single mainland port, for the sake of simplification. Water depth affects substructure mass, which in turn determines how many foundations and towers can be carried in one trip of the installation vessel. A modern 5,000 t vessel is used for one set of simulations and a 8,000 t vessel is used for another set. The day-rate cost of vessels is assumed to scale in proportion to their carrying capacity. In the simulations, distance from port and wind (mean speed) and wave (mean wave height) data are varied. From the results of these simulations, a lookup table for the cheapest strategy is created. This lookup table is shown in figure 4.5 (left).

As the installation costs lookup table depends on mean wind speed at 10 m and mean wave height<sup>1</sup>, it can be used to estimate the O&M costs (see figure 4.5, right). In the aggregated LCoE lookup tables in figure 4.3 and 4.4, that were shown before, fixed values of 8.5 m/s wind speed at 10 m and 1.5 m waves were chosen.

<sup>1</sup> Year round wave climats were simulated and turned out to correlate sufficiently with average wave heights, to allow operation and maintenance cost to be calculated on the basis of average wave heights.

Figure 4.5 OWF installation costs (left) and OWF O&M costs (right)



### Operation & Maintenance (O&M)

The main difference for the OpEx between the three grid connection systems is that for AC and DC, maintenance takes place from the nearest mainland port, while for H&S it takes place from the port on the hub. Several maintenance strategies were simulated using ECN part of TNO model O&M Calculator including 2 and 3 crew transfer vessels with helicopter, 1 service operation vessel plus helicopter and 2 service operation vessels. For each strategy, simulations are run to cover variations in distance from port, wind and wave data. From the results of these simulations, a lookup table for the cheapest strategy (while maintaining sufficiently high availability) is created. This lookup table is shown in figure 4.5 (right).

From the lookup table it can be concluded that both distance to port and wave height only have a limited influence on O&M costs. There appears to be only 3.5 % O&M costs difference between nearshore areas with low waves (45 M€) and far offshore areas with high average waves (47 M€). Therefore a hub with O&M facilities appears to offer only a modest cost advantage to AC and DC radial. A separate study is being conducted to further analyse this aspect.

#### 4.1.3 GCS cost formulas

Cost for each of the three considered grid connection systems (GCS) and their individual components have been determined by the NSWPH consortium. The costs components that were taken into account are offshore transformer substation costs which scale with water depth, export cables to shore costs which scale with cable length and onshore transformer substations costs which are fixed costs. The OpEx for the GCS is defined per component and either assumed as a fixed amount or as a percentage of the CapEx of that component. Entering the costs of the various components into the LCoE formula results in LCoE GCS lookup tables. Figure 4.6 and 4.7 show these lookup tables for radial AC and DC.

Figure 4.6 LCoE GCS in case of radial AC

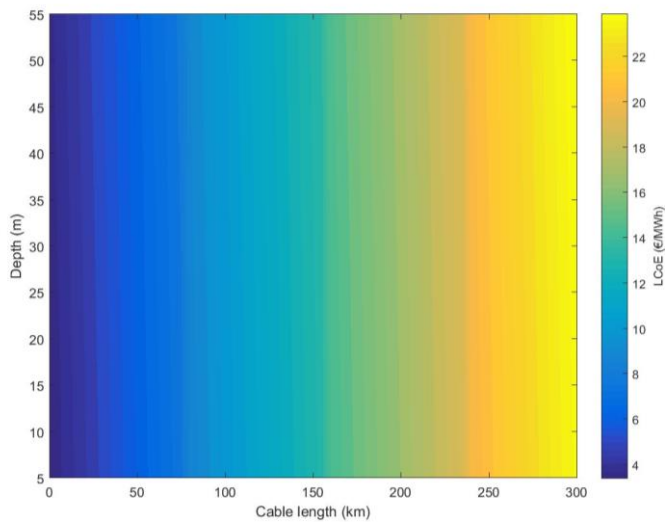
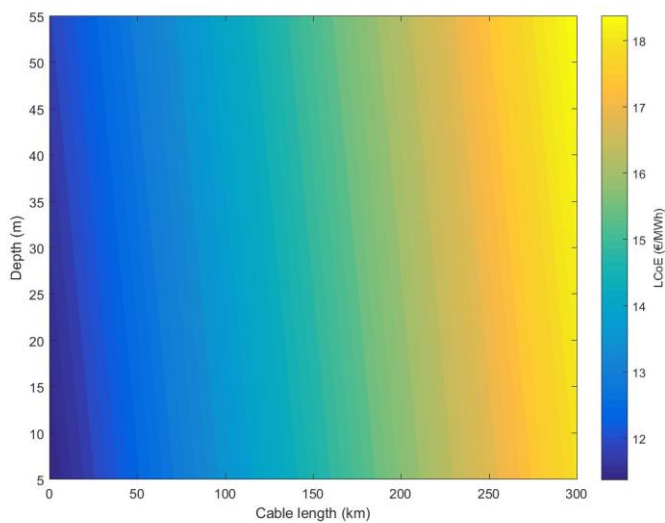


Figure 4.7 LCoE GCS in case of radial DC



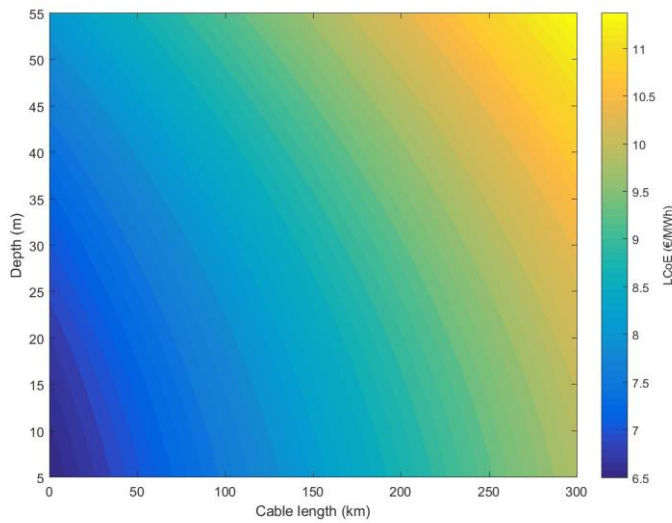
The starting point for the reference H&S GCS is that 12 farms of 1 GW are connected to a hub. The energy is exported from the hub to the mainland by means of six export cables of 2 GW. Five of these cables go to the nearest connection point in five different North Sea countries. One goes to the second nearest connection point in either UK or Germany, depending on which point is nearest. The H&S concept has three additional cost components:

- costs of the civil works to create a sandy island;
- costs of an additional 290 km of AC 66kV cables between the 12 OWFs and the hub;
- costs of additional electrical switching gear on the hub to make trade between different countries possible.

The total GCS costs for the H&S cluster is shared equally by the 12 OWFs. Figure 4.8 shows the LCoE GCS lookup table for H&S. This lookup table has a stronger relation with water depth the comparable lookup tables for radial AC and DC, due to the sandy island. The colour legend of the three lookup tables also reveal that the total CSC costs of H&S are lower than those of radial AC and DC because of economies of scale.



Figure 4.8 LCoE GCS in case of H&S



#### 4.1.4 LCoE uncertainty margins

LCoE results of this study are based on 2030 technology which is not available today. These LCoE numbers should therefore not be compared with the LCoE numbers of today. The purpose of these numbers for the future is to compare the economic attractiveness of future OWF locations across the North Sea.

In order to determine OWF and GCS cost formulas for 2030, extrapolations of technological developments were done and assumptions were made on future economic parameters. These extrapolations and assumptions introduce uncertainty. In order to estimate the magnitude of the uncertainty, a conservative and an optimistic assumption was made for each LCoE component. Table 4.1 shows these two assumptions per component. The uncertainty margins of the LCoE per grid connection type were deducted by entering these conservative and optimistic assumptions in the LCoE formula. The last three rows of table 4.1 show these uncertainty margins. The uncertainty margin for H&S of -32 % +53 % is higher than margins of AC and DC because H&S is a new GCS for which there are no experience numbers.

Table 4.1 Uncertainty margins on LCoE input components and results

Component	Assumed uncertainty margin	Explanation
CapEx OWF (M€)	-7 % +14 %	<p>There are no real cost data available for a 15 MW wind turbine. It is, however, possible to calculate the material volumes needed to construct a 15 MW wind turbine with a rotor diameter of 250 m with reasonably accuracy. Furthermore, it is assumed that the future trend in component cost is comparable with past developments. This implies that innovations achieved in the past will continue in the future, which induces an uncertainty margin of +/-10 % for CapEx OWF.</p> <p>Decommissioning cost were not included in the LCoE of this study. ECN part of TNO has estimated the costs of decommissioning comparable (170 M€) or lower (120 M€) than the installation costs. The present values of these costs are respectively 70 M€ and 50 M€. Including these costs in the CapEx uncertainty shifts the margin of +/-10 % to -7 % and +14 %.</p>
OpEx OWF (M€/year)	+/-25 %	The uncertainty is explained by the fact that there is substantially less data available to extrapolate the O&M costs from the present size to the 15 MW wind turbine.
CapEx and OpEx GCS AC (M€)	+/-10 %	The specified AC radial concept is relatively close to that of several (to be) realized offshore wind projects, rendering the uncertainty range small.
CapEx and OpEx GCS DC (M€) and (M€/year)	-10 % +15 %	The specified DC radial concept is relatively close to that of (to be) realized projects, as such the uncertainty range is small.
CapEx and OpEx GCS H&S (M€) and (M€/year)	-20 % +30 %	The uncertainty range is explained by the fact that several factors which impact the cost assumptions, are still to be validated as the H&S concepts has not yet been applied. On the one hand potential risks need to be accounted for, substantiating the upper range, while an optimization of the island design substantiates the lower range of the CapEx.
AEP (TWh/year)	-4.9 % +4.3 %.	Uncertainty in wind resources and consequently the yield of a wind farm is set at 4 % . In general the annual average wind speed uncertainty is assumed to be approximately 4 %, which is the 20 year uncertainty. The uncertainty in the wake analysis is actually quite small and it is assumed that this can be included by increasing the uncertainty in the average wind speed by 1 % to 5 %. This uncertainty does not include the variation of wind speed from year to year which can be much more than 4 %. The energy yield uncertainty based on a 5 % uncertainty in the average wind speed is determined to be - 4.9 % and +4.3 %.
Annuity (years)	-21 % +26 %	Uncertainty of the annuity is determined by the assumptions on the nominal discount rate, inflation rate and the depreciation period (see table 4.1). A nominal discount rate between 4.0 % and 5.0 % and an inflation rate between 1.0 % and 2.0 % result in a real discount rate between 2.0 % and 4.0 %. The depreciation period or reasonable OWF lifetime is between 25 and 35 years. This results in an annuity between 16 and 25 years.
LCoE for AC (€/MWh)	-29 % +41 %	This is the resulting uncertainty margin of an LCoE calculation with the above mentioned uncertainty assumptions per component for AC radial.
LCoE for DC (€/MWh)	-29 % +46 %	This is the resulting uncertainty margin of an LCoE calculation with the above mentioned uncertainty assumptions per component for DC radial.
LCoE for H&S (€/MWh)	-32 % +53 %	This is the resulting uncertainty margin of an LCoE calculation with the above mentioned uncertainty assumptions per component for H&S.

From table 4.1 one can conclude that the LCoEs calculated in this study have an uncertainty range of approximately -30 % to +50 %.

It may be noted that decommissioning costs, blade degradation and wind hysteresis were not included in the LCoE calculations in this study. To account for the omission of decommission costs, they were included in the uncertainty margin of CapEx OWF. Including these decommissioning costs in the CapEx uncertainty increased the margin from of +/-10 % to -7 % and +14 %.

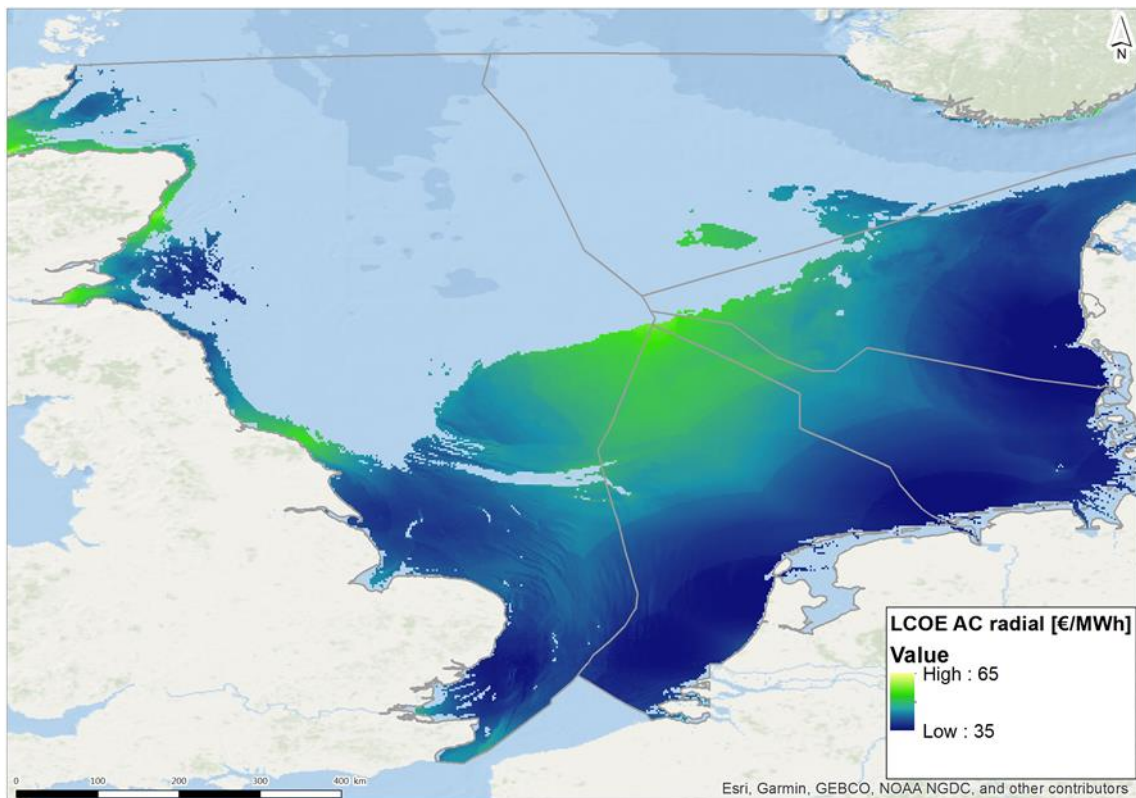
According to ECN part of TNO, blade degradation cost are marginal. Monitoring results in wind farms show that energy yields are mainly determined by wind speed and are not diminishing as the OWF ages and turbine blades degrade. Yield losses due to high wind speed hysteresis is probably also negligible, as the shut down time is limited. Modern turbines no longer shut down at wind speeds higher than 25 m/s, but continue producing at a lower level.

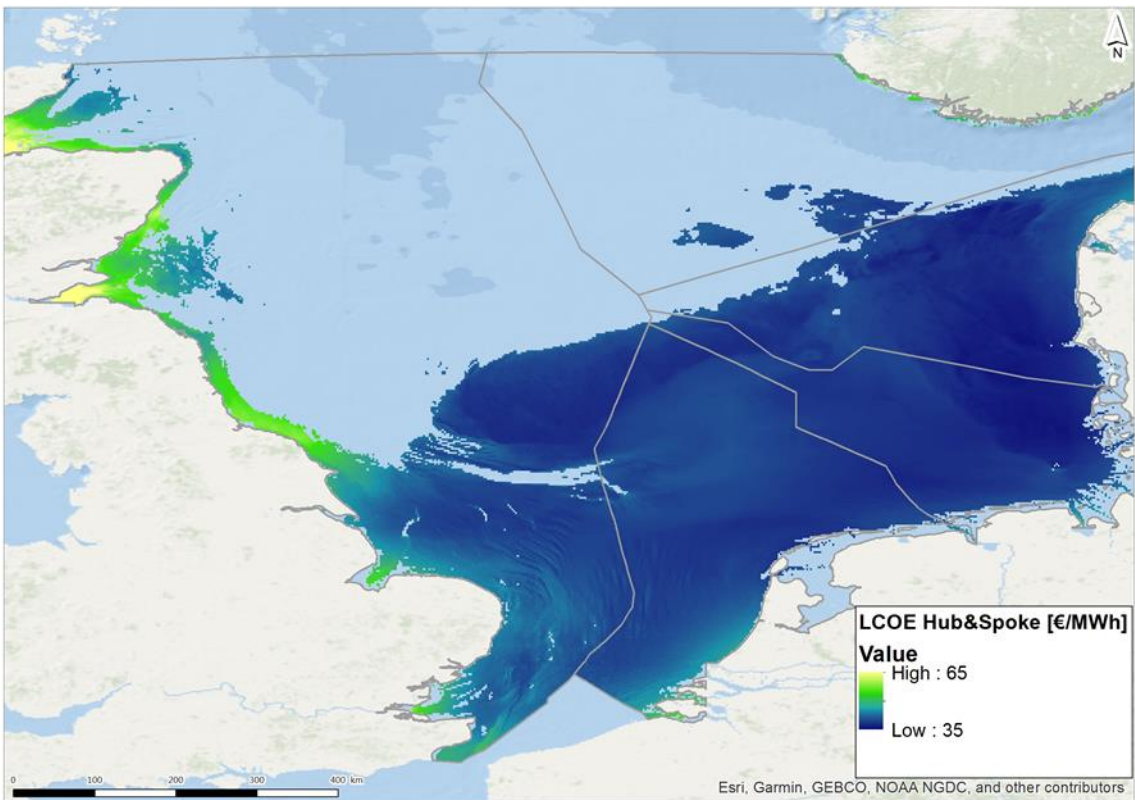
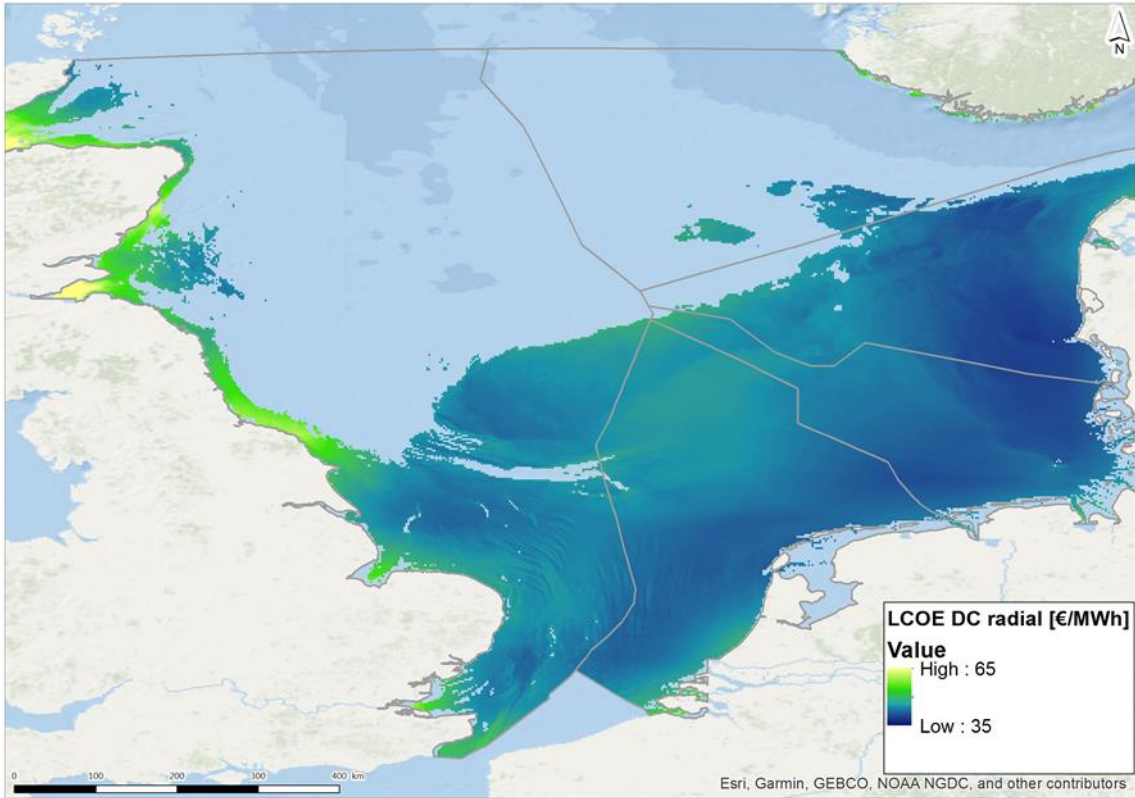
#### 4.1.5 LCoE maps

Figure 4.5 shows the LCoE maps that were created by means of the cost formulas described in the previous paragraphs. There is a separate LCoE map for the three grid connection systems AC radial, DC radial and H&S.

The AC map shows that locations with a relatively low LCoE in case of an AC GCS can be found close to shore. According to the DC map locations with a relatively low LCoE in case of a DC GCS are situated slightly further from shore. The H&S map reveals that locations with relatively low LCoE, when applying H&S GCS, are found everywhere except for the most central part of the study area and nearshore.

Figure 4.5 LCoE maps per grid connection system (top to bottom: AC radial, DC radial and hub and spoke)





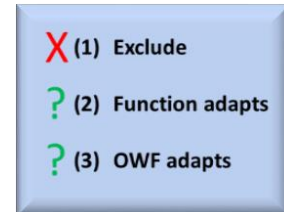
Source: LCoE mapping model developed in this study

## 4.2 LCoE-R mapping

In this study not only LCoE maps, but also LCoE-R maps are developed. LCoE-R maps include the cost of encountering other user functions. For each spatial user function a map is created that reflects the monetary value of the risk of encountering that function when developing an OWF. The spatial risk maps are made by multiplying reference spatial user maps (as presented in appendix I) with a risk formula. Risk formulas are developed on the basis of a previous societal cost benefit study (Hoefsloot et al., 2018) in which the risk of each user function was specified in concertation with the relevant stakeholders.

### 4.2.1 Spatial risk principles

In principle, there are three ways to monetarize spatial risk: exclusion of zones, function adaptation or OWF adaption. This results from the fact that every time an OWF encounters a spatial user function, there are three ways to deal with a potential spatial conflict, that each lead to different costs.



**1. Exclusion of zones:** zones with other user functions are excluded from the search area for wind energy. This is the most explored option so far in search studies for new OWF locations. The calculation of spatial costs now boils down to the cost difference per produced MWh between locations claimed by other sea users and locations not yet claimed by other sea users.

**2. The user function adapts to the OWF:** when an OWF encounters another sea user, this user function adapts itself to the energy production. This could mean that the function moves to another location. Then there will be movement cost (e.g. military exercises are moved to another area). It could also mean that the function ceases to exist and then its net benefits will be lost (e.g. the fish will not be caught). Another possibility is that the user function stays inside the wind farm, i.e. there is co-use. In such cases the user function may suffer efficiency losses<sup>1</sup> (e.g. fishing is carried out less efficiently in wind farms). In case the user functions adapts, the spatial costs are the damage cost of the effected user function.

**3. The OWF adapts to the user function:** when another sea user is met, OWFs can also adapt themselves in such a way that damage to the other user is prevented or mitigated. This could entail an adjustment of the wind farm layout (e.g. moving a couple of turbines to respect the helicopter zone of an oil & gas platform). This leads to extra farm development cost (e.g. extra cable length to connect turbines). It could also involve taking extra precautionary measures (e.g. shutting turbines down for the sake of bird migration) or restoration measures (e.g. applying Building with Nature solutions to stimulate nature restoration). In case the OWF adapts, the spatial cost are equal to costs of actions taken by the wind farm developer.

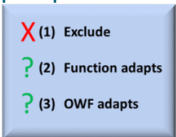
In the LCoE-R calculation, only the last two options are considered, as the approach of this spatial study is to avoid excluding potential OWF locations.

Ideally cost of both user function adaptation and OWF adaptation would be determined for all relevant spatial user function. This would reveal which of these two options is the cheapest and then the cheapest option could be used to calculate the LCoE-R. In practice, this does not seem relevant for every user function. Table 4.6 gives an overview of the selected option(s) and underlying motives for the spatial cost calculation of each user function.

<sup>1</sup> Either due to extra production cost (e.g. extra transport cost for fishing vessels) or yield reductions (e.g. less fish caught).

