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Innovations for Port of Den Helder Infrastructure following offshore wind developments

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Since April 1st ECN and TNO have joined forces.

Summary

A study to investigate opportunities for the Port of Den Helder in the energy transition is performed by ECN part of TNO, with the support of a consortium of nine partners, all stake holders in the Port of Den Helder. Although it is foreseen that activities related to the oil and gas (O&G) industry will decrease in the coming years, a simultaneous rapid increase in the offshore wind sector will see growth in operations and maintenance (O&M) and a number of other activities, which will have a substantial impact on the Port of Den Helder.

The main conclusion of this study is that the transition to a carbon-free renewable energy system provides the Port of Den Helder with great business opportunities. The reasons for these opportunities are:

1. Central location of the Port of Den Helder, providing efficient access to all areas of the North Sea, giving possible economic advantages for offshore wind developers and O&M contractors, compared to other ports.
2. Good infrastructure in the port and presence of Den Helder Airport nearby, from which helicopters could support primary offshore wind O&M vessels, leading to increased availability of offshore wind farms (OWFs).
3. State of the art logistics and supply companies, presently mainly active in Oil & Gas, that are equipped to serve the offshore wind energy industry as well.
4. Very good gas infrastructure, proximity to three major pipelines importing a majority of the gas produced in the Dutch economic zone in the North Sea, leading to opportunities in hydrogen production from offshore wind energy.
5. Possible storage areas in the vicinity of the Port of Den Helder for products from biomass related activities such as seaweed and algae cultivation.

The impact of several innovations that are soon expected in modern ports in the move to a *Port 4.0* (comparable to *industry 4.0)* such as autonomous shipping and improved onshore logistics, is investigated. These innovations also will influence future development activities at the Port of Den Helder.

This study also quantifies infrastructure requirements at the Port of Den Helder in terms of quaysides, warehouses and logistic spaces that are needed in order to participate in the growing offshore wind activities in the North Sea. Besides offshore wind, the development of other activities such as hydrogen production, biomass and seaweed cultivation is also described, and the possibility of the Port of Den Helder's involvement in these sectors is investigated.

Although there are plenty of business opportunities in the coming decades, it should be mentioned that this does not automatically lead to a guaranteed success for the Port of Den Helder. Other ports on the Dutch coast also have good facilities and an established track record (especially in the construction of offshore wind farms); and are seen as competitors to the Port of Den Helder in the offshore business. In order to be successful in the future growth of the offshore renewable energy sector, it is necessary that the Port of Den Helder positions itself as a strong contender by investing in the required infrastructure and technological innovations discussed in this study..

In 2nd edition of this report some editorial modifications have been applied. Draught has been changed to depth when it relates to the depth requirements of the harbour and figures 3 and 7, containing harbour area allocations, have been updated to the current situation.

Contents

Appendices

List of Abbreviations

BOP	Balance of Plant
CCS	Carbon Capture and Storage
CTV	Crew Transfer Vessel
DHSS	Den Helder Support Service
DHTC	Den Helder Training Centre
ECN	Energy Centre of the Netherlands
ETV	Emergency towing vessel
FTE	Full time equivalent
HKN	Hollandse Kust (Noord) Wind Farm Zone
HKW	Hollandse Kust (West) Wind Farm Zone
HKZ	Hollandse Kust (Zuid) Wind Farm Zone
IJV	IJmuiden Ver Wind Farm Zone
KPI	Key Performance Indicator
LOA	Length Overall
NAM	De Nederlandse Aardolie Maatschappij
OWF	Offshore wind farm
O&G	Oil and Gas
O&M	Operations and maintenance
PoDH	Port of Den Helder
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
SES	Surface Effect Ship
SV	Support Vessel
SOV	Service Operation Vessel
TNW	Wind Farm Zone Ten Noorden van de Waddeneilanden
UGS	Underground Gas Storage
WT	Wind Turbine

1 Introduction

The project *Innovations for Port of Den Helder Infrastructure following offshore wind developments* is a cooperation of ten partners.

The project partners are:
1 ECN PART OF TNO + (project manager)
2 NV PORT OF DEN HELDER (PoDH)
3 DEN HELDER SUPPORT SERVICES (DHSS)
4 CHC (CHC)
5 ACTA MARINE (Acta Marine)
6 ONTWIKKELINGSBEDRIJF NOORD-HOLLAND NOORD (NHN)
7 PETERSON OFFSHORE HOLDING (Peterson)
8 NAM Den Helder (NAM)
9 NEW ENERGY COALITION (NEC)
10 ENGIE (Engie)

The Offshore logistic hub in Den Helder is based on three pillars: the seaport, the airport and a knowledge port, together representing the Offshore Energy Gateway of Den Helder. All the project partners participate in investigations to implement innovations related to the energy transition, particularly offshore wind.