Table 4.6 Spatial user functions and their basis for cost calculation

Spatial user function	Selected risk principle 	Motivation	Description of the spatial cost
Military zones	Function adapts	It does not seem possible to make OWF compatible with military exercises. Therefore the option that the user function adapts is selected.	<p>If a large part of a military zone (i.e. &gt;20 %) is covered by wind turbines, the zone becomes unusable for military exercise, so there will be cost of practicing elsewhere: relocation cost.</p> <p>If a small part of a military zone (&lt;20 %) is used for wind energy, it is possible to mitigate this change by adapting the procedures i.e. adapting the organization and planning of military exercises: reorganization costs.</p>
Nature: sea mammals	OWF adapts	Trying to get mammals to adapt to OWF is not relevant/possible; the key of nature policies is not to disturb mammals	The spatial cost are equal to cost of preventing mammal disturbance: the extra costs of gentle piling (compared to regular piling).
Nature: birds	OWF adapts	Attempting to get birds to adapt to OWF is not relevant nor feasible, as it is difficult to create sufficient new bird habitats and to actively influence bird flying routes.	The spatial cost are equal to the cost of preventing bird population losses by turbine shut downs: the cost of energy yield reduction. Damage to migratory birds due to collisions can be prevented by real time radar monitoring of birds: at >500 birds per km <sup>2</sup> /hour at rotor height, turbines are shut down. Experience near shore: 30 hours per year shut down. Damage to sea birds, due to habitat loss, can possibly be prevented by larger turbines & larger inter turbine space. Maybe, increasing food availability (fish) and/or turbine shut downs during foraging periods can also help; deterring birds should be avoided as it evokes habitat loss instead of limiting it.
Nature: bats	OWF adapts	Attempting to get bats to adapt to OWF is not relevant/possible as it is difficult to actively influence their flying routes. Wind turbines & oil & gas platforms seem to attract bat to forage on insects.	The spatial cost are the cost of turbine shut down i.e. energy production losses. Bats mainly migrate along the shores of the North Sea. They seem to only fly across the sea from Norway to UK. If an OWF interacts with a bat flying route, turbines need to be shut down 10 hours per day, during 45 days in September and August at wind speeds of <5 m/s. They only fly at night and at low wind speeds.
Nature: habitats	OWF adapts	Adapting habitats to OWF, seems difficult as this would require large scale nature development at sea. It would also not be in line with European nature protection policies, which appointed certain areas to safeguard them from being harmed by economic activities.	The spatial cost of building OWF in protected nature areas can be estimated in terms of the cost of actively enhancing nature restoration by applying Building with Nature solutions. Marine ecosystems can be enhanced by stimulating reef builders such as flat oysters. This can be realized with nature friendly scour protections or other Building with Nature solutions.
Shipping routes	For minor routes: function adapts  Major routes: the OWF adapts	For shipping routes with low intensity it makes sense that ships sail around wind farms, while for routes with high intensity it makes sense to create a shipping corridor through the wind farm.	For minor routes (< 1 ship/day): wind farm layout without a corridor; the shipping route is adapted, leading to detour costs. For major routes (> 1ship/day): wind farm layout with a corridor, leading to extra cable cost to connect turbines on both sides of the corridor.

Spatial user function	Selected risk principle 	Motivation	Description of the spatial cost
Oil & gas platforms	OWF adapts	Though it is possible to remove oil & gas platforms that are still active i.e. buying them out before the end of the economic life: this not opted for, since their economic life could be extended when wind farms offer them (cheap) energy; this is a spatial opportunity instead of a spatial risk that lies outside the scope of this study <sup>1</sup> .	The spatial costs are the extra cost of adapting the OWF lay out: helicopters that visit oil & gas platforms need a 2.5 NM flying circle. Since the width between wind turbines of the reference OWF is 2 km, moving some monopiles would solve the spatial conflict between platforms and turbines. Moving some turbines leads to extra cable length and thus extra cable cost.
Fisheries	Functions adapts & OWF adapts  The cheapest of two is selected	There are two possibilities in case of fisheries: 1 fisheries could adapt by fishing elsewhere or by fishing less 2 the OWF could adapt by allowing fisheries inside the farm and taking precautions by burying cables deep enough	1 in case of fishery adaptation, the spatial costs are: - the lost value added of lost fishing grounds: this is the if case the fleet becomes inactive (fishing yield is lost, but fishing cost also stop); - the lost turnover of the fishing ground: this is the case if the fleet remains active (fishing yield is lost, but costs continue). Since fishermen have no intention to stop fishing due to wind farm developments, the turn over loss (the highest of the two) is used in this study. 2 in case of OWF adaption i.e. co-use the spatial cost are comprised of fishing inefficiencies and cable burial cost. Fishing boats may catch the same amount of fish as before the wind farms were built, but their fishing is less efficient. The cost of inefficiency may amount to 14 to 40 % of the yearly turn over. On top of this cables in the OWF needed to be buried deeper (1m) than without fishery co-use to prevent damage by trawling. This leads to extra cable costs.
Cables & pipes	OWF adapts	User functions adaptation is less relevant, since it seems difficult to move the cables- property of others- that are already there and actively used.	The spatial cost are OWF adaption cost. In case of cables and pipes interfering the OWF, the farm lay out does not need to be adapted, since there is sufficient space to always keep the required 500 m distance to cables. There will, however, be more cable crossings at locations with high cable density. Therefore the spatial cost are equal to the cost of extra cable crossings.
Sand mining	Function adapts	It is not possible to make OWFs compatible with sand mining. Sand mining can, however, adapt to OWF. Here a distinction needs to be made between: - electricity cables passing through a mining site: mining should now respect sufficient distance from the cable i.e. work around it; - an OWF inside a mining site: the sand of this site can no longer be extracted and it needs to be extracted at the nearest possible alternative mining site.	The spatial costs in case of cables passing through a mining site are extra sand mining cost: the in situ transportation cost increase when working around the electricity cable.  The spatial costs in case of an OWF inside a mining site are equal to the extra ex situ transportation cost of sand mining i.e. The extra the cost of moving to another mining site.

Source: adapted from Hoefsloot et al., (2018)

<sup>1</sup> For simplicity it was assumed that all O&G platforms present in 2014 will still be in operation. No assumptions on decommissioning or new developments were made. Appendix I6 discusses this in more detail).

Table 4.6 shows that the spatial cost of encountering military zones, minor shipping routes and sand mining are based on the principle that user functions adapts. Mostly the reason for choosing this principle is the impossibility of difficulty to make OWFs compatible with the user function, while the user function can adapt to the OWF.

The spatial costs of encountering nature (mammals, birds, bats, protected areas), major shipping routes, oil and gas platforms, cables and pipes are based on the principle that the OWF adapts. Mostly the reason for this choice is that it is relatively easy to adapt the wind farm lay out, while it is difficult or impossible for the user function to adapt to OWFs.

Only for fisheries the spatial cost are determined both in terms of function adaptation and in terms of OWF adaptation. Based on the calculation results the principle that generates the lowest cost could be selected.

As explained in chapter 3.1.4, process costs are not included in spatial planning costs.

## 4.2.2 LCoE-R calculations

In the previous paragraph the spatial risks of encountering other sea users were specified in terms of spatial cost. In table 4.7 the spatial cost calculation formulas are presented. Since the calculations of spatial cost are done on the basis of GIS maps of the spatial user function (see Appendix I), this table also shows the units of the legend of the these maps. Since the spatial cost are included in the LCoE-R maps, it is also indicated whether the cost are added to the capital expenditure or to the operational expenditure.

### Military zones

The spatial costs of military zones are different for small zones and large zones. Based on earlier stakeholder interviews (Hoefsloot et al., 2014 and 2010), it is assumed that in case of small zones, a reference wind farm may render the zone too small for future practice and the organizations using the zone need to relocate their exercises. In case of large zones a reference park may leave the zone useable, but military exercises need to be reorganized. In previous societal cost studies (Hoefsloot et al., 2014 and 2018) these cost were estimated in concertation with the Dutch ministry of defence. This resulted in expected relocation cost of 0.75 M€/year and expected reorganization cost of 2 M€ once (Hoefsloot et al., 2014 and 2018). The cost formula divides these cost over the total km<sup>2</sup> of a military zone.

### Nature: sea mammals

The spatial cost in relation to mammals is the extra cost of gentle piling. These are already included in the LCoE calculation (in the CapEx component i.e. The installation costs for the turbines) as gentle piling is the standard building method. Calculating them again as a spatial cost would introduce a double counting and is therefore refrained from.

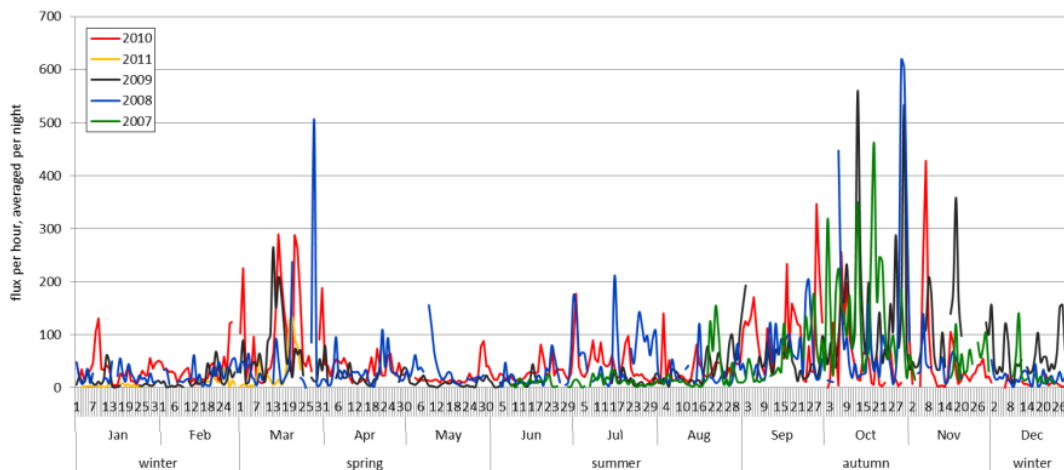
### Nature: birds

The spatial cost of birds pertains to lost energy yields due to shutting down turbines when large numbers of birds are detected at rotor height. Presently, license prescriptions for OWFs state that at more than 500 birds per hour at rotor height turbines need to shut down in order to prevent collision victims. Experience so far is that this leads to approximately 30 shut down hours per year for OWFs near the coast (Kamp, 2016).

Figure 4.6 shows radar monitoring data on birds' fluxes at rotor height in the Southern part of the North Sea in the years 2007 to 2010. The peaks in early spring, which show fluxes of more than 500 birds per hour, are most likely migratory birds flying from the Netherlands to the UK. Peaks in autumn, which also have more than 500 birds per hour, probably reflect birds migrating from Sweden to the UK and to European mainland.



Figure 4.6 Occurrence of birds in fluxes per hour at a rotor height



Source: Krijgsveld et al., (2015)

Figure 4.6 also shows that there are lower peaks as well: approximately seven peaks per year of more than 200 birds per hour. These findings suggest that in order not to cumulatively surpass the potential biological removal limits of bird populations, turbine shut down hours may increase when the amount of deployed megawatts increases in the North Sea. As a result the spatial costs of building OWFs in migratory routes and probably also in sea bird sensitive areas, will also increase.

The issue with sea birds is that they are permanently present and they suffer from both habitat loss and collision. Damage to sea birds can possibly be prevented by larger (and thus fewer) turbines and larger inter-turbine space, though there are species for which this does not work. When these options become exhausted, maybe increasing food availability through Building with Nature solutions and/or turbine shut down during foraging periods may also help. This is highly uncertain. The spatial cost of sea birds is therefore also highly uncertain.

In order to account for the fact that the cost of migratory birds may increase and the costs of sea birds cannot be properly accounted for due to the lack of knowledge on effective mitigation measures, a sensitivity analysis was carried out in which the known cost i.e. The shut down costs, were increased. In this analyses the number of curtailment hours was increased by 500 hours (i.e. 7 seven peaks of 70 hours) for the most sensitive areas and by 100 hours for the least sensitive areas of the WSI-map. The spatial cost resulting from this analysis is included in figure 4.10 (top row, right side). In the LCoE-R calculation the lower (presently relevant) 30 hour per year is used.

#### Nature: bats

The spatial costs concerning bats are lost energy yields of temporary turbine shut down. Though the numbers to calculate these cost are available, no bat flying routes are found in the relevant parts of the study area and therefore these cost are not calculated.

#### Nature: habitats

The spatial costs in relation to protected nature areas are determined on the basis of taking extra measures to stimulate nature restoration inside the OWFs. The cost formula is based on the Building with Nature solution 'scour protection' that stimulates reef builders i.e. flat oysters. These costs are estimated to approximately 130 k€ per monopile (Lengkeek et al., 2017).

It may be noted that there are also other Building with Nature solutions, such as sea bed mattresses and bio-huts for cod. The costs of these measures are not known yet. Pilot projects are needed to determine these costs.

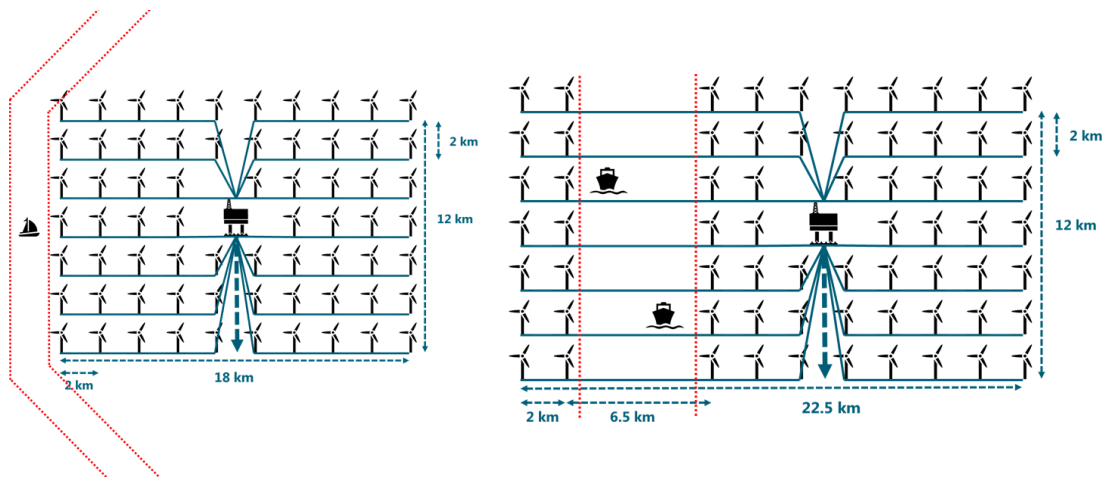
### Shipping routes

The spatial costs of minor shipping routes are calculated as average detour cost of ships that need to sail around the OWF. The calculation formula for the detour cost is based on an average extra sailing distance of 6.6 km (see figure 4.6), a growth factor of 1.3 reflecting a high economic development scenario (Romijn *et al*, 2016) and transportation cost of 38 €/km (www.rwseconomie, cost barometer deep sea, 2016)<sup>1</sup>.

The spatial costs of major shipping routes are calculated by determining the cost of creating a corridor with a width of 6.5 km (see figure 4.7). Such a corridor requires 7 to 10<sup>2</sup> extra cables of 6.5 km at a cost of 220 k€/km (ECN part of TNO estimate for this study)<sup>3</sup>.

For both major and minor routes, a fixed extra safety cost (for radar and surveillance) of approximately 10-12 k€/km<sup>2</sup> is added (based on Hoefsloot *et al.*, 2018). Furthermore, it may be noted that for minor shipping routes it is possible to also include the societal cost of the extra environmental pollution (i.e. emissions of CO<sub>2</sub>, NO<sub>x</sub> and PM10) for each extra detour kilometre: the environmental cost double the transport cost per km (Hoefsloot *et al.*, 2018).

Figure 4.7 Calculating the spatial cost of shipping routes: minor (left), major (right)



### Oil and gas platforms

The spatial cost of oil and gas platforms are the costs of adapting the lay out of the wind farm in such a way the helicopters can safely land on the platforms. Since helicopters require a flying circle of 2.5 NM (Hoefsloot *et al.*, 2018), approximately sixteen turbines need to be moved 2 to 6 km, whenever a platform is encountered (see figure 4.8). Moving turbines requires cable length and thus extra cable costs. The average cost for inter array cable is estimated at 220 k€/km (ECN part of TNO estimate for this study). Dividing the extra cable cost by the area of the flying circle results in a cost of approximately 330 k€/km<sup>2</sup>. When applying this cost number to the reference map with oil and gas platforms, overlap between helicopter zones is removed, in order not to overestimate spatial costs<sup>4</sup>.

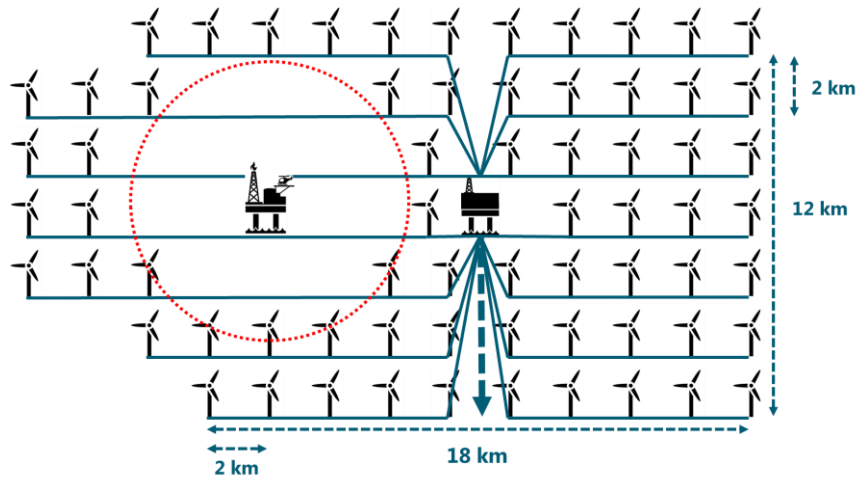
<sup>1</sup> Cost per km<sup>2</sup> are derived by the dividing the cost by the area the reference windfarm.

<sup>2</sup> Depending on whether the corridor is vertically (7 turbines) or horizontally (10 turbines) passing through the windfarm.

<sup>3</sup> Cost per km<sup>2</sup> are derived by the dividing the cost by the area of the corridor.

<sup>4</sup> After drawing OWFs in the GIS mapping tool (see chapter 4), it was discovered that there are attractive farm location that have so much overlap between helicopter zones, that one can actually not adapt the wind farm, so the oil & gas function needs to adapt. This switch from 'OWF adapts' to 'function adapts' requires a different cost estimate: a cost formula that reflects the extra cost of using boats instead of helicopters to visit the wind farms. This function is not developed in this study. Consequently, the present spatial planning cost of oil & gas platforms may be underestimated for locations with many overlapping helicopter zones.

Figure 4.8 Calculating the spatial cost of oil and gas platforms



### Fisheries

The spatial costs of fisheries are determined in two different ways: on the basis of fishery turn over loss and on the basis of co-use which causes fishing inefficiencies plus costs for burying inter array cables one m deeper (than in case of no fishery co-use) to prevent trawlers from damaging these cables (Hoefsloot et al., 2018).

Yearly turn over loss is estimated to amount to approximately  $3.5 \text{ M€}/\text{km}^2$  (Hoefsloot et al., 2018) for the most important commercial species (i.e. sole and plaice fisheries). Fishing inefficiencies are estimated to amount up to maximally 40 % of the turnover<sup>1</sup> (based on Oostenbrugge et al., 2015). The extra cable cost are estimated to be approximately  $60 \text{ k€}/\text{km}^2$  (Hoefsloot et al., 2018). Combined, this results in a yearly spatial cost for co-use of approximately  $3.4 \text{ M€}/\text{km}^2$ .

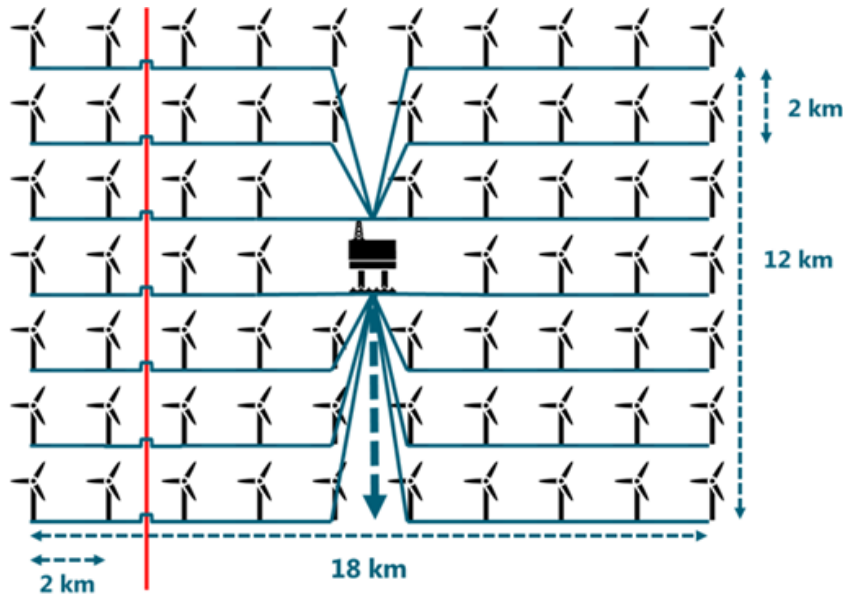
It turns out that the two different cost calculations result in approximately the same cost figure:  $3.5 \text{ M€}/\text{km}^2$  and  $3.4 \text{ M€}/\text{km}^2$  per year. Since these cost are already very small compared to wind energy cost, the highest of the two (and not the intended lowest of the two) is used in the LCoE-R calculation.

### Cables and pipes

The spatial costs of cables and pipes are calculated on the basis of the number of extra cable crossings that are needed to cross the cable or pipe safely with the OWF electricity cables. Figure 4.9 shows that on average 7 to 9 extra crossing are needed per 12 to 18 km cable/pipeline. The cost of cable crossings are estimated at 1.1 M€ each (ECN part of TNO estimate for this study).

<sup>1</sup> This is a sector estimate; scientific estimates amount to 14 % (based on Oostenbrugge et al., 2015)

Figure 4.9 Calculating the spatial cost of cables & pipes



### Sand mining

The spatial cost of sand mining is calculated differently for electricity cables passing through mining sites and for OWFs built within mining sites. If a mining area is intersected by a OWF cable, there will be extra 'in situ' mining cost as the mining ship need to work around the cable. These extra mining costs are estimated at approximately 11 M€/year per cable that passes through a sand mining area (Hoefsloot et al., 2018)<sup>1</sup>. If an OWF is placed inside a mining area, it is no longer possible to extract sand there. In such cases there will be extra 'ex situ' mining cost. The sand (a layer of 2 to 6 m) needs to be extracted elsewhere leading to extra cost of 0.078 €/m<sup>3</sup> sand per km extra distance (Blue Economy, 2011). Given the size of the reference OWF, the mining always needs to be moved 12 to 18 km further away. On average this leads to an extra mining cost of 2.3 M€/km<sup>2</sup> once for a layer of 2 m.

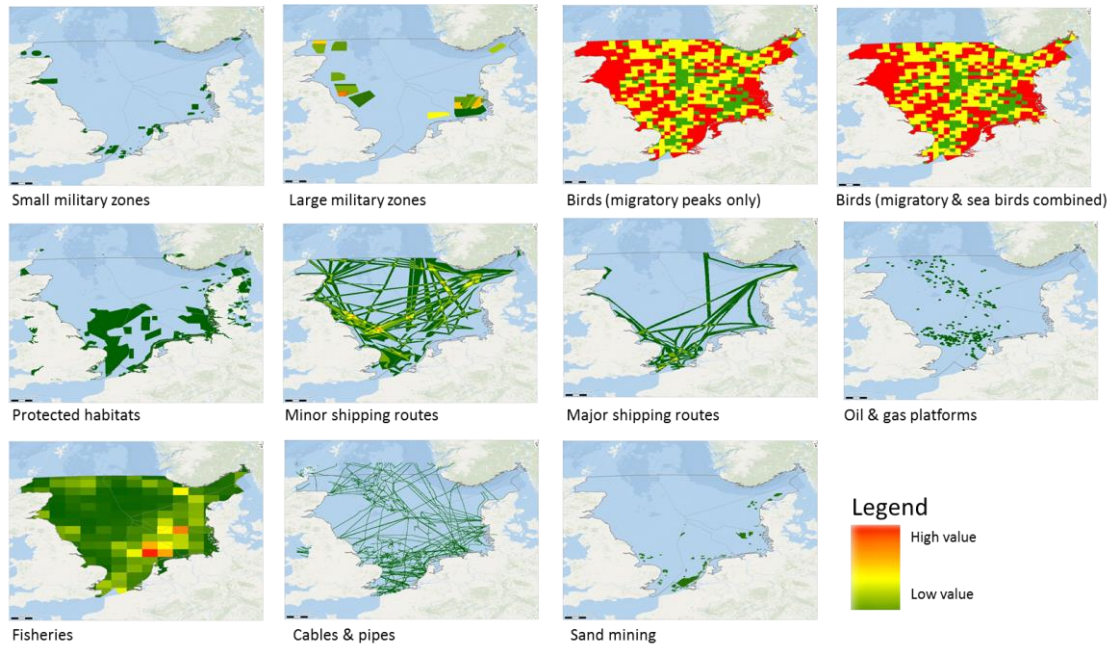
It may be noted here that this spatial cost is in fact an *option value*: mining sites are appointed to ensure sand provision in the long run. Whether and when the sand at a specific location is extracted is not known in advance. This depends on sand demand for both beach nourishment and industry. Availability of sand close to the demand, i.e. near the destination, determines the mining cost and explains why sites are appointed with an eye on long term potential needs. Since the actual extra mining costs to be caused by wind farms will be lower than the estimated option value loss, the spatial cost of sand mining may be overestimated. However, the aim of this study is to calculate spatial risk and when building OWFs in mining sites, one runs the risk of losing the full option value.

### 4.2.3 LCoE-R maps

LCoE-R maps are created by applying the spatial adaptation cost formula, that were described in the previous paragraph, to the spatial user maps presented in Appendix I. Figure 4.10 shows the resulting spatial cost maps per user function.

<sup>1</sup> The spatial costs of grid connections are not included yet in the LCoE-R calculations of this study. So far, sand mining is the only use function for which the grid connection may induce spatial cost. It is, however, possible, that this will also become the case for nature i.e. protected habitats, for example due to license prescription concerning sea floor temperature raise.

Figure 4.10 Individual spatial cost maps



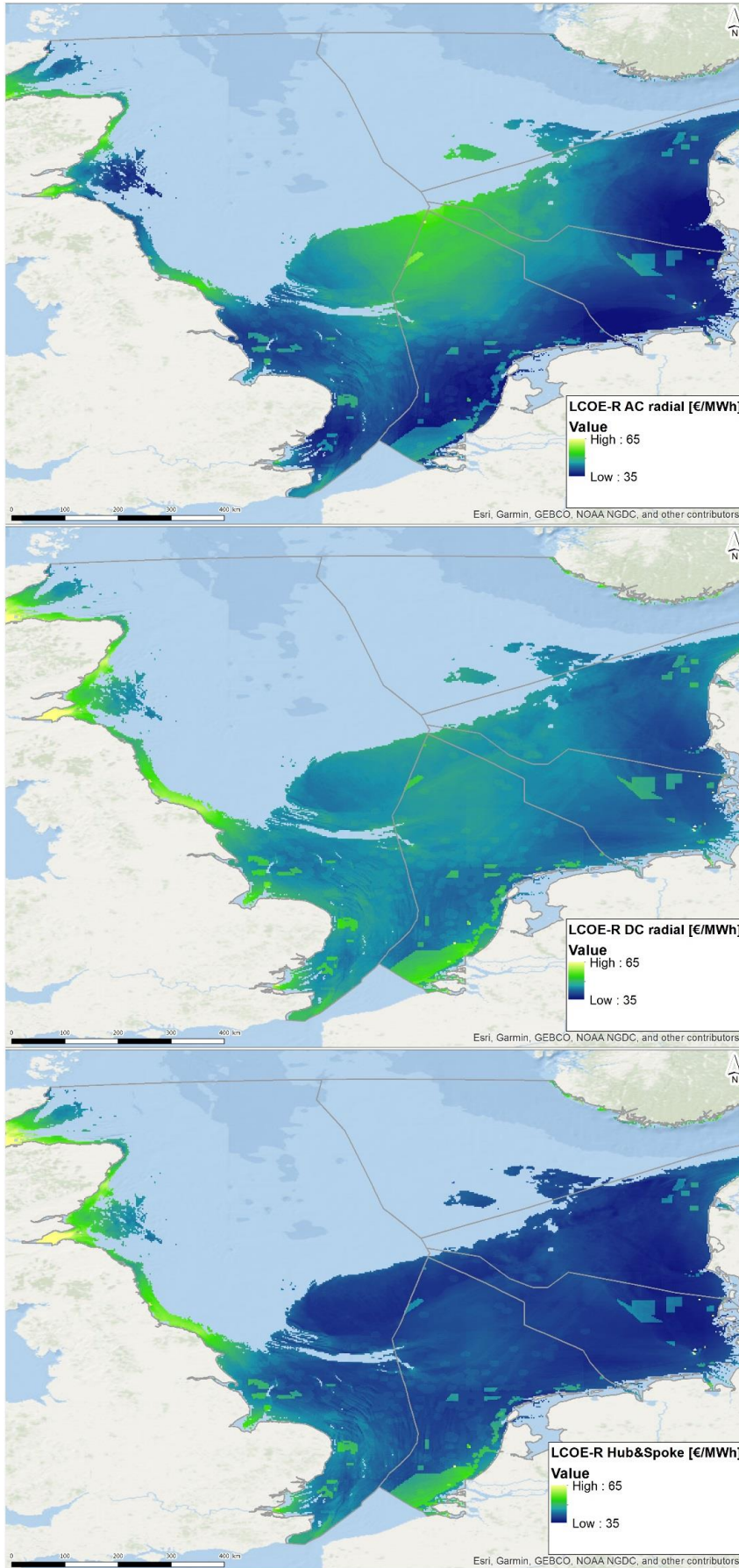
Source: LCoE-R mapping model developed in this study

The range of the monetary value differs per user function, but the red colour always reflects the highest value, while the green colour represents the lowest value<sup>1</sup>. For some user functions, such as small military zones and protected habitats, there is hardly any variation in cost, because the cost depend on the presence of the user function and not use intensity. For other users functions, such as large military zones, minor shipping routes and fisheries there is much variation in cost. This variation is caused by difference in use intensity. For example, for fisheries (bottom left) the costs are highest (red) where the most fishing activity takes place, i.e. areas that are relatively frequently trawled.

The spatial risk costs (i.e. spatial adaptation costs) are added to the LCoE maps (see figure 4.5), to create LCoE-R maps. Figure 4.11 shows the LCoE-R maps for the AC, DC and H&S connection type. In these three LCoE-R maps, the spatial costs of the individual user maps are added up. This means that the costs of multiple user functions at one location are included in the LCoE-R maps. It is remarked here, that the cumulative spatial risk costs caused by clusters of OWFs are not included in the LCoE-R maps. Furthermore the impact of spatial users shifting to another area and creating adaptation cost at the new location has not been accounted for, as it is outside the scope of the study.

<sup>1</sup> Colours are relative within one image and cannot be compared to the other images.

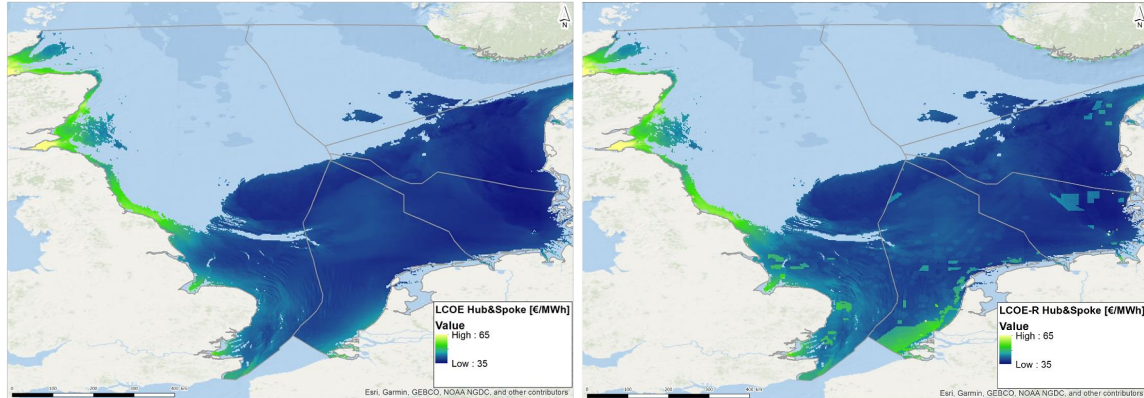
Figure 4.11 LCoE-R maps per grid connection system (top to bottom: AC radial, DC radial and H&S)



Source: LCoE-R mapping model developed in this study

In order to illustrate the difference between a LCoE map and a LCoE-R map, figure 4.12 shows both maps for the H&S grid connection system.

Figure 4.12 LCoE (left) and LCoE-R (right) maps for the H&S grid connection system



Source: LCoE-R mapping model developed in this study

A visual inspection of both maps reveals that LCoE-R map has more green coloured areas near the Dutch and English coast and at some distance of the German coast: these green areas have higher LCoE-R due to the spatial planning risk of sand mining. The spatial planning risk of sand mining turns out to be the risk that dominates all of the spatial planning risks in the levelized cost of energy, as the costs per km<sup>2</sup> for the sand mining function, seem to be the highest.

# 5

## IDENTIFYING POSSIBLE NEW OWF LOCATIONS

In this chapter possible new OWF locations for the period after 2030 are identified by means of the LCoE-(R) mapping model that was described in the previous chapter. The mapping model has a drawing tool that allows the user to draw new wind farms in the North Sea and immediately check the LCoE-R of both individual farms and of a set of farms.

Three different identification perspectives are applied: an economic perspective (i.e. low LCoE-R), a visibility perspective and a nature conservation perspective. This results in three different sets of possible new locations. After checking the LCoE-(R) and the capacity of the three sets with possible new locations, a preferred set is selected. For the preferred set a more detailed location specific grid connection will be created in chapter 6. The preferred set with possible new locations is prepared for that purpose by reshaping the OWFs to match the 1 GW size of the reference wind farm.

### 5.1 Searching for new locations from different perspectives

On the basis of the LCoE-R maps that were presented in figure 4.11 in chapter 4, three different sets of possible new OWF locations were composed from three different perspectives:

- 1 low LCoE-R;
- 2 visibility from shore;
- 3 nature conservation.

The sets with possible new locations were composed, while keeping in mind that approximately 180 GW is needed to decarbonize the power sector in the North Sea region. Given the already planned capacity of 75 (55 up to and 20 after 2030) GW in the baseline, sets with approximately 110 GW additional capacity are strived for.

The grid connection system of each new location was determined as follows: AC was used for farms nearshore (up to 80 km), DC for isolated farms far from shore (more than 80 km) and H&S for clustered farms far from shore (more than 80 km). Some DC farms were selected in spite of their relatively high LCoE-R. This was done in order to allow for extra analyses on the cost difference between the three different grid connection systems at a later stage of this study.

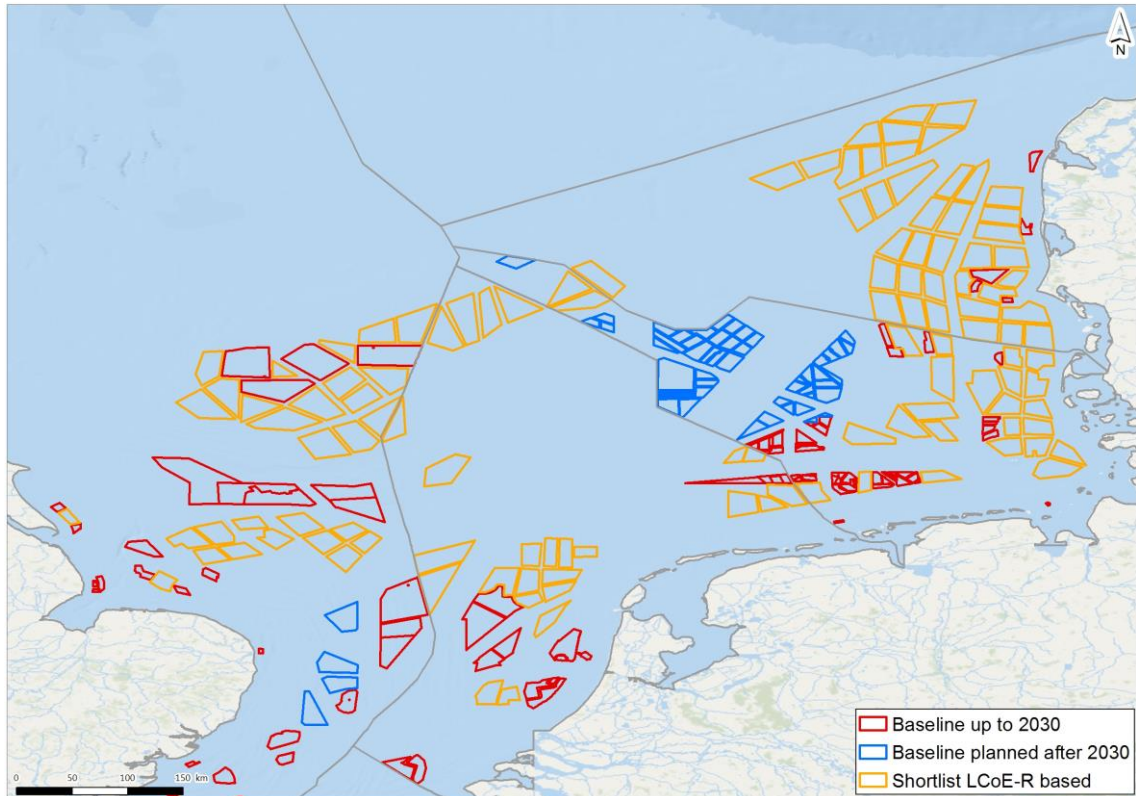
#### 5.1.1 Set with possible new locations based on low LCoE-R

The LCoE-R based set with possible new locations was created by visual inspection of the LCoE-R colour maps of figure 4.11 in chapter 4. Polygons with a hosting capacity of approximately 1 GW were drawn in the dark blue areas of the colour maps. AC radial and H&S locations with a LCoE-R lower than approximately 45 €/MWh were included in the set. Since DC locations have a relatively high LCoE-R. Only three DC locations were included. This was done to allow for a check on how DC locations influence the overall LCoE of a grid roll-out path at a later stage of this study.



The LCoE-R based search exercise resulted in a set of possible new locations with total capacity of 110 GW. The locations of this set are presented as orange coloured polygons in figure 5.1. This figure also shows baseline OWF locations, planned by national governments, up to and after 2030. These represent a total capacity of approximately 75 GW.

Figure 5.1 Set with possible new locations based on low LCoE-R



Source: LCOE-R mapping model developed in this study

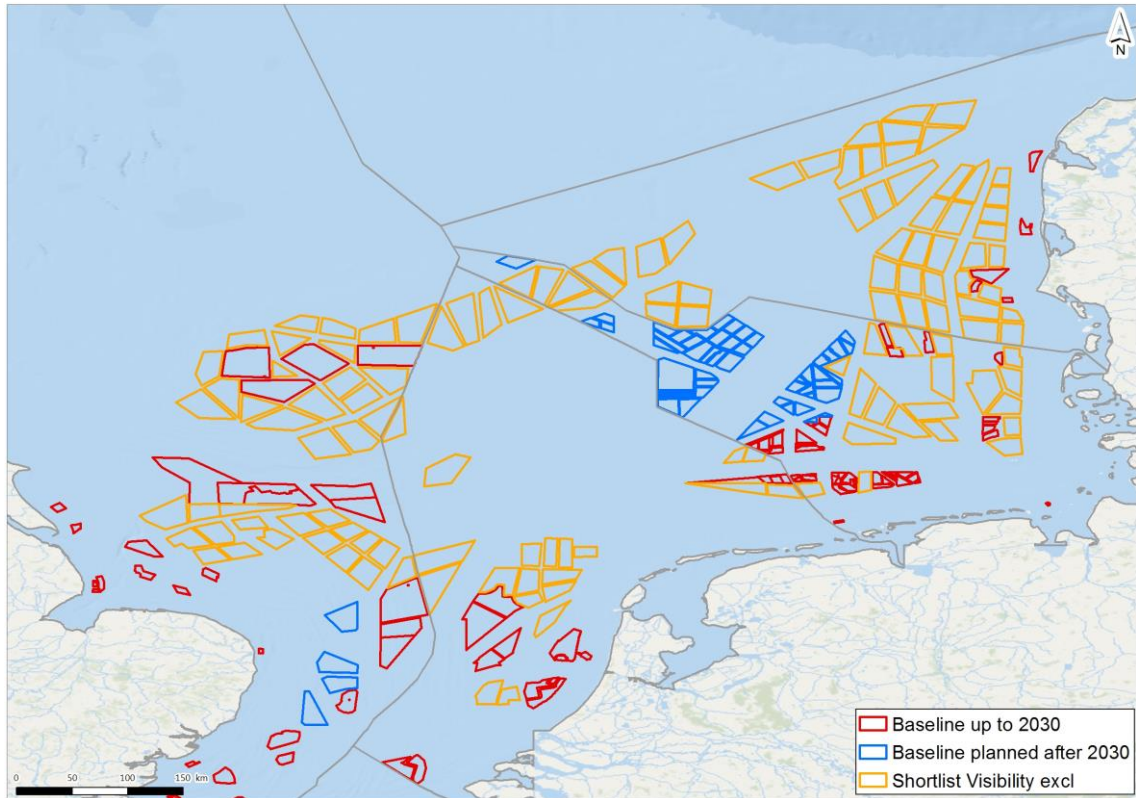
### 5.1.2 Set with possible new locations excluding visibility from shore

Visibility is an important aspect of offshore wind farms, that is not included in the spatial risk calculation and therefore unaccounted for in the LCoE-R. Sullivan et al. (2013) and Crawford (2016) investigated the visibility of wind farms. Their combined study results suggest that OWFs can:

- dominate the view up to 8 km from shore;
- be clearly visible up to 16 km from shore;
- be noticed by the casual observer up to 30 km from shore;
- be noticed by the concentrated observer up to 40 km from shore.

On the basis of this information, OWF locations were selected at a distance of more than 40 km from shore. The choice was made to set the distance for Denmark at 20 km, since the threshold for being clearly visible is less than 20 km and the Danish coast already has OWFs at less than 5 km from shore. This exercise resulted in a set with possible new locations with a total capacity of 120 GW. Figure 5.2 shows the locations (in orange) that are included in the visibility set.

Figure 5.2 Set with possible new locations based on visibility exclusion



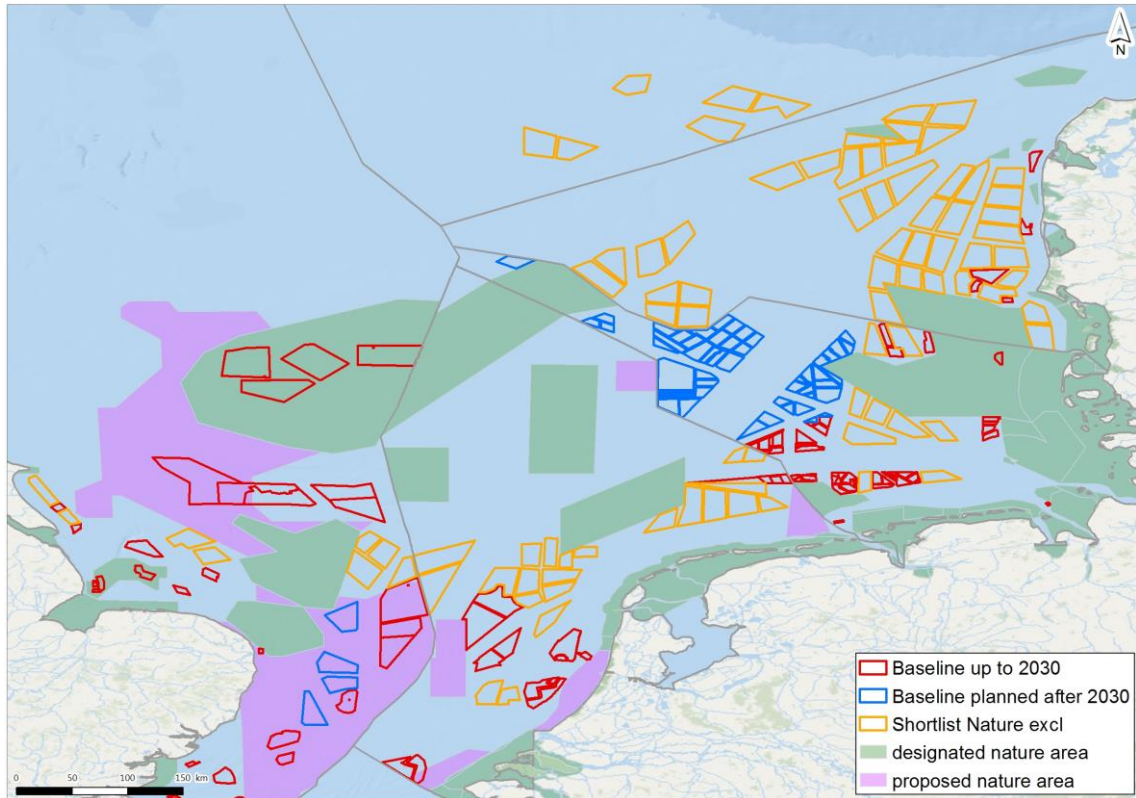
Source: LCOE-R mapping model developed in this study

### 5.1.3 Set with possible new locations excluding nature protected areas

The North Sea contains protected nature areas. A set of possible new OWF locations was created by drawing OWF polygons in the dark blue areas of the LCoE-R colour map projected on a map with designated and appointed nature areas. No polygons were drawn in the nature areas. This resulted in a set with possible new locations with total capacity of 77 GW. The locations included are shown in figure 5.3.

The identified 77 GW is not sufficient to meet the Translate COP21 target of 180 GW. For that purpose an additional capacity of 110 GW is needed. In chapter 7 a sensitivity analysis is carried out in relation to this: extra OWFs adjacent to nature conservation areas are added (outside the dark blue areas) in order to discover how the average LCoE-R is effected when the 180 GW target needs to be realized while simultaneously avoiding the nature areas.

Figure 5.3 Set with possible new locations based on nature exclusion



Source: LCoE-R mapping model developed in this study

## 5.2 Selection of a preferred set with possible new locations for grid roll-out

In table 5.1 the three sets of possible new OWF locations for the period after 2030 are compared for the sake of selecting a preferred set for which a location specific grid roll-out path will be designed in chapter 6. In order to provide a complete overview, table 5.1 also includes the baseline OWFs up to and after 2030, which have already been planned by the national governments of the North Sea countries.

Table 5.1 Comparison of the three different sets with possible new locations

Set with possible new locations	Number of OWF	Surface (km <sup>2</sup> )	Capacity (3.6 MW/km <sup>2</sup> ) (GW)	LCoE (€/MWh)	LCoE-R (€/MWh)
Baseline up to 2030	99	13,000	55*	-	-
Baseline planned after 2030	24	5,000	20**	39	40
LCOE-R based set	113	31,000	110	37	38
Visibility based set	130	34,000	120	37	38
Nature based set	87	21,000	77	38	38
<b>OWF roll-out list after 2030 = Baseline planned after 2030 + LCOE-R based set</b>	<b>137</b>	<b>36,000</b>	<b>130</b>	<b>37</b>	<b>38</b>

\* The power density of these OWFs deviates from the power density of the reference farm which is 3.6 MW/km<sup>2</sup>.

\*\* This capacity is recalculated for a power density of 3.6 MW/km<sup>2</sup>; see appendix I, table I.1.

Table 5.1 show that the LCoE-R of the baseline planned after 2030 and of the three sets with possible new locations ranges from 37 to 39 €/MWh. The LCoE-Rs are slightly higher and range from 38 to 40 €/MWh. It is noted here that these LCoE ranges are numbers for the future (after 2030) that cannot be compared with the today's LCoEs nor with current bid prices or market values. The numbers strongly rely on multiple assumptions that introduce uncertainties as described in table 4.1 in paragraph 4.1.4. The presented LCoEs are merely meant to enable a comparison of locations.

A more detailed inspection of the numbers presented in table 5.1 shows that the visibility based set and the nature based set of possible new locations have higher average LCoEs and LCoE-Rs than the LCoE-R based set. This is due to those two sets containing relatively more wind farms further offshore. Locations further from shore tend to have a higher LCoE and LCoE-R. The LCoE differences amount to 0.5 to 1.0 €/MWh for respectively the visibility and nature based set. For the LCoE-R a comparable difference is found.

Such cost differences may seem small, but they need to be multiplied with the annual energy production to see the actual cost difference that will occur every year during the 30 years of lifespan of the wind farm. Multiplying these cost differences with the average annual energy production of 570 TWh<sup>1</sup>, reveals an extra energy production cost (including spatial planning cost) of 250 M€/year million for visibility based and 440 M€/year for nature based, recurring every year for the next 30 years. Considering the extra cost to society of the visibility and nature based sets of possible new locations, the LCoE-R based set is selected as a basis for designing a grid roll-out pathway in chapter 6.

#### Impact of spatial planning risk

It is interesting to note that all three sets list were composed by taking spatial planning risk into account: the selection was done on the basis of LCoE-R and not on the basis of LCoE. The average difference between the LCoE and LCoE-R is 0.6 €/MWh. This means that the selected locations do have other user functions.

The cost difference of 0.6 €/MWh may seem little, but when taking into account a total annual energy production of the OWFs after 2030 (130 GW) of 600 TWh/year<sup>2</sup>, the spatial planning risk costs add up to 360 M€/year for a period of 30 years.

#### Grid roll out list

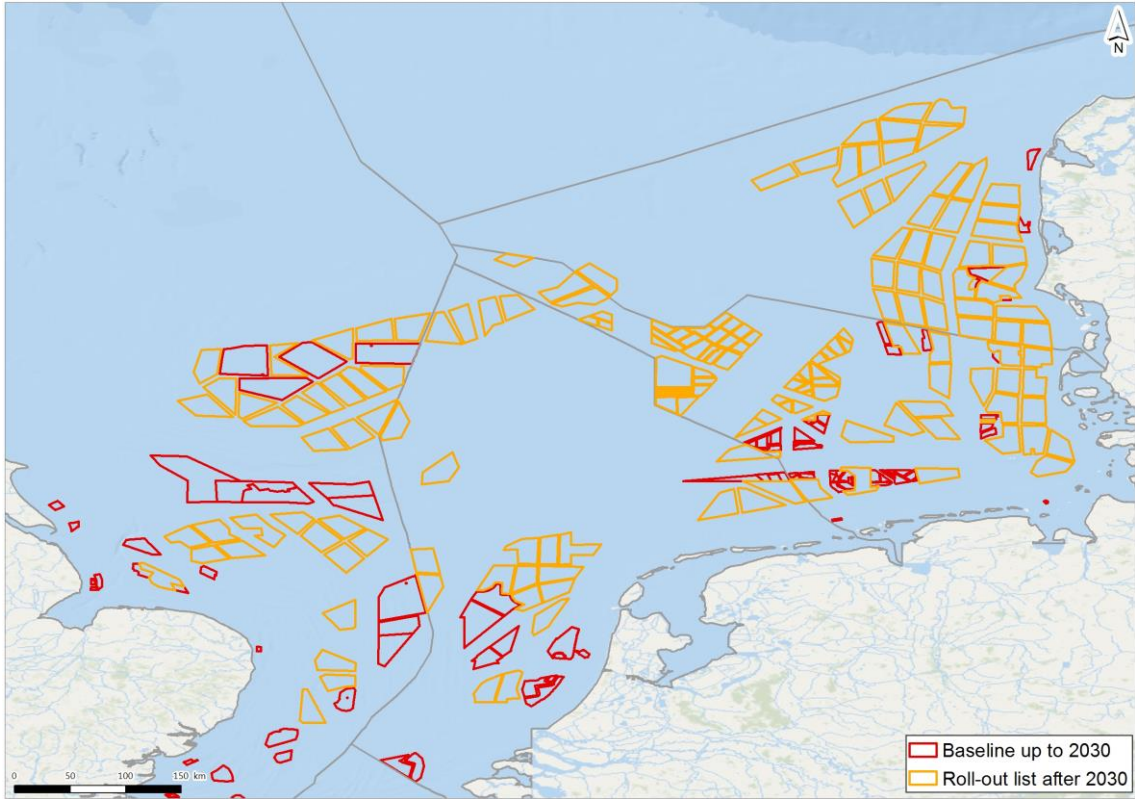
Since the LCoE-R based set with possible new locations contains sufficient capacity and has the lowest average LCoE-R, this set was selected for further grid design. Figure 5.4 shows the roll-out list, which contains the possible new locations of the LCoE-R based set plus the planned OWF locations of the baseline after 2030. The planned OWF locations up to 2030 are not included in the roll-out list, because this studies is about offshore wind energy after 2030. In chapter 6 roll-out pathways will be developed for the locations included in the roll-out list.

---

<sup>1</sup> This is the average energy production (AEP) of the LCoE-R based set with possible new locations.. It is derived from the GIS AEP-map.

<sup>2</sup> This is the average energy production (AEP) of the roll-out list. It is derived from the GIS AEP-map.

Figure 5.4 OWF roll-out list after 2030



Source: LCOE-R mapping model developed in this study

# 6

## GRID ROLL-OUT PATHWAYS

This chapter describes how different grid roll-out pathways were designed for the OWF roll-out list after 2030. In the first two paragraphs it is explained how inter-OWF wake losses were accounted for and how the grid roll-out was optimized. In last two paragraphs the identified roll-out pathways are presented and a preferred pathway is selected. It may be noted that in this chapter LCoE and not LCoE-R maps are the basis of the calculations. The risk component was used to identify possible new locations, but is not needed to design the offshore grid that connects these locations to the onshore grid.

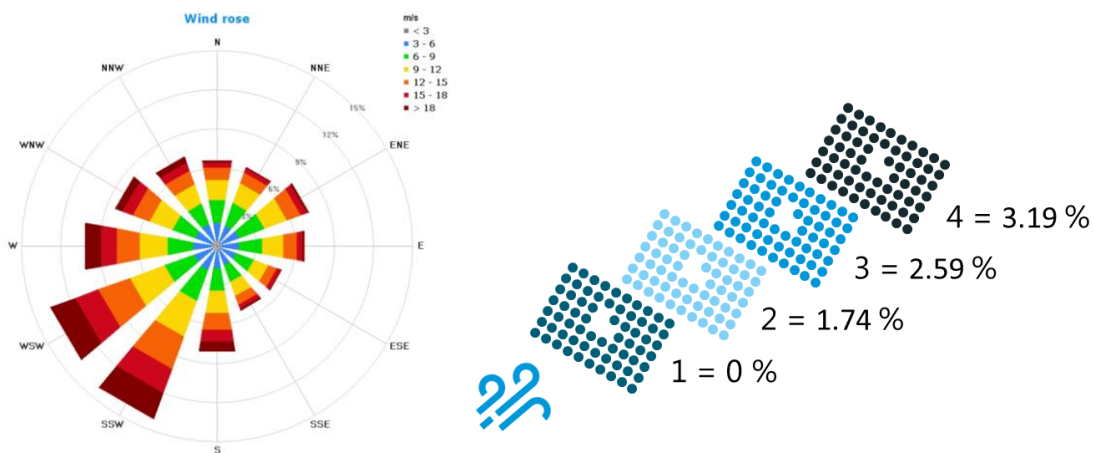
### 6.1 Adding inter-OWF wake losses

So far, only wake losses inside the OWF were accounted for in the LCoE calculations. Now that the exact list of OWF locations to be rolled out has been identified, inter-OWF wake losses can be included in order to obtain a more accurate estimate of the overall LCoE.

ECN part of TNO performed an inter-OWF wake loss analysis, describing the wake loss that OWF locations impose on each other. The results of this analysis show that four wake loss categories can be distinguished based on the number of neighbouring OWFs which are aligned in the dominant wind direction: a single OWF and a cluster of 2, 3 and more than 4 OWFs. Figure 6.1 illustrates this. The larger the cluster, the larger the wake loss factor for that cluster. As a result:

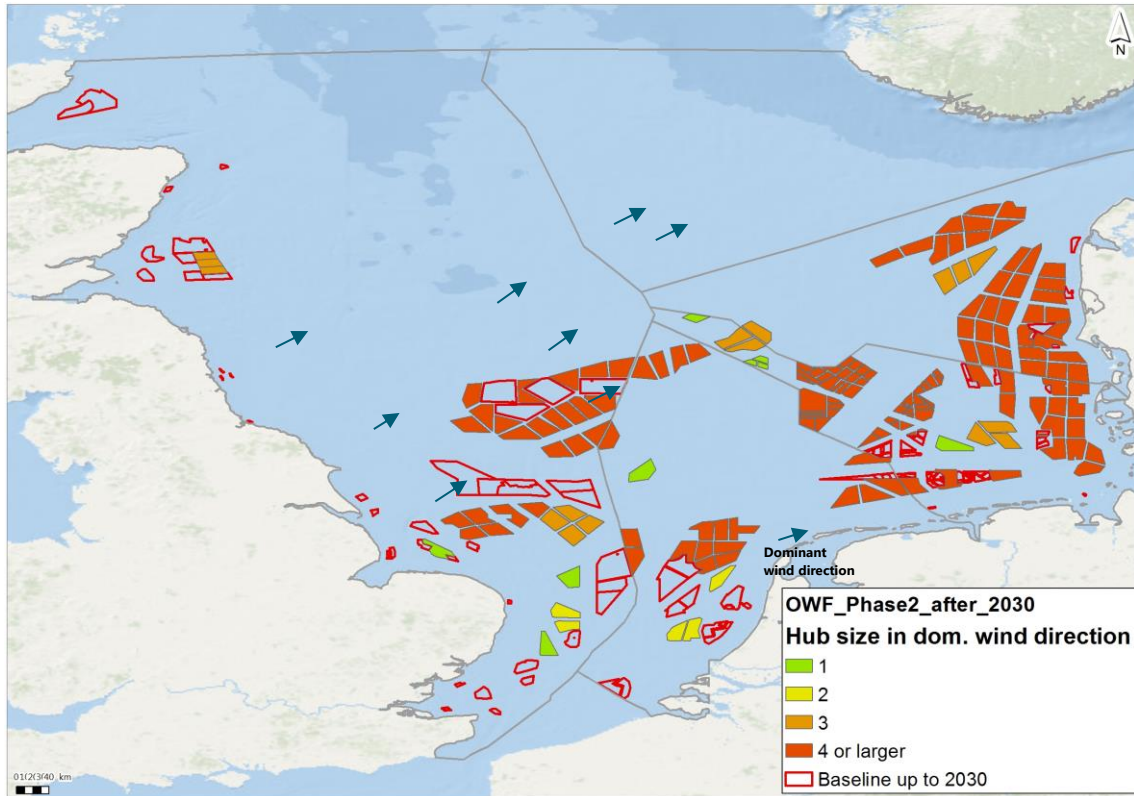
- one isolated OWF has no additional wakes losses on top of internal wake losses;
- two OWFs clustered have 1.74 % additional wake losses on top of internal OWF wake losses;
- three OWFs clustered have 2.59 % additional wake losses on top of internal OWF wake losses;
- four OWFs clustered have 3.19 % additional wake losses on top of internal OWF wake losses.

Figure 6.1 Wind rose (left) and inter-OWF wake losses (right)



On the basis of a dominant wind directions map, all locations of the roll-out list were assigned a wake loss category. Figure 6.2 shows the results of this exercise. The colour legend of this map reflects the four wake loss categories: green being an isolated wind farm, yellow a cluster of two farms, orange a cluster of three and red a cluster of four or more farms. By introducing these intra-OWF wake losses, the overall LCoE of the OWF roll-out list after 2030 increases with approximately 1 €/MWh.

Figure 6.2 OWF roll-out list after 2030 with wake loss rows



Source: LCOE mapping model developed in this study

## 6.2 Grid optimization and economies of scale

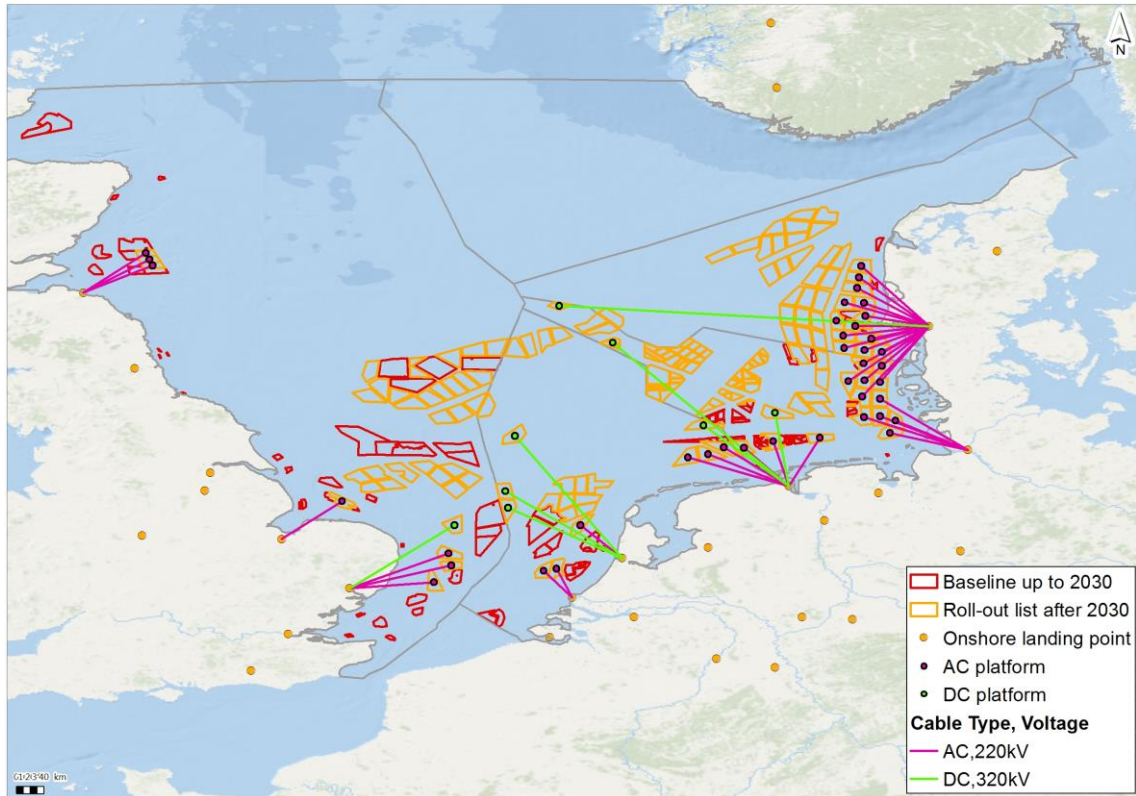
In order to design a grid for the roll-out list that results in a relatively low overall LCoE, a GIS drawing tool was developed. With this tool different grid roll-out pathways can be created and the average LCoE of these pathways can be calculated by taking the following steps:

- 1 determining the centre point of each wind farm of the roll-out list;
- 2 automatically generating AC and DC cables for farms that have an AC or DC connection according to the roll-out list;
- 3 selecting locations for hubs and choosing which farms are to be connected to each hub;
- 4 choosing the type of cable that connects each farm to a hub: for farms within 30 km of the destination hub AC cables of 66KV and for farms between 30 and 80 km of the destination hub AC 220KV cables are available;
- 5 calculating the total capacity in terms of GW deployed of the hubs and connecting the hub to shore with the number of 2 GW cables matching the capacity;
- 6 calculating hub cost and cable cost (CapEx and OpEx);
- 7 recalculating the LCoE, which now includes both OWF costs and location specific grid connection costs, for individual farms and for the total roll-out pathway.

The following paragraphs explain how AC, DC and H&S connections are designed and how their costs are calculated and included in the LCoE.

In figure 6.3 the AC and DC farms of the roll-out list are connected to the onshore grid. They are connected to the nearest landing point. The pink/fuchsia coloured lines reflect the AC cables, and the light green ones the DC cables. Because the roll-out list contains more AC than DC farms, there are more pink/fuchsia coloured lines than green ones.

Figure 6.3 Designing a grid for the roll-out list: the result of drawing in AC and DC radial connections



Source: LCoE mapping model developed in this study

The H&S-farms are connected directly to a hub with the intra-array cables. This is possible up to about 25-30 km from the OWF edge. In order to obtain economies of scale, hubs are located in such a way that the number of OWFs, that can be directly connected to a hub, is maximized<sup>1</sup>.

Wind farms that are further than 30 km away from a hub can also be connected but require an AC substation inside the farm. These substations are connected with 220 kV AC cables to the hub, while the farms are connected with 66 kV cables to the AC substation. This new grid connection system is called AC hybrid. It is a combination of AC radial and H&S<sup>2</sup> that can be applied up to 80 km from the OWF edge. The reader is referred forward to Figure 6.4 and 6.7 in paragraph 6.3.2 for a sketches of the AC hybrid system.

<sup>1</sup> In essence, because the hub is typically at the centre of the connected OWFs.

<sup>2</sup> It may be noted here that the energy loss of this AC hybrid GCS is currently not properly modelled, as it is still using the energy loss of AC radial. Also for farms that are connected this way, OpEx is modelled on the basis of maintenance from the mainland whereas it will actually take place from the hub. This means that the cost estimates for this connection type are not very accurate as they are overestimated.



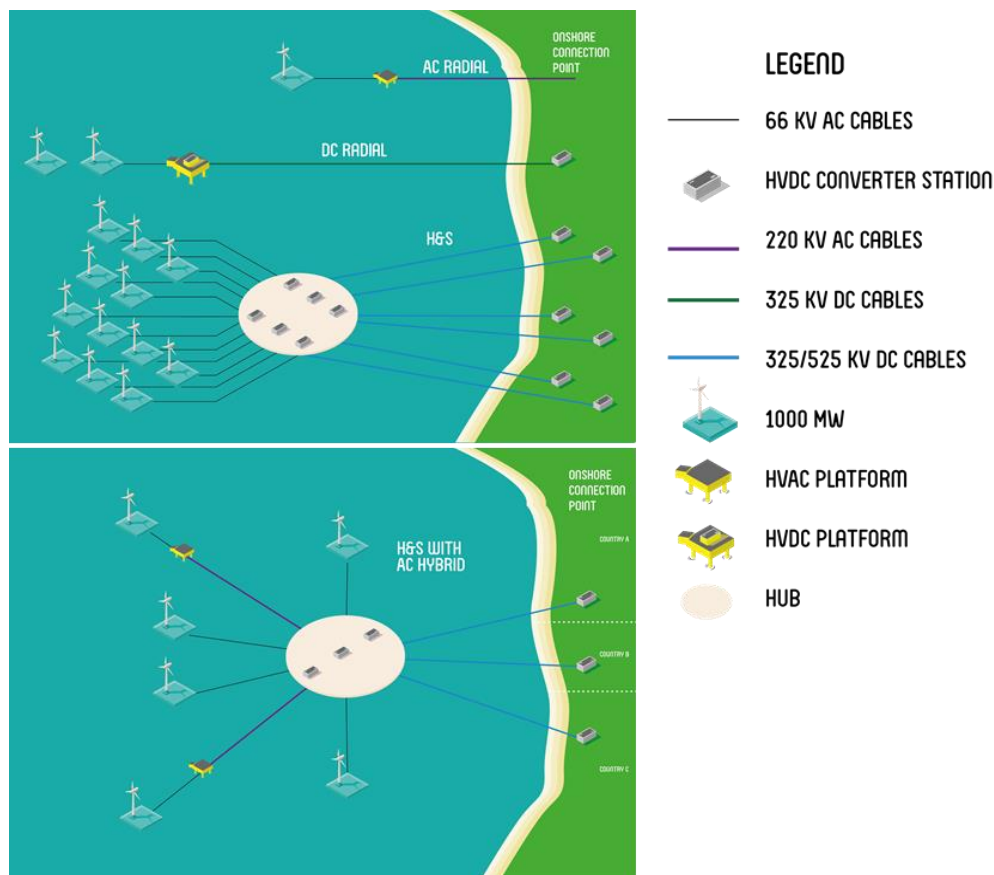
Once all farms are connected to a hub, hub sizes in terms of GW and the required number of 2GW onshore connections are known. While designing a grid roll-out pathway, a balance between short cable distances and serving multiple countries is strived for. The onshore connection points for designing the grid roll-out pathway are derived from a previous analysis that determined the spare capacity per onshore connection point (Vree and Verkaik, 2017). It was assumed that these onshore connection points can handle the connected OWFs' electricity production and no further grid reinforcements were required.

In order to allow economies of scale to be achieved when designing grid roll-out pathways, the costs for the hub foundation were varied, based on the hosting capacity of the hub and the applicable water depth (depending on the location of the hub). This variation in costs allowed the analysis to apply hub sizes ranging from 4-16 GW, thereby allowing hubs other than the initial 12 GW hub. Although large hubs have higher costs than small hubs, the cost per GW are lower for large hubs than for small hubs, as large ones host more OWFs. The hub costs used in this study were derived from a NSWPH consortium study<sup>1</sup>.

### 6.3 Identified roll-out pathways

Following the grid design procedure as explained in the previous paragraphs, two different roll-out pathways were created from two different angles. The first angle was to simply create enough hubs to connect all farms included in the roll-out list using 66 kV cables. The second angle was to reduce the number of hubs by connecting more farms to one hub by means of the AC hybrid GCS and realise economies of scale. Figure 6.4 illustrates these two angles.

Figure 6.4 GCS concepts used to design roll-out pathways: without (top) and with (bottom) AC hybrid

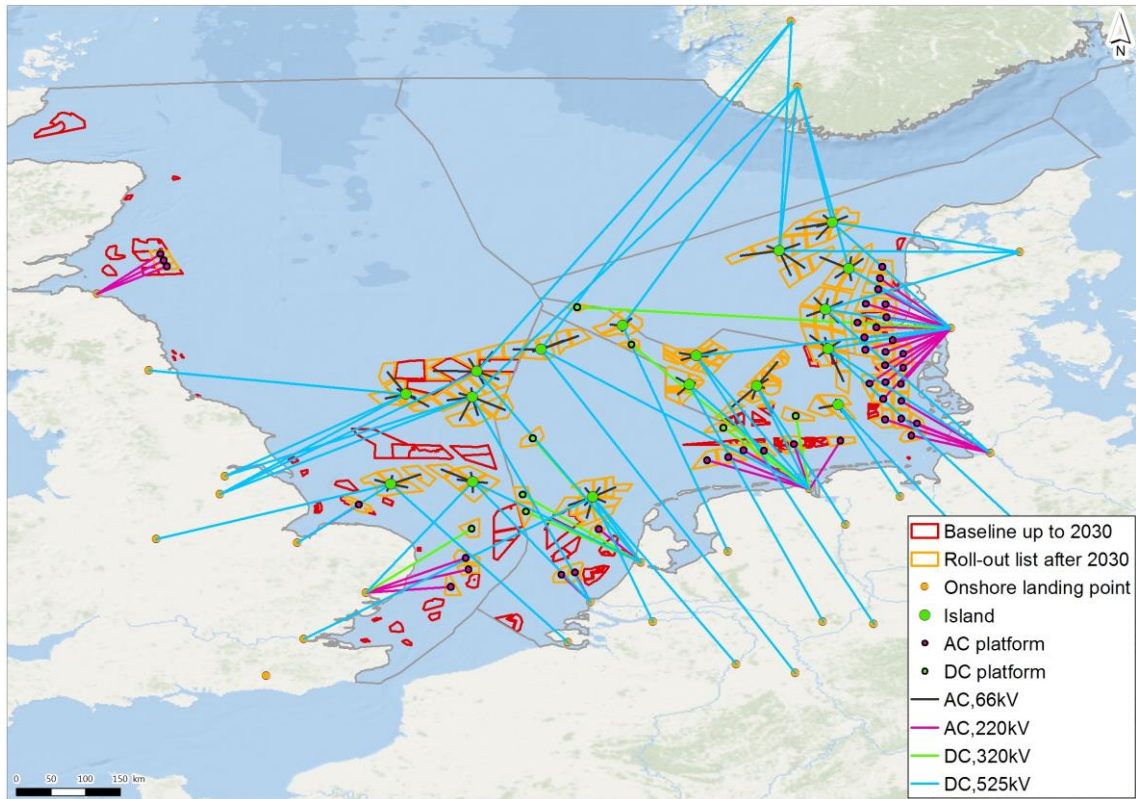


<sup>1</sup> In hub costs applied in this study pertained to hubs in the form of sandy islands.

### 6.3.1 Pathway 1: Enough hubs

Figure 6.4 (top) shows a sketch of the grid connection system used to design a roll-out pathway with enough hubs to connect all hub and spoke OWFs with a maximum distance of 30 km: the reach of the 66 kV cables. Figure 6.5 shows the map in which all identified H&S farms are connected in this manner.

Figure 6.5 Pathway 1: Enough hubs<sup>1</sup>

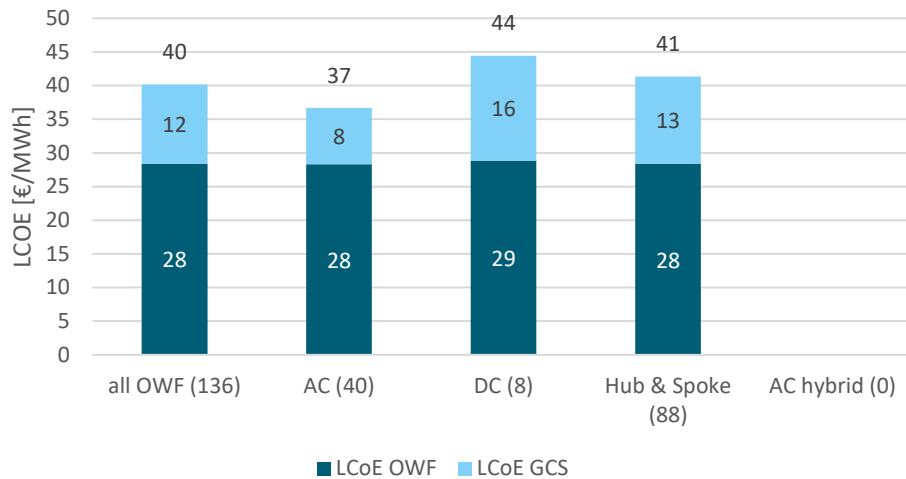


Source: LCoE mapping model developed in this study

This pathway contains 17 hubs with a HVDC conversion capacity hosted by a single hub ranging from 3 to 8 GW. The average LCoE of this pathway is 40 €/MWh. This is higher than the average LCoE of the roll-out list of 37 €/MWh that was presented in the previous chapter. The cost increase is a result of accounting for inter wind farm wake losses and as a result of adding location specific grid connection costs. Figure 6.6 shows the breakdown of the LCoE-results of this pathway.

<sup>1</sup> As a first approximation for minimising grid integration cost, deeper inland connections have been considered which connect offshore transmission cables to locations where available connection capacity is expected based on fossil fuel phase-out scenarios.

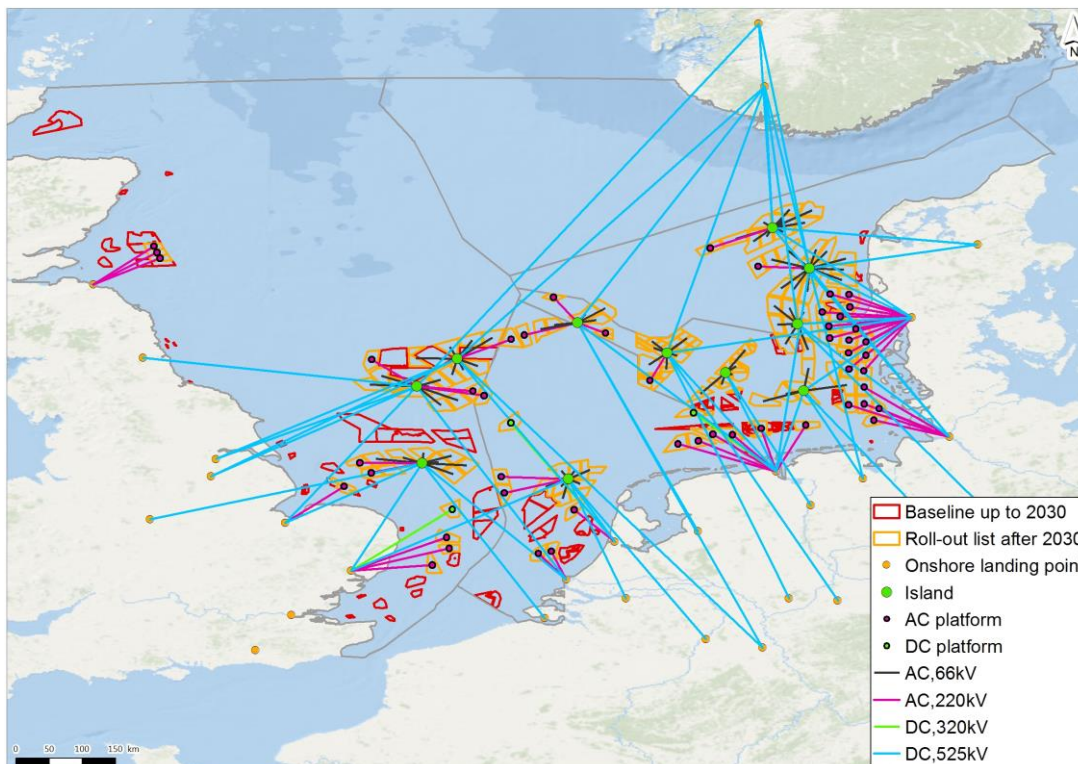
Figure 6.6 LCoE results of the enough hubs pathway



### 6.3.2 Pathway 2: Large hubs

Since the first pathway contained many hubs (17) with a hosting capacity of 3-8 GW, a second pathway was created that contained less, but larger hubs to enable economies of scale. This was done by connecting all farms outside the 30 km range with an AC substation to the hub (the AC hybrid GCS). Also some DC farms were coupled with the AC hybrid GCS to nearby (30-80 km) hubs. Lastly, AC farms further than 80 km from the landing point and within 30 km of a hub were also coupled to a hub. Figure 6.4 (bottom) shows a sketch of the AC Hybrid concept, while figure 6.7 shows the roll-out pathway that was designed by applying this concept.

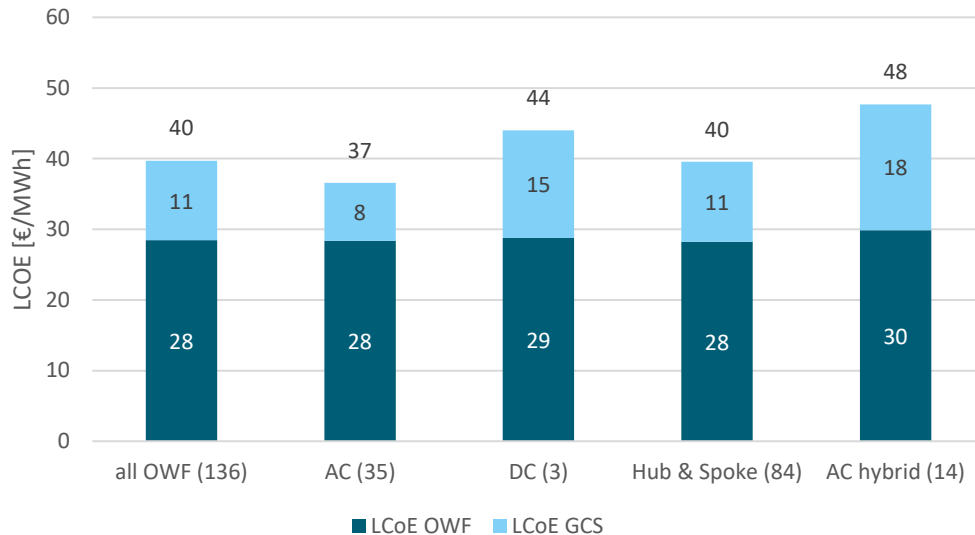
Figure 6.7 Pathway 2: Large hubs



Source: LCoE mapping model developed in this study

This pathway contains 11 hubs with a HVDC conversion capacity hosted by each hub ranging from 4 to 14 GW. Compared to the first path way, the number of hubs is reduced by 6, while the maximum hub capacity is increased by 6 GW. The average LCoE of this pathway is 40 €/MWh. This is comparable to the 'enough hubs' pathway, but a more detailed inspection of LCoE breakdown reveals that the LCoE of the 'large hubs' pathway is approximately 0.4 €/MWh lower than the 'enough hubs' pathway. Figure 6.8 shows the breakdown of the LCoE of this roll-out pathway.

Figure 6.8 LCoE results of the large hubs pathway



This LCoE breakdown shows that the farms connected with AC hybrid may themselves be relatively expensive, but they reduce the overall LCoE of the roll-out pathway. This demonstrates that considering the GCS of individual OWFs on a case by case basis may not yield the overall optimum cost for society. In order to minimize the cost to society, the total expected roll out of both OWF and transmission assets should be considered from an Internationally Coordinated Roll Out (ICRO) perspective.

### 6.3.3 Capturing economies of scale

The modest LCoE difference between the two presented pathways is an indication that there are economies of scale to be gained by reducing the number and increasing the size of hubs. This hypothesis was tested by adapting the grid design of three locations:

- 1 Dogger Bank: this location was selected since it contains the most hubs and consequently the potential for realizing economies of scale by reducing the number of hubs seems large here;
- 2 Nord-Ost Passat and H2-20: for this location changing DC radial to AC hybrid could potentially capture economies of scale;
- 3 Nearshore Denmark: two AC farms were changed to H&S and connected to the nearest hub to obtain economies of scale.

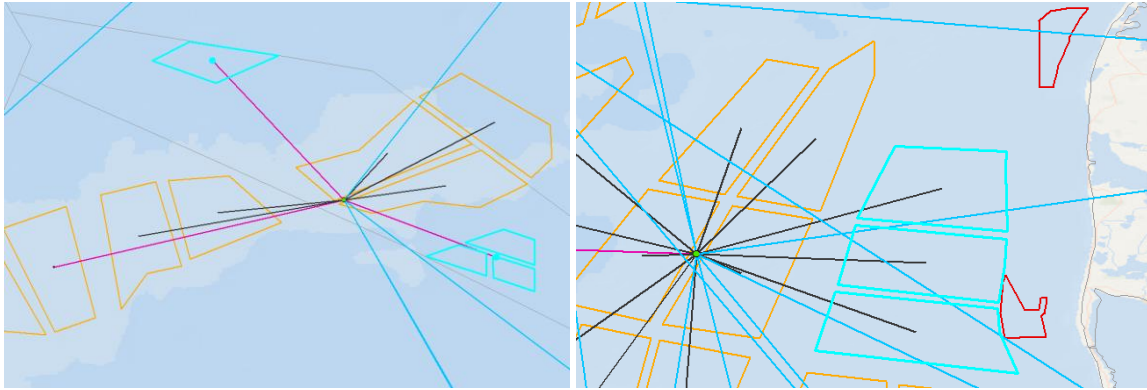
#### Test location 1: Dogger Bank 5 to 3 hubs

The average LCoE at Dogger Bank is estimated to be 43 €/MWh for a grid design with 5 hubs of 4 to 6 GW. By replacing the 5 small hubs on the Dogger Bank by 3 larger ones of 8, 10 and 12 GW, the average LCoE drops with 1.0 €/MWh for this location. Apparently, the relatively expensive AC hybrid farms are out weighted by the reduced hub costs.

### Test location 2: DC radial changed to AC hybrid for Nord-Ost Passat and H2-20 (Germany Zone 5)

In pathway 1, the German OWFs Nord-Ost Passat and H2-20 were connected with DC. Figure 6.9 shows these two locations. Their LCoEs were 46 and 47 €/MWh respectively. If one connects these locations with AC hybrid, their LCoEs drop with 0.5 and 0 €/MWh respectively. This rather modest cost reduction suggests that there are no significant economies of scale to be gained by coupling DC farms to nearby (30-80 km) hubs.

Figure 6.9 Nord-Ost Passat and H2-20 (left) and nearshore Denmark (right)



Source: LCoE mapping model & grid drawing tool developed in this study

### Test location 3: AC radial changed to H&S nearshore Denmark

In pathway 1 there are three AC farms near the Danish shore that are within reach of a hub. By changing their connection type to H&S and connecting them to this hub, the average LCoE of this Danish location drops with 0.2 €/MWh, capturing a modest economies of scale advantage.

From the three test locations one can conclude that economies of scale can be realized by introducing larger hubs and connecting as many as possible farms to these hubs. Connecting far from shore DC farms with a relatively expensive AC hybrid system and/or connecting near shore AC farms also seems to generate modest economies of scale advantages. Further testing where the optimum lies for the hosting capacity of the hub can be done in a later stage of the NSWPH project.

## 6.4 Selection of preferred grid roll-out pathway

From the previous paragraphs it can be concluded that the identified grid roll-out pathway with large hubs has a slightly lower LCoE compared to the pathway with enough hubs. Since this study focusses on costs only, the 'large hubs' pathway is selected as a preferential pathway. Although this study focuses on the cost factors of OWF locations, spatial planning as a whole needs to balance cost information with several other tangible and intangible criteria. Hence, these other factors could influence the eventual optimum roll out pathway.

The results of the economies of scale roll-out exercises suggest that pathways enabling economies of scale by means of larger hubs that serve many farms, results in slightly lower overall LCoEs, even if the relatively expensive AC hybrid grid connection system is applied.

For further optimization, increasing the hub size without having to use the AC hybrid type could be an interesting option. There seem to be two different ways to realize this:

- by increasing the wind farm power density, so that more GW can be realized within 30 km of the hub;
- by investigating if 25-30 km is really the maximal distance for the direct connection to the hub via the 66 kV intra-array cables.

The sensitivity analysis in chapter 7.1 investigates the idea of increasing the power density of the wind farms.

# 7

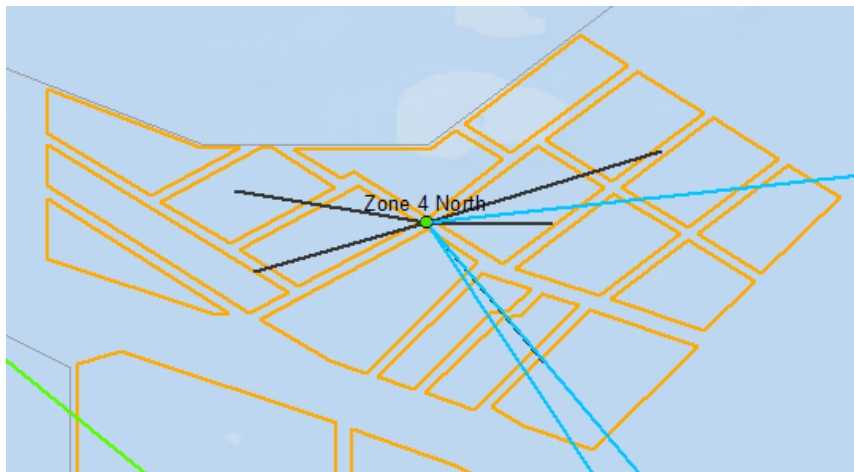
## SENSITIVITY ANALYSES

In this chapter the results of three different sensitivity analyses are presented. The first analysis reveals the potential for capturing economies of scale by increasing power density in combination with large hubs. The second analysis shows how the LCoE is impacted if the H&S GCS is not used and all OWFs of the roll-out list were to be connected with AC or with DC only. The third analysis presents what happens to the LCoE if nature conservation areas are swapped by adjacent areas so that the amount of GW deployed is aligned with the Paris i.e. The 'Translate COP21' target, while nature areas are excluded.

### 7.1 Sensitivity to wind farm power density

The key question of this sensitivity analysis is 'What happens to the LCoE if a higher wind farm power density is applied?' In order to find the answer to this question a test location in the German Zone 4 was selected, since the German OWFs are currently developed with a power density range of 10 to 17 MW/km<sup>2</sup>, which is significantly higher than the 3.6 MW/km<sup>2</sup> of the reference farm of this study. Figure 7.1 shows the test location: Zone 4 North hub and its surrounding H&S farms.

Figure 7.1 Test location for power density with grid connection H&S)



Source: LCoE mapping model & grid drawing tool developed in this study

In order to redesign the test location with higher power densities, the farms were 'unclustered' to undo the previous design that used a reference power density of 3.6 MW/km<sup>2</sup>. Subsequently, the capacity of each polygon was calculated in terms of MW with higher densities of 6.4 and 14.4 MW/km<sup>2</sup>. On the basis of these capacities the locations were clustered again into farms of approximately 1 GW. Since different power densities have different wake losses, the annual energy production was recalculated while taking into account the relevant losses. Table 7.1 shows the wake loss factors in relation to power density that were used in this calculation.

Table 7.1 Wake losses for different OWF power densities compared to an isolated reference farm

Turbine distance expressed in rotor diameter D	8D	6D	4D
density (MW/km <sup>2</sup> )	3.6	6.4	14
1 OWF	0.0 % (reference)	+1.3 %	+7.9 %
2 OWF cluster	+1.7 %	+4.5 %	+11 %
3 OWF cluster	+2.6 %	+5.6 %	+12 %
≥4 OWF cluster	+3.2 %	+6.4 %	+14 %

Source: ECN part of TNO, 2018

After recalculating the annual energy production, the farms were connected to the new, larger, hubs. The OWF and hub locations were not changed. In other words: only the size of the hub was altered, not the location, so the hub size impact can be isolated. Finally, the number of cables from the hub to the shore was increased to match the new hub capacity. Subsequently, the LCoE was recalculated. Figure 7.2 shows the results of this experiment.

Figure 7.2 Sensitivity of LCoE to farm power density

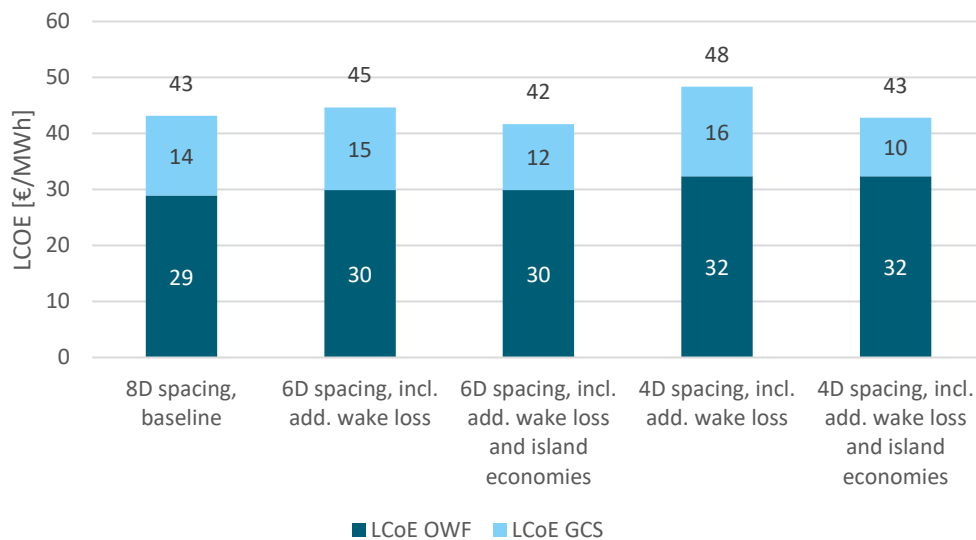


Figure 7.2 shows that applying higher power densities without taking the economies of scale advantage of hub size into account, would- of course- only increase the LCoE. But when these economies of scale are accounted for the LCoE is reduced (with 1.5 and 0.4 €/MWh for densities of 6.4 and 14.4 MW/km<sup>2</sup> respectively) in spite of the fact that wake losses are higher at higher power densities.

Figure 7.2 also suggests that there is an optimal power density between 3.6 (8D) and 14.4 MW/km<sup>2</sup> (4D), as the LCoE realized with a power density of 14.4 MW/km<sup>2</sup> (4D) of 43 €/MWh is 1.1 €/MWh higher than the LCoE realized with a power density of 6.4 MW/km<sup>2</sup> (6D), but 0.4 €/MWh lower than the LCoE with a power density of 3.6 MW/km<sup>2</sup> (8D).

On the basis of these results it is concluded that hub economies of scale, based on sandy island hubs, seem to surpass wake loss diseconomies of scale. This means that using a reference farm with a higher power density (than 3.6 MW/km<sup>2</sup>), e.g. more comparable power densities as used in German farms, may further reduce the LCoE, while at the same time it reduces the space consumption of offshore wind farms and thereby also spatial planning conflicts. Further analysis is required to determine the optimum OWF power density and to reveal the tipping point of where the impact of wake losses becomes dominant.

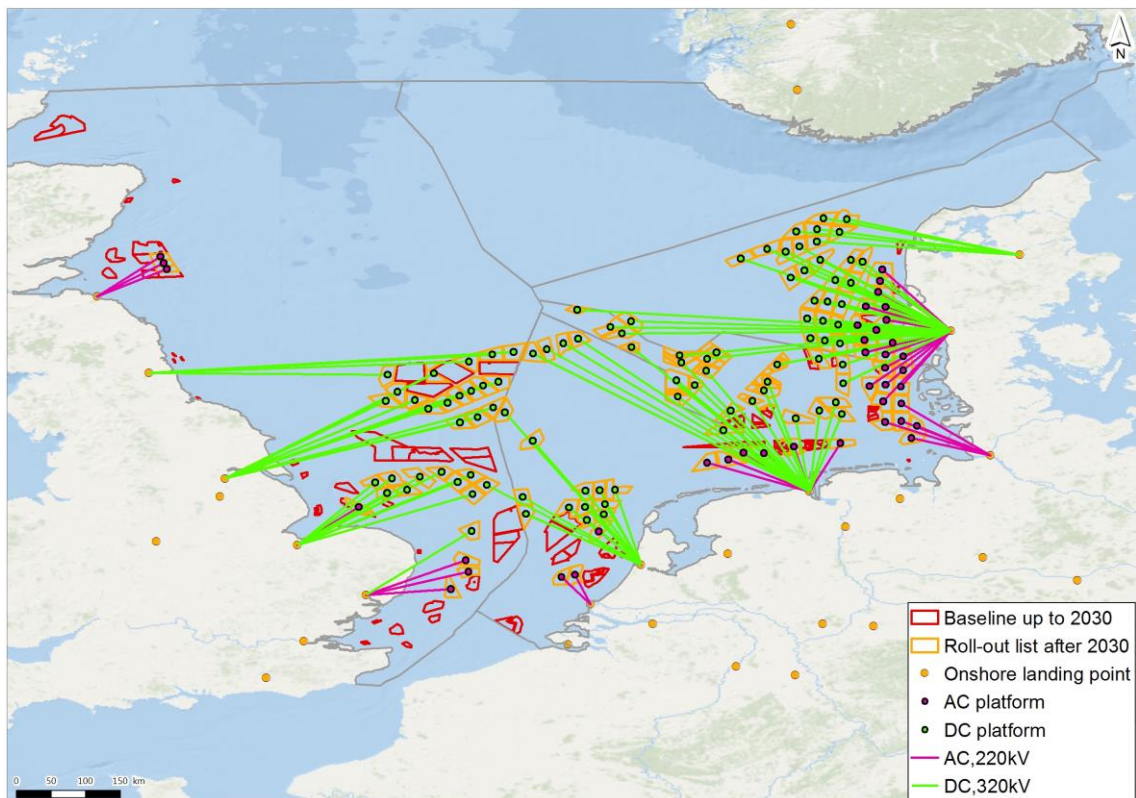
## 7.2 Sensitivity to no hubs

The LCoE breakdowns of the ‘Enough hubs’ and ‘Large hubs’ roll out pathways show that the average LCoE of H&S locations is higher than the average of AC locations but lower than the average LCoE of DC locations. A more detailed inspection of the LCoEs of individual AC, DC and H&S locations, however, reveals that the LCoE range of the different grid connection systems have much overlap. This evokes the question of what the LCoE of the roll-out list would be, when no hubs are used. In other words: *‘what if all newly identified locations are connected with just AC or DC, and no hubs are applied?’* In order to answer this question all farms of the roll-out list with a H&S GCS were changed into farms using the DC radial GCS, while the AC-locations were not changed. Subsequently the LCoE was recalculated.

This pathway is comparable with the NIRO scenario, as defined in the Urgency and Benefit study (Vree and Verkaik, 2017). In this scenario no hubs are applied and the OWFs are connected radially to the nearest onshore grid connection point. As such, in this scenario it is allowed to connect an OWF that is developed in another country’s EEZ. To enable this, strong international coordination is needed.

Figure 7.3 shows the roll-out design of the ‘no hubs’ pathway.

Figure 7.3 Grid roll-out pathway without hubs

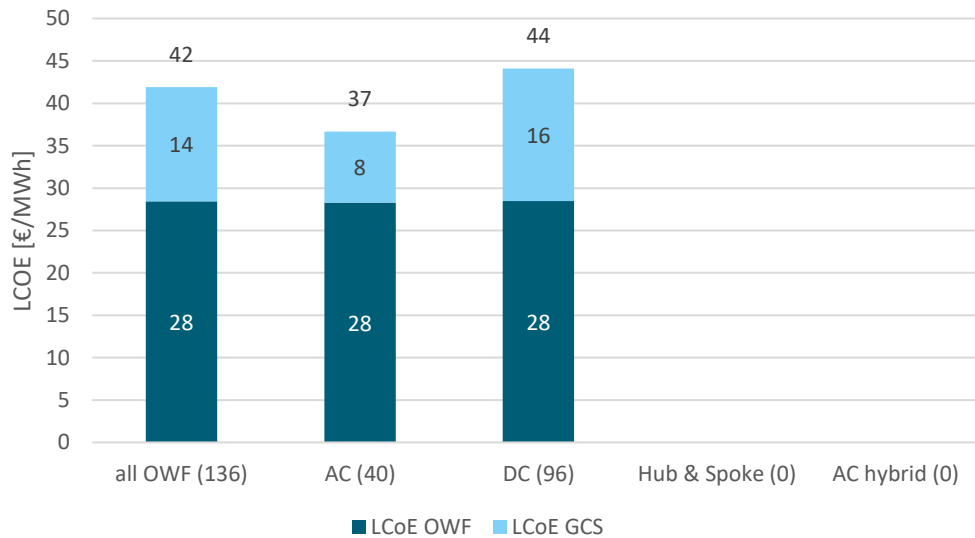


Source: LCoE-mapping model developed in this study



Figure 7.4 show the breakdown of the LCoE results of this exercise. This reveals that not using hubs for those farms that could be connected to one, increases the LCoE by approximately 2.2 €/MWh compared to the roll-out pathway with large hubs (pathway 2)<sup>1</sup>. Considering the annual energy production of the roll-out list of approximately 600 TWh /year, this amounts to an extra societal cost of approximately 1,300 M€/year for the 30 years lifetime of the OWFs.

Figure 7.4 LCoE results of no hubs pathway



### 7.3 Sensitivity to including areas just outside nature areas

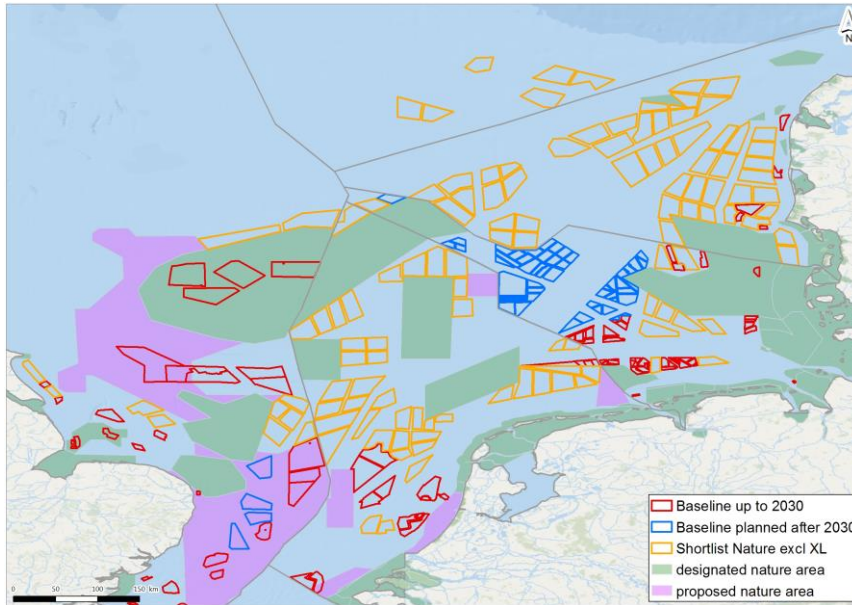
In chapter 5.1.3 a set of possible new OWF locations was composed that excludes nature areas. By excluding all the nature areas insufficient deployment capacity<sup>2</sup> was found to meet the Paris/ Translate COP 21 target to decarbonize the power sector in the North Sea region. In this paragraph it is checked 'what will happen to the LCoE if OWFs adjacent to nature areas are added so that the amount of GW deployed is aligned with the Paris agreement targets?'

In figure 7.5 extra OWF locations are added just outside the nature areas. This results in a set of possible new locations with a capacity that does match the Paris target. This set has a total capacity of 110 GW. However, the question remains how do the new OWF impact the LCoE.

<sup>1</sup> Taking into account the current grid connection approach, which lacks international coordination, the relative LCoE would thus increase even further, according to this analysis.

<sup>2</sup> The nature based set with possible new locations contained only 77 GW of the required 110 GW.

Figure 7.5 A set of possible new locations based on nature exclusion after adding additional OWFs



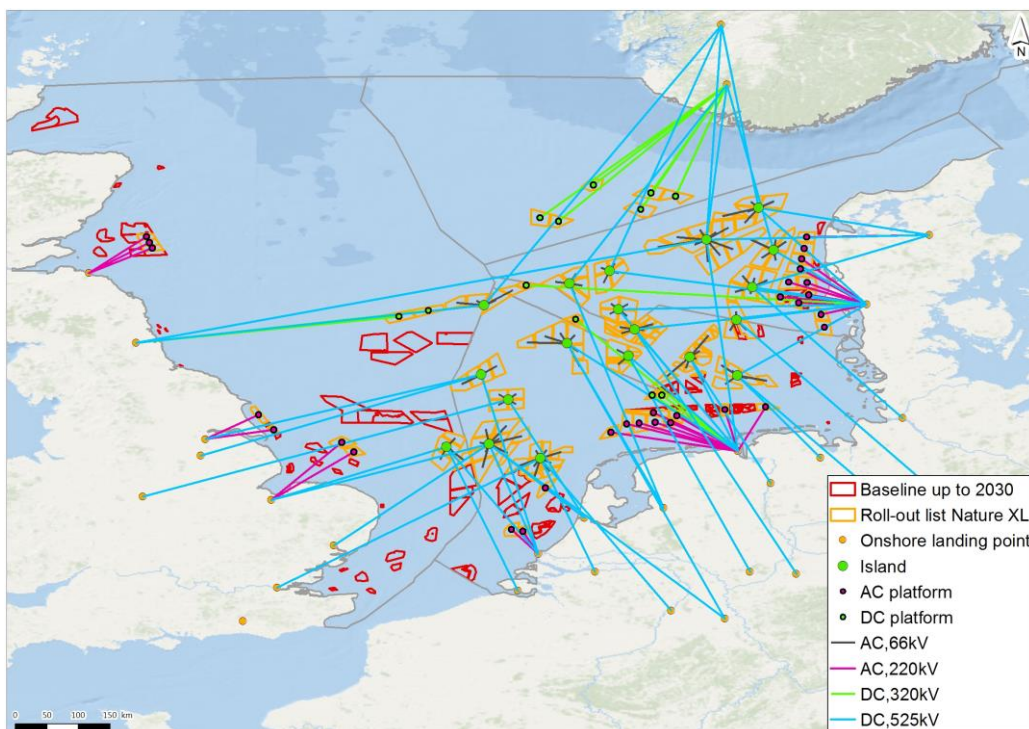
Source: LCoE-R mapping model developed in this study

In order to answer this question two grid roll-out pathways were designed for the new nature exclusion based set of possible new locations:

- one with simply enough hubs to connect each farms;
- one with less, but larger hubs.

This is similar to the analysis done in section 6.3. Figures 7.6 and 7.8 show these two roll-out pathways, while figures 7.7 and 7.9 show the breakdowns of their respective LCoEs.

Figure 7.6 Grid roll-out pathway for the 'outside nature areas' set with enough hubs



Source: LCoE-mapping model developed in this study

Figure 7.7 LCOE results of the 'outside nature areas' set with enough hubs pathway

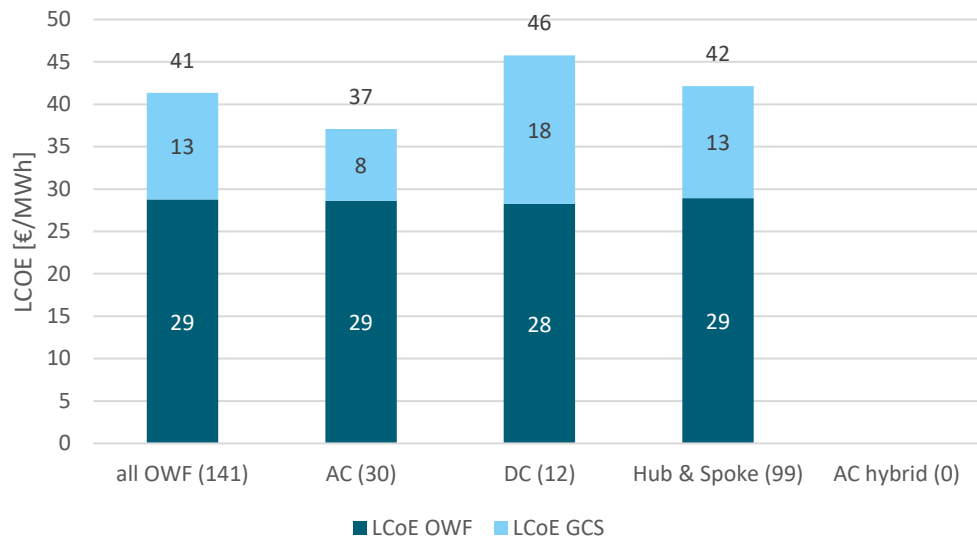
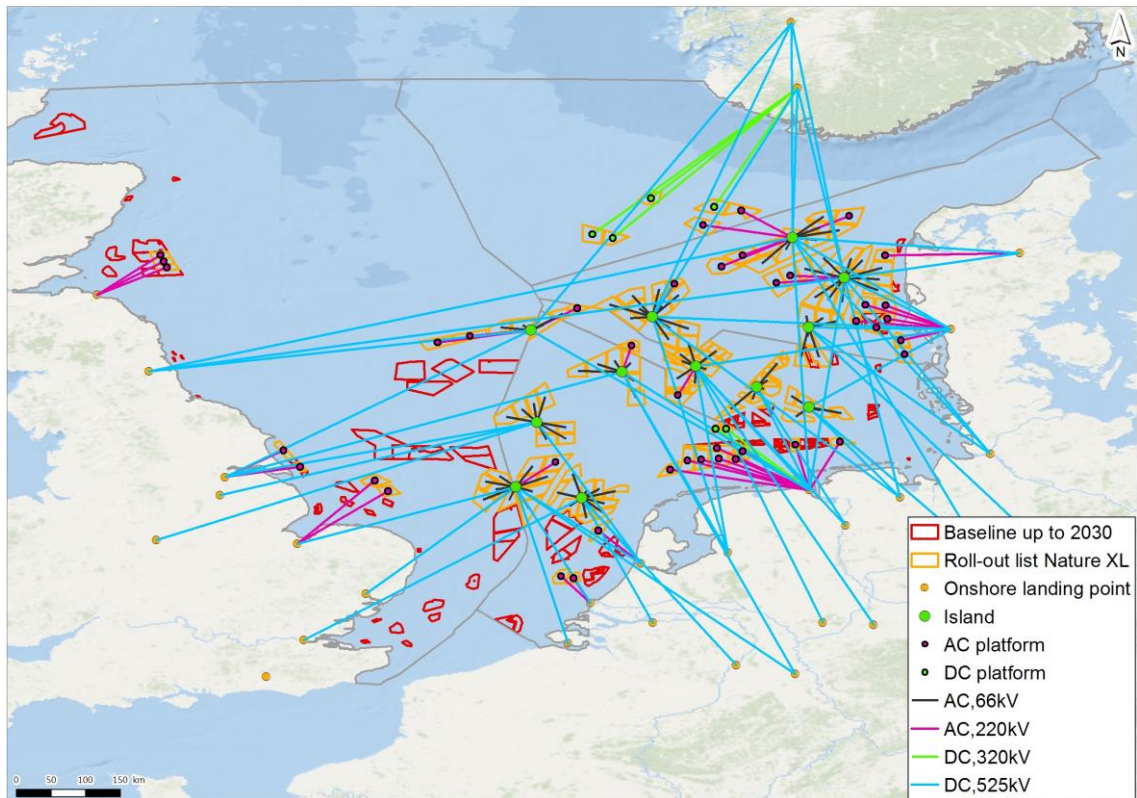


Figure 7.8 Grid roll-out pathway for the 'outside nature areas' set with large hubs



Source: LCoE-mapping model developed in this study

Figure 7.9 LCoE results of the 'outside nature areas' set with large hubs pathway

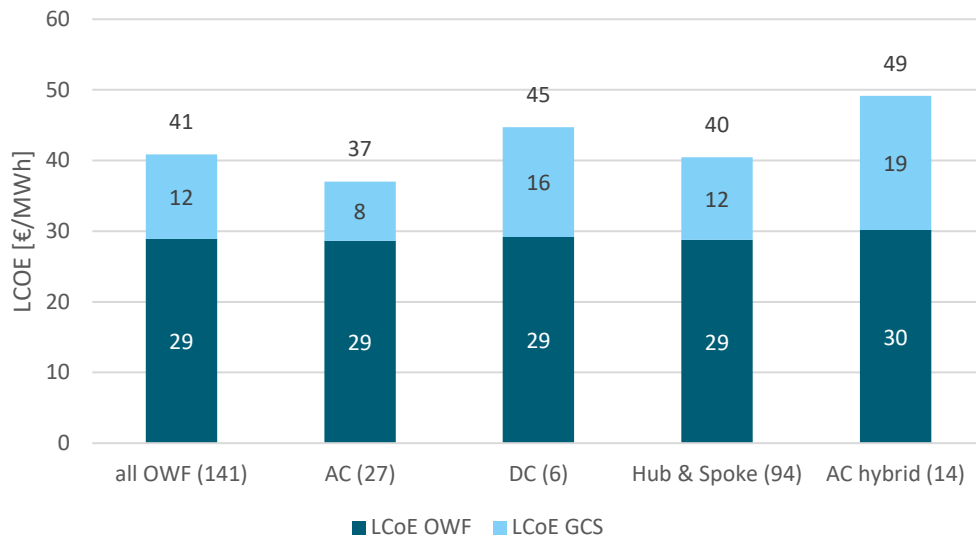


Table 7.2 briefly summarizes the results of this sensitivity analysis in such a way that the cost consequences of adding nature adjacent areas are revealed.

Table 7.2 The cost impact of meeting the Translate COP21 target while excluding nature areas at the same time

Roll-out design	LCoE without nature adjacent locations to realise sufficient capacity	LCoE with extra nature adjacent locations to realise sufficient capacity	Extra cost due extra nature areas in M€/year*
enough hubs	40	41	730
large hubs	40	41	680

\* Given an annual energy production of the roll-out list of approximately 600 TWh/year and LCoE-numbers that were not rounded.

From table 7.2 it can be concluded that adding extra nature adjacent areas, to realize sufficient capacity to meet the Translate COP21 target, induces an extra societal cost of approximately 680 to 730 M€/year for the 30 year lifespan of the OWFs. This cost increase is primarily driven by the facts that the OWFs are 'moved' to deeper waters and that the new OWFs are less clustered and thus capture less economies of scale.

Table 7.2 also shows that pathways without nature adjacent areas yield a roll-out LCoE of approximately 40 €/MWh, while pathways with such areas have a LCoE that is approximately 1 €/MWh higher. This LCoE increase is caused by higher OWF costs as well as higher offshore transmissions cost per MWh of the added nature adjacent locations.

These results demonstrate that there are choices to be made in spatial planning of OWF locations. Avoiding nature areas could increase the LCoE of large scale OWF deployment and subsequently the cost to society of reaching the Paris Agreement climate goals.

# 8

## MAIN RESULTS & FOLLOW UP STUDIES

This chapter provides an overview of the main results of this study and makes some suggestions for follow up studies.

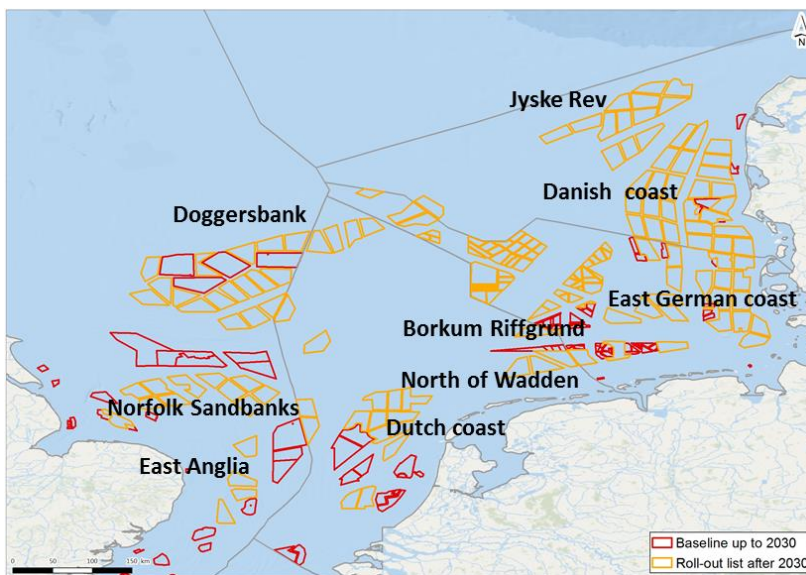
### 8.1 Main results

The main results of this study are possible new OWF locations in the North Sea and their LCoEs, two different grid rollout pathways and their LCoEs plus the results of sensitivity analyses on not applying the H&S grid connection type and on including OWF locations adjacent to nature areas.

#### 8.1.1 Possible new OWF locations and their LCoEs

In this study possible new OWF locations for the period after 2030 were identified using LCoE-R maps. The identified new locations had a total capacity of 110 MW. Together with the already planned baseline locations after 2030 of 20 MW, they form a roll-out list of 130 GW. Figure 8.1 shows a map with the OWF locations of the roll-out list (orange polygons) and the locations of the baseline up to 2030 (red polygons). The baseline farms up to 2030 represent a total capacity of 46 GW, assuming a power density of 3.6 MW/km<sup>2</sup>.

Figure 8.1 Roll-out list and baseline up to and after 2030<sup>1</sup>



Source: LCOE-R mapping model developed in this study

<sup>1</sup> OWF areas depicted in this figure provides a point of departure to stimulate discussion among various stakeholders and do not represent any specific policy recommendation.

The most attractive locations in terms of LCoE are at Borkum Riffgrund (36 €/MWh), facing the Danish coast (37 €/MWh), the Dutch coast (38 €/MWh), at East Anglia, the Eastern German coast, the Jyske Rev plus to the North of the Wadden (39 €/MWh), at the North Norfolk sandbanks (41 €/MWh) and also at the Doggersbank (42 €/MWh)<sup>1</sup>. It is noted here that the LCoEs are numbers for the future that cannot be compared with today's LCoEs.

### 8.1.2 Roll-out pathways and their LCoE

The OWFs of the roll-out list were connected to the grid with two different design strategies: a pathway with enough hubs to serve all the identified farms and one with large hubs in order to capture hub economies of scale. Both roll-out pathways turned out to have an average LCoE of 40 €/MWh, but a detailed inspection of the LCoE breakdowns of both pathways showed that the 'large hubs' pathway has a slightly lower average LCoE than the 'enough hubs' pathway due to lower grid connection cost.

For the roll-out pathway with enough hubs, it was found that the majority of farms had a LCoE between 37 and 45 €/MWh. The more expensive farms were DC farms. In this pathway most hubs could only serve 4 to 6 farms due to the limited connection distance of 30 km, which is caused by 66 kV AC cable technology constraints.

The pathway with large hubs was designed to capture economies of scale of hub size. In order to capture these, the limited hub connection distance needed to be increased. For this purpose a new GCS was introduced: AC hybrid. With the AC hybrid concept it becomes possible to design a roll-out pathway with larger hubs serving 8 to 10 farms. Even though the few OWFs that require an AC hybrid connection are relatively expensive (46-49 €/MWh), they allow the majority of farms to shift to a relatively low LCoE-range (37-40 €/MWh). This shift reduces the average LCoE of the whole roll-out list. The attempt to capture economies of scale with the large hubs pathway that included AC hybrid farms, resulted in a modest average LCoE reduction of 0.4 €/MWh compared to the enough hubs pathway.

### 8.1.3 Sensitivity analyses

In sensitivity analyses additional roll-out pathways were designed to answer the following two questions:

- What if no hubs are applied and farms with a H&S GCS are connected via a DC GCS instead<sup>2</sup>?
- What if nature areas are excluded and extra OWF locations are added outside nature areas to meet Paris Agreement/Translate COP21 target of 180 GW?

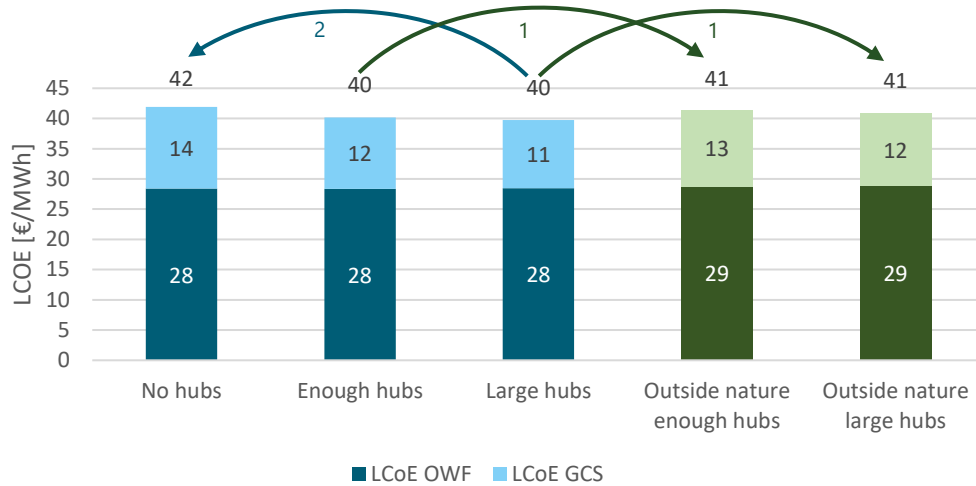
Figure 8.2 shows that not applying the H&S GCS (no hubs) increases the LCoE with 2 €/MWh. This figure also shows that excluding nature areas while realising sufficient capacity increases the LCoE with 1 €/MWh in both a grid roll-out pathway with enough hubs and with large hubs.

---

<sup>1</sup> This ranking shows that Doggersbank does not have the lowest levelized cost per MWh. This is caused by the fact that the UK baseline farms at the Doggersbank are not connected to the hub, which limits the economies of scale of the hub.

<sup>2</sup> AC is not considered as this more costly for farms further offshore than DC.

Figure 8.2 Comparison of all grid roll-out pathways



## 8.2 Follow-up studies

This paragraph discusses topics which should be further investigated in follow up studies, because there exists an information gap and/or they could significantly influence the LCoE. The topics pertain to spatial risk, economies of scale and interconnection benefits.

### 8.2.1 More detailed investigation of spatial risks

All spatial risks, i.e. all spatial user functions, that were included in this study deserve extra detailing in order to get a more accurate estimate of spatial planning risk cost i.e. adaptation costs. For two crucial functions, nature and shipping, some practical suggestions for follow up work are discussed here.

#### Birds

Two different types of birds need to be considered: migratory birds and sea birds. While investigating the spatial planning risk of migratory birds, it was discovered that North Sea covering maps with bird migration routes are not available. These are needed in order to properly estimate the number of shut down hours per year for the possible new farm locations. Without this information one could identify new locations that turn out not be attractive due lost energy production. Additionally, evidence was found suggesting that the shutdown threshold is likely to be increased in the future, possibly resulting in a significant effect on the LCoE. Another aspect that could be taken into account in follow up work on this topic is the possible impact of hub islands on migratory routes.

While determining sea bird risks, information on effective mitigation measures for sea birds turned out to be missing. OWFs may induce a loss of habitat, reducing sea birds' foraging area. Such losses need to be compensated in order not to jeopardize healthy population sizes. Consequently, follow up work on effective mitigation measures for sea birds is needed.

#### Shipping corridor design

During this study it was difficult to create a monetary trade-off between creating a shipping corridor allowing ships to pass through an OWF versus having ships sail around OWFs inducing detour cost. This requires detailed information on shipping densities (including frequencies and vessel types) plus a detailed design of international passages through clusters of OWFs. Appendix III gives an example of a detailed shipping corridor design for planned German farms. A follow up study on this topic could enhance smart corridor designs that limit spatial planning cost and consequently lower the LCoE-R. It can also help to obtain more accurate estimates of the spatial planning costs concerning shipping.

## 8.2.2 Economies and diseconomies of scale

In this study it was found that the H&S GCS has economies of scale which can be further increased by increasing the wind farm power density. A higher power density means that more GW can be connected to a single hub. Increasing wind power density, however, also introduces diseconomies of scale due to wake losses. In this study additional wake losses at higher power densities were simulated for OWF clusters up to 4 GW. Consequently, two types of follow up work seem relevant:

- research on hub (island) cost in relation to hub size and power density to enable a more accurate quantification of economies of scale of hubs;
- research on wake losses for clusters larger than 4 GW to enable a correct quantification of the diseconomies of scale due to wake loss.

## 8.2.3 Include interconnection benefits

This study reveals that the H&S GCS can lower the average LCoE of offshore wind energy production. The fact that a hub is connected with spokes to multiple countries enables two additional benefits that were not quantified in this study:

- interconnection trading between countries can lead to both energy bill savings for consumers and higher profits for producers since energy demand and supply become more synchronized;
- compared to traditional AC and DC radial GCSs, the H&S GCS can help the energy transition by reducing the amount of required grid reinforcements and the energy storage capacity. This can save costs.

In order to quantify these benefits it is suggested to upgrade the LCoE mapping model that was developed in this study with a real time energy trading simulation and to add grid reinforcement and storage costs to the cost calculations of the model.



# 9

## REFERENCES

### Literature

- 1 Blue Economy (2011). Financial impacts sand extraction strategy- price components, Blue Economy commissioned by the Ministry of Infrastructure and Environment, Agency of Water, Rijswijk.
- 2 Bulder, B.H., E.T.G. Bot, G. Bedon, (2018). Optimal wind farm power density analysis for future offshore wind farms, ECN part of TNO commissioned by the Ministry of Economic Affairs of the Netherlands.
- 3 Crawford, M. (2016). What Empirical Research has Established about Wind Farm Visual Impact, S.N., S.L.
- 4 Dubois, C. (2013). Bat mortality check and bat monitoring in the Perwez wind farm, CSD Ingenieurs commissioned by Aspiravi S.A., Namur.
- 5 EZK, (2018). Kamerbrief- Routekaart windenergie op zee 2030. Minister van Economische Zaken en Klimaat, Den Haag.
- 6 Gerrits, S. (2017). Feasibility Study of the Hub and Spoke Concept in the North Sea, s.n., s.l..
- 7 Hoefsloot, N., M. de Pater, E.C.M. Ruijgrok, d. van Gent, I. Laane, R. v.d. West, W. Gotje, (2018). Integral cost-benefit study roadmap offshore wind energy, Decisio & Witteveen+Bos commissioned by the Ministry of Economic Affairs and Climate, The Hague.
- 8 Hoefsloot, N., M. de Pater, G. van der Meulen, (2010). Socio-economic cost effectivity of spatial options for offshore wind energy; SE-CEA Wind energy North Sea, Decisio commissioned by the Ministry of Traffic and Water, The Hague.
- 9 Hoefsloot, N., M. de Pater, M. Wijnen, D. van Gent, R. Abma, E.C.M. Ruijgrok, (2014). SC-CBA wind energy within the 12-mile zone, Decisio & Witteveen+Bos commissioned by the Ministry of Economic Affairs, The Hague.
- 10 Hundleby, G. and K. Freeman, (2017). Unleashing offshore wind potential, BVG Associates commissioned by Wind Europ, s.l.
- 11 IEA, (2013). Technology Roadmap - Wind energy - 2013 edition. International Energy Agency, Den Haag.
- 12 ICES, (2017). The greater North Sea Ecoregion- Fisheries Overview, International Council for the Exploration of the Sea (ICES), Copenhagen.
- 13 Jongbloed, R.H., J.T. van der Wal, H.J. Lindeboom, (2014). Identifying space for offshore wind energy in the North Sea; Consequences of scenario calculations for interactions with other marine uses, Energy Policy, 68: 320–333.
- 14 Kamp, H.G.J.(2016). Decision lot I wind energy location Holland Coast (south), the Ministry of Economic Affairs, published in: Government Gazette, nr. 111, The Hague.
- 15 Klomp, W., C. Hoyng, P. de Vries, (2017). North Sea Wind Power Hub Technical and financial feasibility study final report, Royal Haskoning DHV, Amersfoort.
- 16 Krijgsveld, K.L., R.C. Fijn, R. Lensink, (2015). Occurrence of peaks in songbird migration at rotor heights of offshore wind farms in the southern North Sea, Bureau Waardenburg, Culemborg.
- 17 Lengkeek, W., K. Didden, M. Teunis, F. Driesen, J.W.P. Coolen, O.W. Bos, S.A. Vergouwen, T.C. Raaijmakers, M.B. de Vries, M. van Koningsveld, (2017). Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms; Towards an implementation guide and experimental set-up, Deltares, WUR and Bureau Waardenburg, Delft.
- 18 Leopold, M.F. , M. Boonman, M.P. Collier, N. Davaasuren, R.C. Fijn, A. Gyimesi, J. de Jong, R.H. Jongbloed, B. Jonge Poerink, J.C. Kleyheeg-Hartman, K.L. Krijgsveld, S. Lagerveld, R. Lensink, M.J.M. Poot, J. Tjalling van der Wal, M. Scholl, (2014). A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea, Imares, Wageningen.

- 19 Limpens, H.J.G.A., S. Lagerveld, I. Ahlén, D. Anxionnat, T. Aughney, H.J. Baagøe, L. Bach, P. Bach, J.P.C. Boshamer, K. Boughey, T. Le Campion, M. Christensen, J.J.A. Dekker, T. Douma, M.-J. Dubourg-Savage, J. Durinck, M. Elmeros, A.-J. Haarsma, J. Haddow, D. Hargreaves, J. Hurst, E.A. Jansen, T.W. Johansen, J. de Jong, D. Jouan, J. van der Kooij, E.-M. Kyheroinen, F. Mathews T.C. Michaelsen, J.D. Møller, G. Pétersons, N. Roche, L. Rodrigues, J. Russ, Q. Smits, S. Swift, E.T. Fjederholt, P. Twisk, B. Vandendriesche,
- 20 M.J. Schillemans, (2017). Migrating bats at the southern North Sea - Approach to an estimation of migration populations of bats at southern North Sea, Rapport 2016.031. Zoogdiervereniging (Dutch Mammal Society), Nijmegen and Wageningen Marine Research.
- 21 Matthijsen, J., E. Dammers and H. Elzenga, (2018). The future of the North Sea; The North Sea in 2030 and 2050: a scenario study, PBL (Planbureau voor de Leefomgeving), The Hague.
- 22 Müller, M., E. Haesen, L.Ramaekers, N.Verkaik, (2017). Translate COP21; 2045 outlook and implications for offshore wind in the North Seas, Ecofys, commissioned by TenneT and Energinet.dk, Utrecht.
- 23 Remy, T., A. Mbistrova, I. Pineda, (2018). Offshore Wind in Europe - Key trends and statistics 2017, Wind Europe, Brussels.
- 24 Romijn, G., P. Verstraten, H. Hilbers, A. Brouwers, (2016). Freight transport and Sea harbours, Welfare and Environment, Scenario study for 2020 and 2050; back ground document, Central Planning Agency, The Hague.
- 25 Sullivan, R.G. L.B. Kirchler, J. Cothren and S.L. Winters, (2013). Offshore Wind Turbine Visibility and Visual Impact Threshold Distances, Environmental Science Division, Argonne National Laboratory, Argonne, Illinois, USA.
- 26 Van der Tak, C., (2009). Traffic impact of wind farms, Marin commissioned by the Ministry of Infrastructure and Environment, Agency of Water, The Hague.
- 27 Van der Tak, C., (2010). Quantitative risk assessment for offshore wind farms in the North Sea, Marin commissioned by the Ministry of Transport, Public Works and Water Management, Wageningen.
- 28 Van Oostenbrugge, H. D. Slijkerman, K. Hamon, O. Bos, M. Machiels, O. van de Valk, N. Hintzen, E. Bos, J. Tjalling van der Wal, J. Coolen, (2015). Effects of seabed protection on the Frisian Front and Central Oyster Grounds; A cost benefit analysis, Wageningen University and Research Centre, Wageningen.
- 29 Vree B., N. Verkaik, (2017). North Sea Infrastructure - Urgency and Benefits; Cost reduction opportunities through regional coordination, Ecofys, Utrecht.
- 30 Vree, B., N. Verkaik, M. Goher-ur-Rehman, (2017). A comparative LCOE analysis of a national incremental and international coordinated roll-out for the Dutch Dogger Bank area, Ecofys, Utrecht.

#### Websites

- 1 [www.rwseconomie.nl](http://www.rwseconomie.nl) (=website Ministry of Waterways): cost barometer Deep Sea Shipping, (2016).
- 2 <https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2> (=website National Oceanic and Atmospheric Administration, NOAA): climate forecast system, (2018).

#### Maps and GIS data

- 1 Emodnet, (2017). GIS shapefiles EMODnet Human Activities, Environment, Natura 2000, update 'Natura 2000 End 2017', by the EEA in 2018, downloaded from [www.emodnet-humanactivities.eu/search-results.php?dataname=Natura+2000](http://www.emodnet-humanactivities.eu/search-results.php?dataname=Natura+2000).
- 2 TenneT TSO GmbH, (2018). GIS shapefiles for German offshore wind farms.
- 3 UNEP/GRID-Arendal, (2015). Cartograph Riccardo Pravettoni, downloaded from [www.grida.no/resources/7643](http://www.grida.no/resources/7643).
- 4 Wageningen Marine Research, IMARES, (2014). GIS shapefiles for North Sea covering user functions.

# Appendices





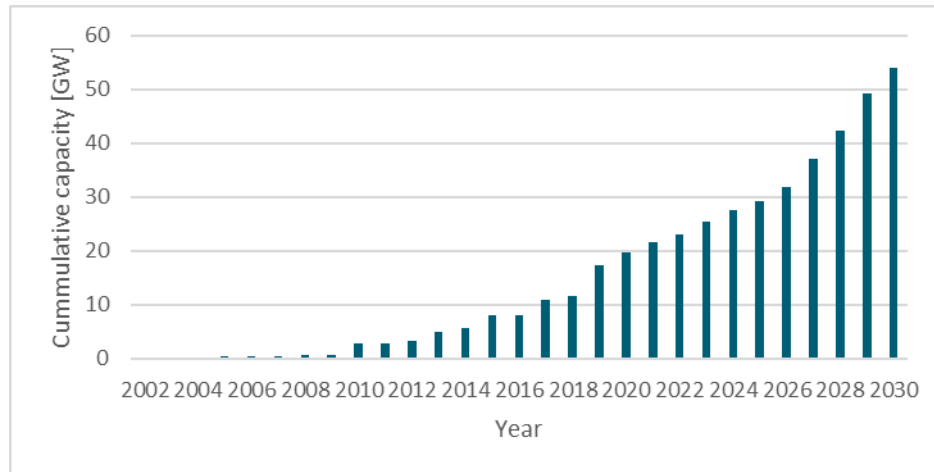
## APPENDIX: TRENDS IN SPACE USE OF THE NORTH SEA

In this appendix trends in the space use of the North Sea are investigated. Trends in offshore wind energy production are described, followed by all other spatial user functions. The aim of the investigation is to forecast where different types of sea use take place by the year 2030.

## I.1 Wind energy

Figure I.1 shows the development of offshore wind energy capacity in terms of the cumulative installed capacity in GW. A rapid capacity growth can be discerned.

Figure I.1 Cumulative and annual offshore wind energy installation



Source: LCoE mapping model developed in this study (2018)

Table I.1 shows the cumulative capacity per country, for three different development scenarios. The sheer fact that three scenarios are distinguished indicates that the capacity growth is uncertain.

Table I.1 Offshore wind power cumulative capacity to 2030

	Central scenario (GW)	Low scenario (GW)	High scenario (GW)
United Kingdom	22.5	18	30
Germany	15	14	20
Netherlands	11.5	4.5	18.5
Denmark	4.3	3.4	6.1
Norway	-	-	-
Sum	53	40	75

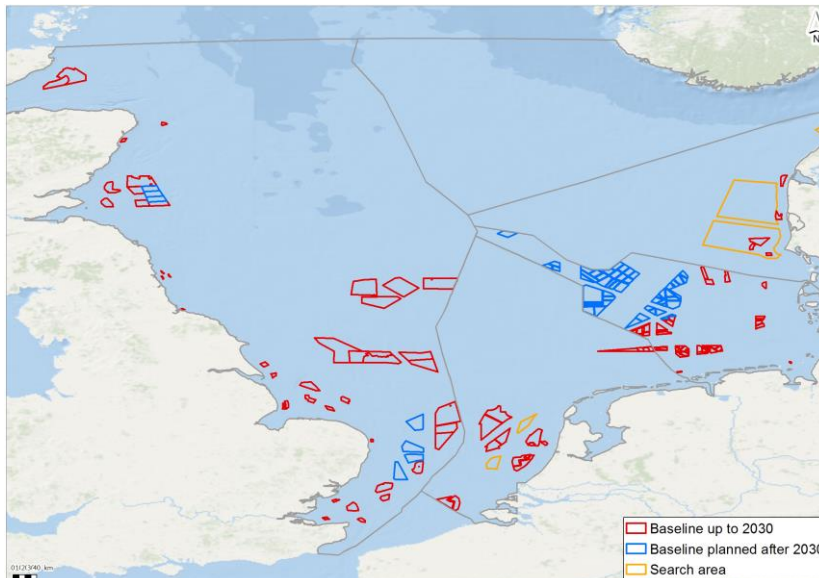
Source: (Remy et.al., 2018)

To define the baseline for the year 2030, certain capacities and certain locations need to be included, leaving all other locations as subjects of the study, i.e. open to be or not to be selected as potential new locations after 2030. In order to realize this, the operational, permitted and planned locations of the Urgency and Benefits study (Vree and Verkaik, 2017) were taken as a starting point. Subsequently, this set was verified and adjusted to the latest policy developments in the relevant countries. Figure I.2 shows the resulting baseline:

- up to 2030 a cumulative capacity of 54.8 GW (this roughly matches with the central scenario of table I.1);
- after 2030 an extra capacity of 25.9 GW.

This adds up to total amount of 74.3 GW deployed in the baseline. In this spatial study the amount of 54.8 GW is considered to be a fixed amount. The extra of 25.9 GW is adapted to the (lower) wind power density of the reference farm used in this study: this means that it stands for 19.5 GW.

Figure I.2 Offshore wind energy reference map

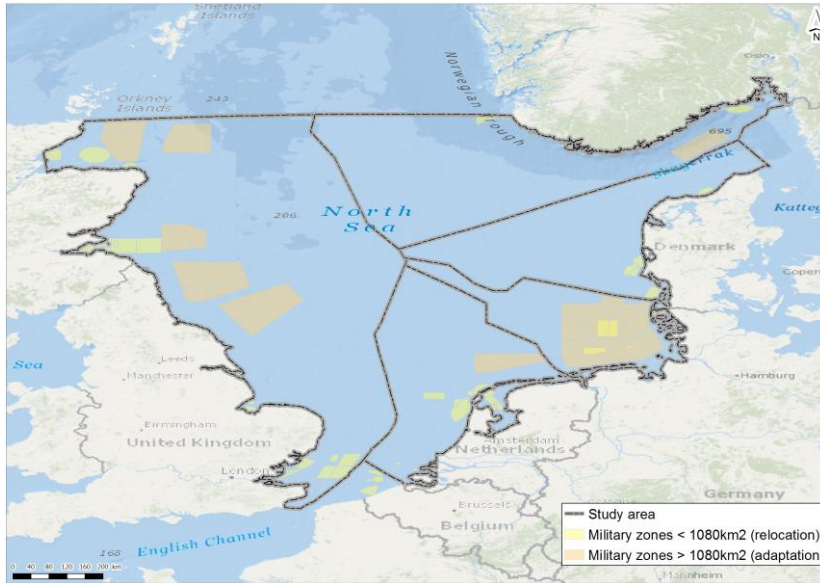


Source: adapted from Vree and Verkaik, (2017)

## I.2 Military use

Of course the military situation in 2030 is unknown. Military zones are, however, rarely moved and the situation in 2030 is not expected to be much different from today. Possibly the recent American demands for Europe to increase military defence expenditure might result in an expansion of practice zones. It might just as well lead to extra investments in military equipment or to more expenses on military interventions in conflict zones. Given the lack of clear indications, the military zone map of IMARES (Jongbloed et al, 2014) is used to create a reference map that shows whether or not a location used for military purposes. Figure I.3 shows this reference map.

Figure I.3 Military zones reference map



Source: Jongbloed et al., (2014)

The reference map includes both navy and military exercise zones. It would be tempting to only include navy zones as air forces zones will not be affected by wind farms. This was, however, not opted for. A detailed inspection of the data in this military map revealed that air force use includes shooting and bombing. This means that building wind farms in air force zone will lead to adaptation cost either for the wind farm or for the air force.

It may be noted that military zones sometimes overlap: this means that a zone is used by more than one military organisation. Such multiple user situations increase the spatial planning cost, because wind farms built in such areas have an impact on more than one military organisation.

### I.3 Nature

The North Sea is a dynamic ecosystem, which makes it difficult to predict its state in 2030. For offshore wind farm development in this study, however, only those ecological aspects are relevant that are impacted or that have spatial claims. Though OWFs may impact many species, the relevant species that need to be considered according to nature policies and/or legislation are sea mammals, birds and bats. Besides these species, legally protected areas claim space, which means that there is a spatial risk when planning OWFs in such areas.

#### Sea mammals

Sea mammals, such as porpoises and seals, are sensitive to the noise that is produced when building an offshore wind farm. Noise can deter them, but it can also render them deaf, consequently impacting their feeding and mating habits and impacting their population size. Sea mammals are distributed widely in the North Sea but there are no North Sea covering maps showing these densities. Consequently, the baseline for 2030 is not mapped.

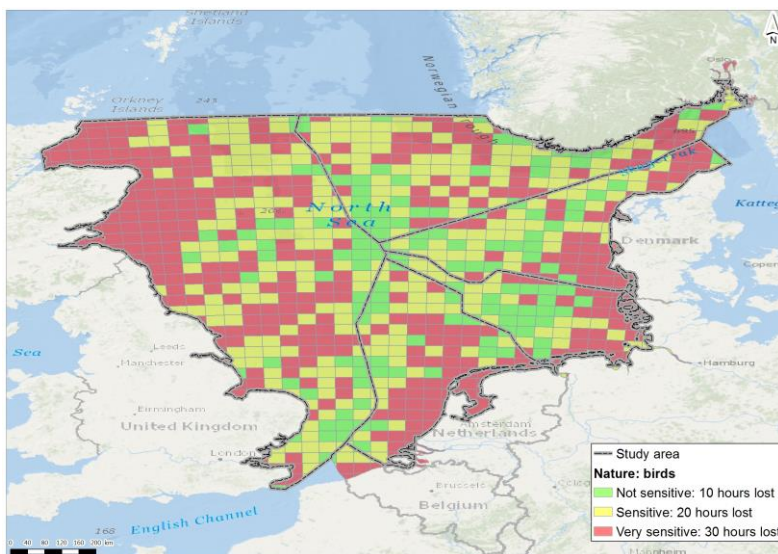


### Sea birds and migratory birds

Sea birds can be found everywhere in the North Sea, but certain areas are more 'wind farm sensitive' than others, due to differences in birds densities and behaviour difference between bird species. There is no information on how developments such as climate change and fishery policies<sup>1</sup> will impact the presence of sea birds across the North Sea. Consequently, a recently produced Wind farm Sensitivity Index (WSI) map of IMARES (Jongbloed et al., 2014) is used as a reference map for sea birds in this study (see figure I.4).

The wind farm sensitivity index (WSI) is comprised of the following bird parameters: flight manoeuvrability, flight altitude, percentage of time flying, nocturnal flight activity, sensitivity towards disturbance by ship and helicopter traffic, flexibility in habitat use, biogeographical population size, the adult survival rate and the European threat and conservation status. Each parameter is scored on a 5-point scale per bird species. Subsequently, the species specific sensitivity score is multiplied with the natural logarithm of its density and then summed over all species to obtain the wind farm sensitivity index (WSI) for a location.

Figure I.4 Sea bird WSI reference map



source: Jongbloed et al., (2014)

The WSI map shows that especially areas along the coast (red colour) seem to be of greatest concern, probably because of relatively high population densities caused by breeding colonies. Some breeding birds forage at sea and thus fly back and forth to the mainland. At the moment there is no information on how habitat loss i.e. loss of foraging area, impacts sea bird populations<sup>2</sup>. As a result the present situation is used as a reference.

Migratory birds follow specific routes and are only present in certain periods of the year. It is generally known, that both climate change and land use (i.e. habitat provision on land) have an impact on bird migration routes. Assuming that large wind development will help to meet climate targets, the impact of land use changes will, however, remain. Given these considerations, one could use present migratory maps as a reference. Since there is no suitable migratory route map available (i.e. a map containing the flying routes of all relevant species), the spatial planning risk of migratory birds cannot be included in this study. In order to 'correct' for this omission, a sensitivity analysis is carried out in which the spatial planning risk of sea birds is heightened.

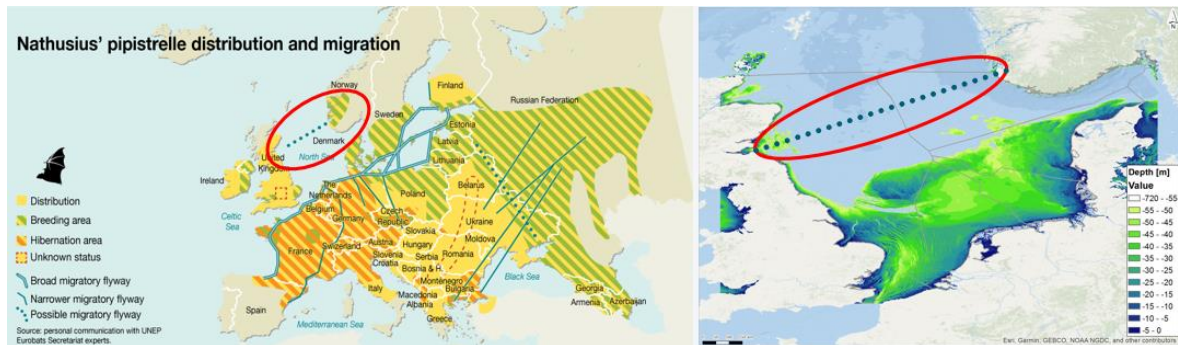
<sup>1</sup> Fishing influences food availability and thus bird populations.

<sup>2</sup> This is why ecological predictions studies resort to the assumption that 10 % of the displaced birds die (Leopold et al., 2014) in order to predict impacts of OWF on bird populations.

## Bats

Population density and migration routes of bats are currently investigated. Recent investigation results show that the most relevant species for offshore wind farms is the Nathusius' Pipistrelle. The number of animals migrating along the North Sea coast is estimated at approximately 40,000 per year, but this estimate is very uncertain (Limpens et al., 2017). Though it is not known what bat distribution and migration will look like in 2030, wind farms seem to attract bats as they can use them to forage on e.g. insects (Figure I.5 shows that only one potential migration route lies within the study area). Figure I.5 also shows that this potential route happens to be in the deepest part of the sea: locations that are unlikely to be selected on the basis of their (relatively high) LCoE. Given these findings, the spatial risk of bats is considered to be negligibly small and therefore not calculated in this study.

Figure I.5 Bats reference maps

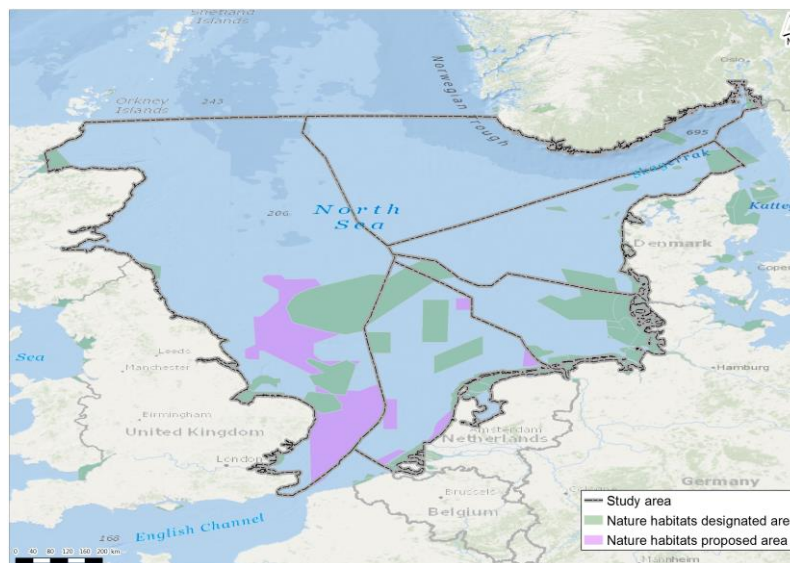


Source: Adapted from Limpens et al., (2017) [left]; depth map from this study with the sketched migration route [right]

## Protected areas

The North Sea contains several types of protected nature areas, such as areas protected by Birds and Habitats Directive with the aim to establish the wide Natura 2000 network. Though new areas may be appointed in the future, e.g. in reaction to offshore wind farm development, significant changes are not expected before 2030. Figure I.6 shows the map with protected areas that is used as the baseline in this study. This map was based on the nature conservation map of IMARES ( Jongbloed et al., 2014). It includes both appointed and proposed areas. For the Dutch coast the Klaverbank is added, since this area is bound to be appointed shortly.

Figure I.6 Protected nature areas reference map

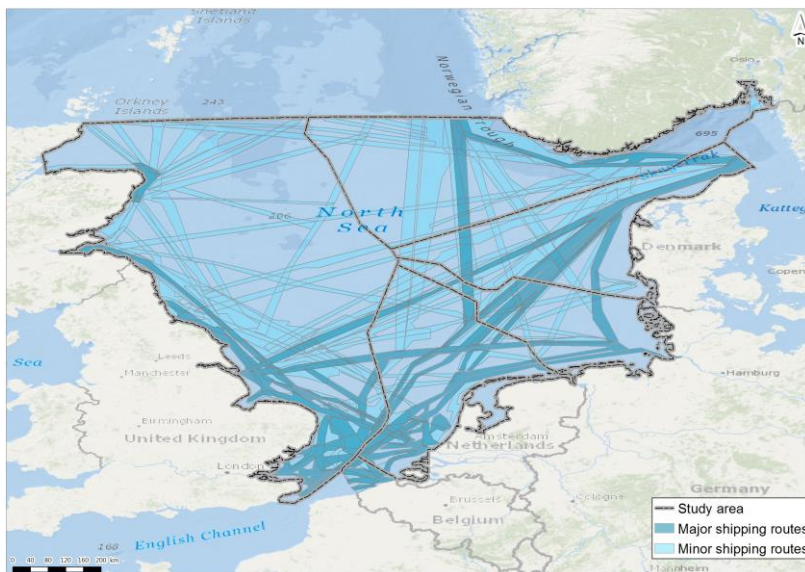


Source: adapted from Jongbloed et al., (2014)

## I.5 Shipping routes

The North Sea contains a vast amount of major and minor shipping routes. Though shipping routes can be adapted, it is assumed that the shipping routes in 2030 will not deviate significantly from the present situation, but the shipping density i.e. the number of passages per year, will grow every year. Since it is the shipping density that determine the magnitude of the adaptation cost i.e. the cost that occur when an OWF is built in a shipping route, a North Sea covering density map is needed for this study. As the density map by Imares (Jongbloed et al., 2014) is a North Sea covering map containing major routes with high density and minor routes with low density, it is used in this study. Figure I.7 shows this map.

Figure I.7 Major & minor shipping routes reference map



Source: adapted from Jongbloed et al., (2014)

In order to update this map to reflect the shipping situation in 2030 official growth rates of shipping activity are used. Two growth rates are available:

- a rate of 1.4 % per year for a high economic development scenario;
- a rate of 0.5 % per year for a low economic development scenario.

These rates are the official growth rates for deep sea shipping published by the Dutch Central Planning Agency (Romijn et al., 2016). They are used as standard figures in societal cost benefit analyses. In this study the rate for a high economic development scenario was used for the sake of not underestimating the adaptation cost of shipping while calculating the levelized cost of energy including spatial risk (LCoE-R).

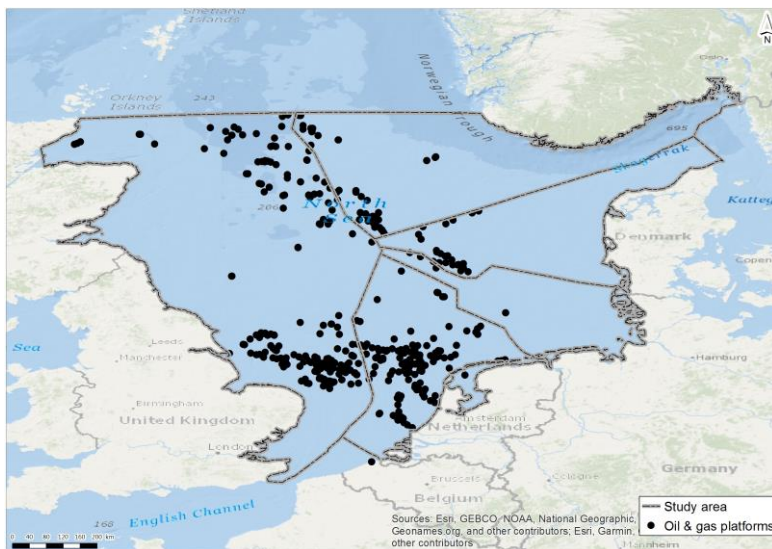
It is noted here that a distinction needs to be made being shipping routes with a certain density and corridors within OWFs. In Germany detailed designs have recently been made to create shipping corridors for the existing and planned wind farms (see Appendix III for illustrations and extra explanation). Since these corridors have no densities and are not connected to the existing shipping routes (they seem to stop at the Danish border), they are not included in the reference map for shipping routes. It would require a separate study to connect the corridors to the existing international routes and to predict their future use (read: shipping density).

## 1.6 Oil & gas platforms

The North Sea contains many oil & gas platforms that induce a spatial planning risk due to the helicopter zones around them. A zone of 2.5 NM around the platform is needed for safe helicopter landings. Though many oil & gas platforms are to be decommissioned in the near future, information on which platforms will be gone by the year 2030 is confidential. On top of that, wind farm development may provide a spatial planning opportunity besides a spatial planning cost: the economic lifespan of some platforms can probably be prolonged if offshore wind farms offer them (cheap) energy to pump up the remaining oil & gas, which would not happen in a situation without wind energy being available.

In this study only the spatial planning risk of oil & gas platforms is determined on the basis of the helicopter zones around the platforms. Figure I.8 shows the map that is used as the reference for oil & gas platforms. The spatial planning opportunity is not determined, since this lies outside the scope focus of this study.

Figure I.8 Oil & gas platforms reference map

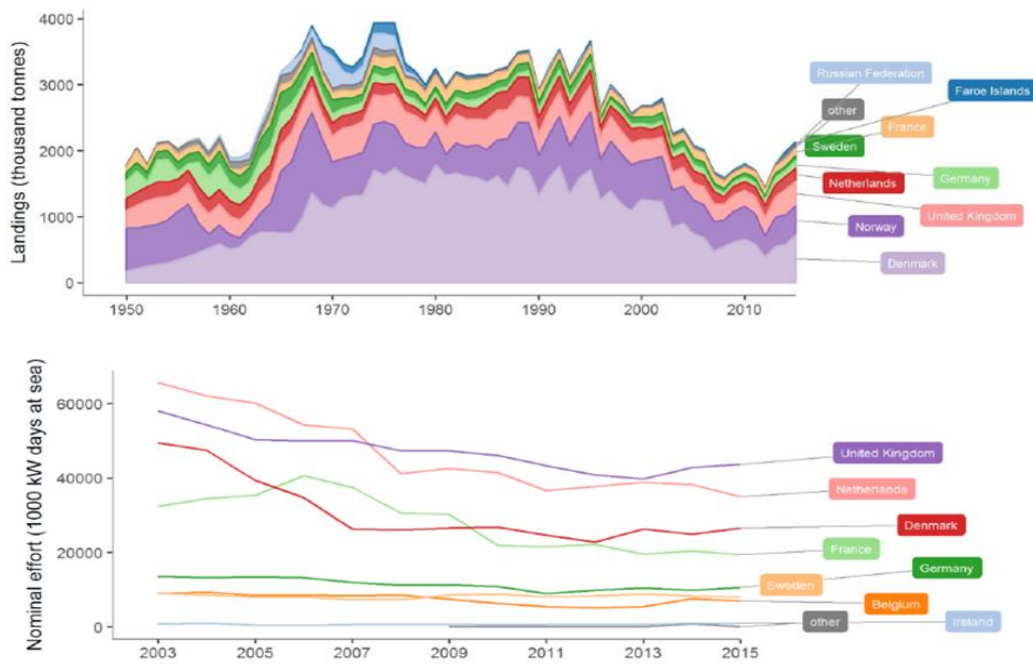


Source: Jongbloed et al., (2014)

## 1.7 Fisheries

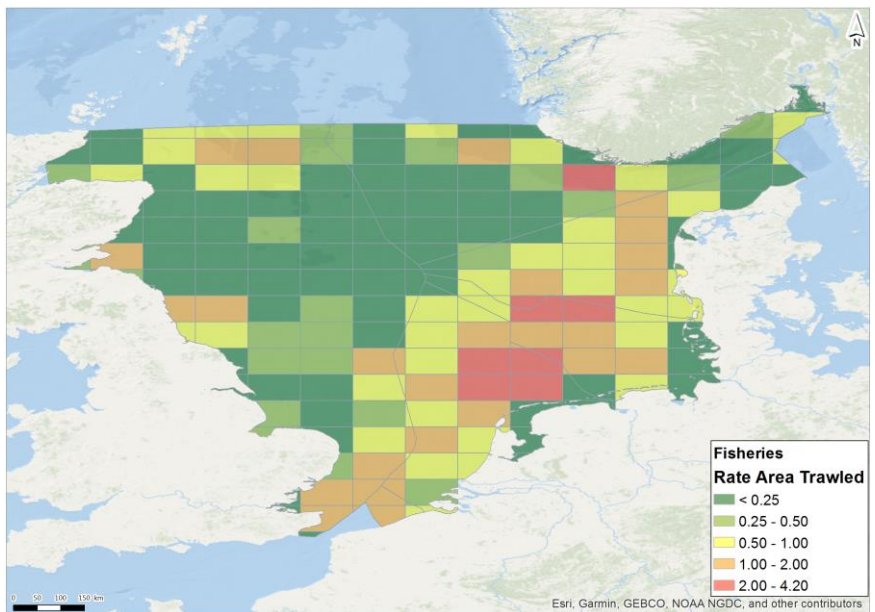
The entire North Sea is used for fisheries, but some locations are trawled more heavily than others. The most important developments that determines magnitude of fishery activities in 2030 are, besides wind energy, the EU regulations on fishing. Since fishing yields have a large natural variation, it does not make any sense to try and determine fishing yields for the year 2030 (see Figure I.9). Fishing efforts are presumed to be more stable than fishing yields. In order to determine the spatial planning risk of fisheries, a fishing effort map of IMARES (Jongbloed et al., 2014), showing the present fishing efforts in terms of percentage trawled, is used as the reference. Figure I.10 shows this map. It may be noted that certain areas are trawled more than 100 % (up to 400 %). Such areas are visited several times a year by (different) fishing boats.

Figure I.9 Variation in fishing yields & fishing efforts



Source: ICES, (2017)

Figure I.10 Fisheries reference map

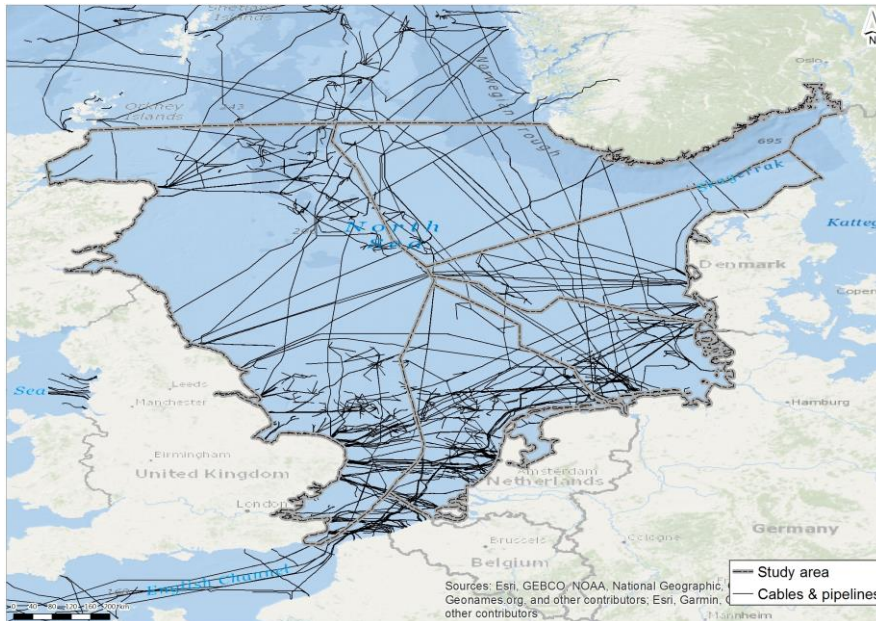


Source: Jongbloed et al., (2014)

## I.8 Cables and pipelines

There is a large amount of cables and pipelines in the North Sea. Though especially new telecom cables will be added and old pipelines - due to decommissioning of oil & gas platforms - will be removed, it is too complex, i.e. a study all by itself, to update the available maps for the year 2030. Consequently data of the present situation is used as a reference. Figure I.11 shows the reference map that is used in this study to determine the spatial planning risk of cables and pipes.

Figure I.11 Cables and pipelines reference map



Source: Jongbloed et al., (2014)

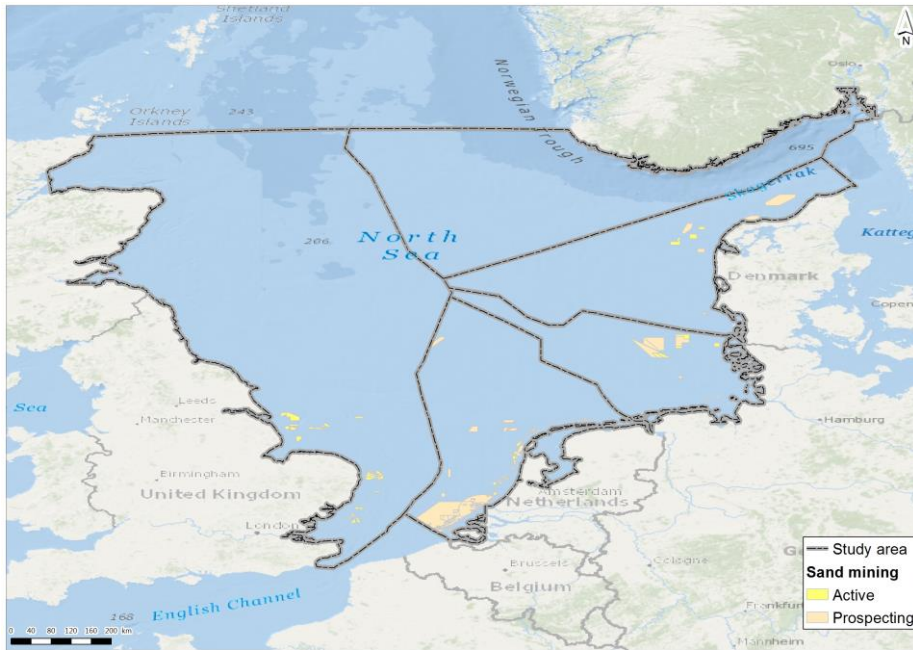
It may be noted that cable costs are declining. As a result the interest for cable corridors that combine cables is growing (Hoefsloot et al., 2018). This reduces the magnitude of spatial planning risk of cables and pipes.

## I.9 Sand mining

The North Sea is an important source of sand that is used for coastal defence and as a building material. On the one hand climate change increases the sand demand for coastal sand nourishments. On the other hand, offshore wind energy may help to reduce climate change and thus reduces the sand demand for coastal defence. The sand demand for building purposes depends on general economic developments. One would expect it to grow over time. Since sand mining areas are appointed in order to cover the sand demand for the next 100 years, maps with the presently appointed mining sites could serve as a reference. In this study the mining site map of IMARES (Jongbloed et al., 2014) is used as reference. This map (see figure I.12) includes both active and prospected sites. Sites to be closed soon are excluded from the map if the closure date is known.

The actual sand mining activities are quite dynamic. Sand is taken whenever and where ever it is needed, though the is key is to find sand as close as possible to its destination as transport cost are high. This is why the spatial planning risk that sand mining generates is actually a so called option value: the value of mining sites is to keep the option open to extract sand if needed.

Figure I.12 Sand mining sites reference map



Source: Jongbloed et al., (2014)



## APPENDIX: SPATIAL COST CALCULATION FORMULAS



In this study a first attempt is made to roughly calculate the spatial adaptation cost that occur whenever an OWF meets an existing user function. The cost numbers used in this study were mainly derived from a previous societal cost study for OWFs in the North Sea (Hoefsloot et al., (2018). In this societal cost study the focus was on how OWFs and other user functions impact each other and these impacts were estimated in monetary terms on the basis of intermediate stakeholder information. No extensive cost studies were available for each user function. Consequently, this study also provides rough cost estimates that merely reflect the order of magnitude of spatial adaptation costs. Extra spatial (GIS) analyses and extra data collection is needed to obtain more accurate cost estimates.

Table II.1 Spatial cost calculation formulas

Spatial user function	Map used	Units of the legend of the used map	Spatial planning risk formula	Cost type	Sources
military zones	IMARES military zones (2014)	yes/no (and zone contours; zones may overlap due to multiple users)	zones < 1.080 km <sup>2</sup> : relocation costs of 0.75 M€/year divided by km <sup>2</sup> of the zone; zones > 1.080 km <sup>2</sup> : adaptation cost of 2 M€ (once) divided by km <sup>2</sup> of the zone	relocation: OpEx; adaptation: CapEx	Hoefsloot et al., (2014); Hoefsloot et al., (2018)
nature: sea mammals	no map	not relevant	not relevant: cost are included in building cost (CapEx) of the OWF and are thus already included in LCoE not should not be included again in LCoE-R	-	Hoefsloot et al., (2014)
nature: birds	IMARES WSI Birds (2014)	wind turbine sensitivity classes (1,2,3)	assign the % of hours lost per year to each grid cell containing nature; i.e. assign 0.3 %, 0.2 % or 0.1 % to each grid cell	lost kWh production	Hoefsloot et al., (2018); Kamp, (2016)
nature: bats	Eurobats, (2017)	yes/no flying route	no formula, as there are no flying zones in the search area of this study	-	Limpens et al., (2017); Kamp, (2016); Dubois, (2013)
nature: habitats	IMARES nature conservation, (2014)	yes/no appointed nature area	39 k€/km <sup>2</sup> for Building with Nature measures	CapEx	Lengkeek et al., (2017)
shipping routes	IMARES shipping routes (2014)	< 1 ship/day and > 1 ship/day	minor routes: 994 €/(km <sup>2</sup> *year) & 10.5 k€/km <sup>2</sup> *year for safety; Major routes: 119 k€/km <sup>2</sup> (once) Variables for sensitivity: growth rate for High (1.4 %) and Low (0.5 %) economic development scenario and factor (2) for environmental cost of maritime transport emissions (CO <sub>2</sub> , NO <sub>x</sub> , PM10).	detour and safety: OpEx cables: CapEx	Romijn et al., (2016); www.rwseconomie.nl: Cost Barometer Deep Sea (2016); Hoefsloot et al., (2010); Van der Tak, (2009; 2010)
oil and gas platforms	IMARES oil an gas (2014)	yes/no oil & gas platform	add an extra cost to the helicopter zones (2.5 NM circle around platforms) of 0.33 M€ to the helicopter zone	CapEx	ECN part of TNO cost estimate (paragraph 2.1.1)

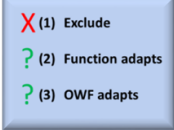
Spatial user function	Map used	Units of the legend of the used map	Spatial planning risk formula	Cost type	Sources
fisheries	IMARES fishing effort (2014)	Fishery effort; trawled area (km <sup>2</sup> /km <sup>2</sup> )	fishery adapts: 3.5 k€/(km <sup>2</sup> *year) inside the OWF* trawled area (km <sup>2</sup> /km <sup>2</sup> ); OWF adapt/co-use: 3.4 k€/(km <sup>2</sup> *year) * trawled area (km <sup>2</sup> /km <sup>2</sup> )	OpEx	Hoefsloot et al., (2018)
cables and pipelines	IMARES Cables and Pipelines (2014)	yes/no cable	0.58 M€/km cable or pipe that passes through the OWF	CapEx	ECN part of TNO cost estimate (paragraph 2.1.1)
sand mining	IMARES, sand extraction (2014)	Yes/no mining area	cable passing through mining site: 11 M€/year per cable passing through a mining area; OWF inside mining site: extra mining cost of 2.3 M€/km <sup>2</sup> once for a layer of 2 m	cables: OpEx OWF: CapEx	Blue Economy, (2011); Hoefsloot et al., (2018)



## APPENDIX: DETAILED DESIGN OF GERMAN SHIPPING CORRIDORS

Table III.1 rehearses how the spatial planning cost, i.e. adaptation cost, for shipping are calculated in this study. To major routes with high shipping densities corridor cost are assigned while to minor routes with low densities detour cost are assigned.

Table III.1 Spatial planning risk adaptation methodology for shipping routes

Spatial user function		Motivation	Description of the spatial cost
Shipping routes major	Major routes: the OWF adapts	For shipping routes with high intensity it makes sense to create a shipping corridor through the wind farm.	For major routes (> 1ship/day): wind farm layout with a corridor, leading to extra cable cost to connect turbines on both sides of the corridor.
Shipping routes minor	For minor routes: function adapts	For shipping routes with low intensity it makes sense that ships sail around wind farms.	For minor routes (< 1 ship/day): wind farm layout without a corridor; the shipping route is adapted, leading to detour costs.

The spatial cost calculations (i.e. the calculation of the cost that occur when an OWF is built inside a shipping route) are based on the shipping density map of Imares (Jongbloed et al., 2014). This is a North Sea covering shipping density map that shows how many ships sail where. Figure III.1 shows where these major and minor routes are located and also how the OWFs are located so that there is a corridor of at least 6 km width for the major shipping routes.

This map does not include the latest shipping corridors that were designed for the German OWFs. It would require a separate study to connect these corridors to existing international routes and to estimate their future densities. Consequently, shipping adaptation costs (one of the Risk components in the LCoE-R calculations) are based on densities of the existing routes. Since the German corridors are - of course - to a large extent tuned to the present densities, the adaptation cost calculation still captures the essence.

Figure III.2 shows the detailed shipping corridor design for the German farms. It can for instance be seen that multiple major and minor routes from the Southwest to the Northeast are now clustered in one big corridor in between the planned after 2030 OWF clusters Zone 3 and Zone 4.

Figure III.1 Major shipping routes with a corridor (left), minor shipping routes with detour costs (right)

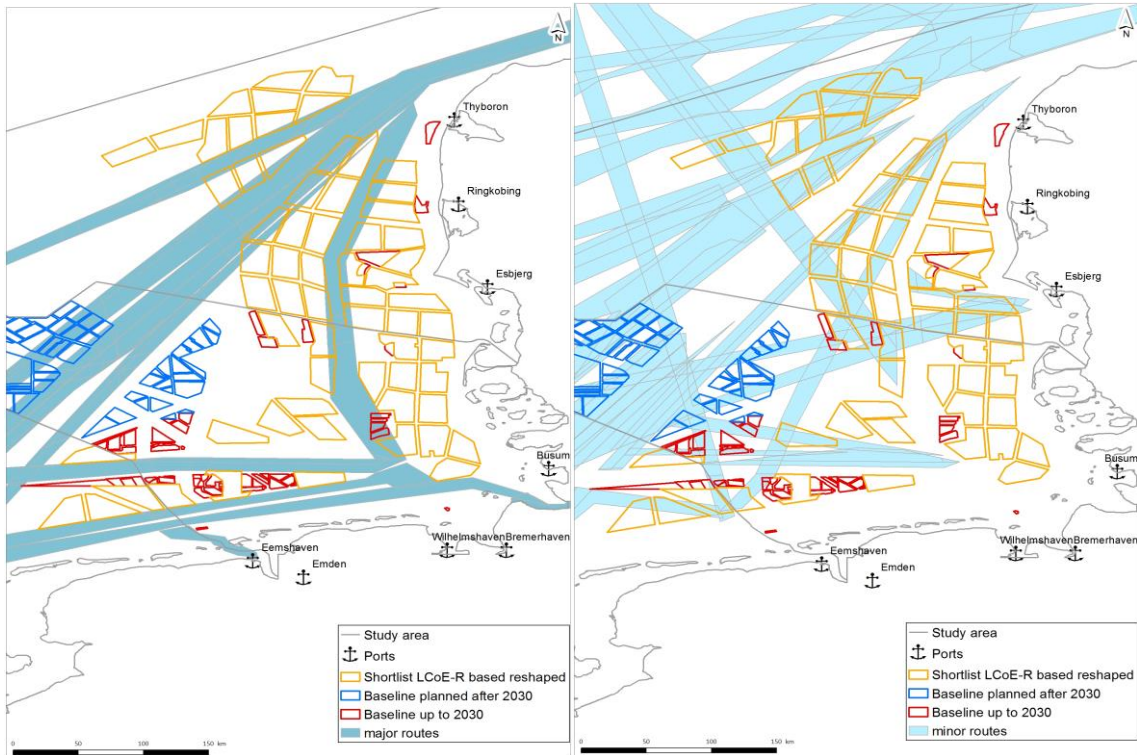
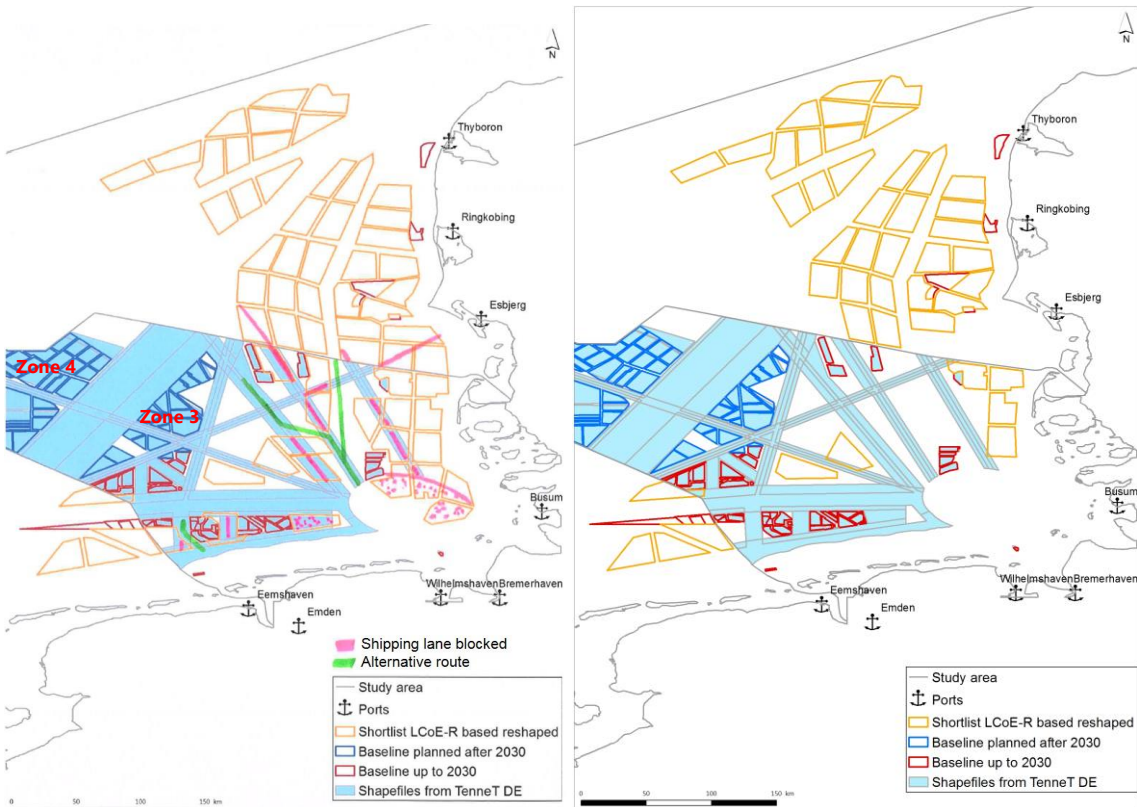


Figure III.2 Shapefiles TenneT TSO GmbH, (2018) with blockages and alternative routes (left) & LCoE-R based set with possible new locations excluding shipping (right)



*Identification of possible new OWF locations according to the non-exclusion principle.*

It is interesting to notice that the (LCoE-based) set with possible new locations contains new farms inside the new German shipping corridors. All German baseline farms (before and up to 2030) respect the new corridors. New OWFs were placed inside corridors because:

- these locations had good LCoE-(R)s;
- the non-exclusion principle that is a key starting point of this study.

Figure III.2 shows that the non-exclusion principle means that shipping routes/corridors are not excluded but at the same time it is ensured that ships are able to take a detour to sail around a park (green lines).

To determine the impact of excluding shipping routes after all, an exercise was done in which all the farms were removed that are in the new corridors, assuming that the corridors continue to Denmark and so on (all farms touched by pink lines). This resulted in 20 farms and 20 GW less and an LCoE increase for the remaining farms of 0.4 €/MWh.

This exercise is comparable to exercise that was done for nature in chapter 5.1.3: excluding the farms in nature areas and checking what this does to the amount of GW and for the average LCoE.

It seems tempting to now add new parks to have the same amount of GW as before removing the farms inside the shipping corridors- similar to what was done for nature, by adding nature adjacent farms- and check what that does with the LCoE. This exercise was not carried out because it leads to relatively expensive sand mining areas: (see figure III.3).

Figure III.3 LCoE-R map showing German corridors (black lines) and sand mining areas (light blue/green patches)