Figure 1 The offshore logistic hub at the Port of Den Helder

The traditional energy industry of oil and gas (O&G) in the North Sea is expected to change substantially. Currently the O&G industry has a large influence on all activities in the Port of Den Helder. Innovations in logistics, shipping and inspection, for example remote control and autonomous shipping, are foreseen to be developed, which will have a substantial influence on the development of infrastructure at Port of Den Helder. Furthermore, it is expected that the transition to a carbon-free energy system will gradually reduce O&G activities. However, in a renewable energy system, O&G may still be used as a raw materials for a number of industries. It is possible that (larger) infrastructure from O&G will potentially also get a second life in a renewable energy system. Already, the renewable energy industry is increasing its activities in the North Sea and due to the nature of the renewable energy industry (e.g. low power density of the installations compared to O&G installations), the total need for port facilities will most likely increase.

The focus of this project is to investigate opportunities for the Port of Den Helder created by new developments in offshore wind energy in the North Sea and the kind of infrastructure that would be required to ensure that Den Helder can achieve a substantial share of these activities.

The seaport of Den Helder is limited in space and the present capacity usage of the Port of Den Helder is high, meaning that if the level of offshore wind energy activities increases structurally, it would be required to make more space and quayside facilities available. This most likely needs investments in port infrastructure development. This expansion would include areas for storage, warehouses and crew change facilities.

It is not foreseen by the project partners that the Port of Den Helder will have a substantial role during the installation of future offshore wind farms (OWFs). Among others reasons, this is due to, for instance, limited available space in the outer harbour and hinterland. Furthermore it is essential for Den Helder to maintain sufficient space for present parties such as the Royal Netherlands Navy, Netherlands Coastguard and the O&G industry [1]. It is relevant to note that presently the Port of Den Helder is also used by maritime contractors that supply services to wind farm development and installation activities. Therefore it is very likely that Port of Den Helder will have a limited role in the preparation and installation of the future offshore wind farms.

Based on interviews with partners and stakeholders in Port of Den Helder, Appendix A, it is concluded that the Port of Den Helder has state of the art supply and logistics facilities which is presently mainly in use for offshore O&G industry and will be an advantage in the transition to a wind energy O&M port.

1.1 Applied methodology and content of the report

During the course of this project, several workshops were organised and bilateral interviews were held between the various project partners and ECN part of TNO. Some external partners, like the Royal Netherlands Navy and the Netherlands Coastguard have also been interviewed for their opinion on the infrastructure requirements for the development of the Port of Den Helder. The main focus of the interviews was to determine their intentions and influence on potential innovations for the Port of Den Helder. A summary of the workshops with various partners in this project is detailed in Appendix A.

This report is an investigation on the opportunities and challenges for the Port of Den Helder in the forthcoming energy transition, one that is expected to lead to a very large growth of offshore wind energy related activities in the North Sea. In this introductory chapter, a description of the roadmap of the Port of Den Helder and the roadmap of the offshore wind energy development in the North Sea is provided (section 1.2 and section 1.3). Following this, an introduction to the opportunities for the Port of Den Helder in renewable energy activities not related to offshore wind energy is mentioned (sections 1.4, 1.5, 1.6, 1.7).

In Chapters 2 and 3, the infrastructure requirements needed at the Port of Den Helder to participate in activities related to offshore wind energy are detailed. This is done using analysis performed by ECN part of TNO for a reference scenario, a baseline scenario and 3 additional scenarios in three “development periods”. These development periods are defined from the present day until 2030, from 2030 until 2040 and from 2040 until 2050 (section 2.4). In the analysis of the reference scenario, an economic comparison is made between the Port of Den Helder and other ports in the Dutch coast such as the Port of IJmuiden and Groningen seaports in Eemshaven.

In Chapters 4 and 5, opportunities for the Port of Den Helder in other renewable energy activities such as hydrogen and maritime biomass (specifically seaweed) are discussed. Chapter 6 describes the effect of the energy transition on the employment opportunities at the Port of Den Helder including the educational “infrastructure”. In Chapter 7, conclusions from the earlier chapters are drawn and recommendations for future investigations are given.

1.2 Roadmap Port of Den Helder

The roadmap (Routekaart) of the Port of Den Helder from 2017 [1] describes plans for the Port of Den Helder to maintain and extend its activities till 2030. In the roadmap, it is already observed that the energy transition can provide several opportunities to the port. It is also noted that the port needs to be proactive to achieve these opportunities in a dynamic market environment.

Expectations identified for the Port of Den Helder in the roadmap document are:

- O&G activities will continue or maybe even slightly grow in the near term, depending on the price for oil and gas. However the volume of O&G activities will reduce to a minimum by 2050;
- Offshore wind will start to grow with a capacity of ~4.5 GW in 2023 and the Dutch energy agreement of 2013 indicates a very substantial potential of offshore wind capacity in 2050.

It is also indicated that a reduction in O&G activity could be compensated by a growth in offshore wind activity and given the differences in rates of decrease and increase of O&G and offshore wind activities respectively, the total volume of activities for the port in the forthcoming years may even increase. (see Figure 2)

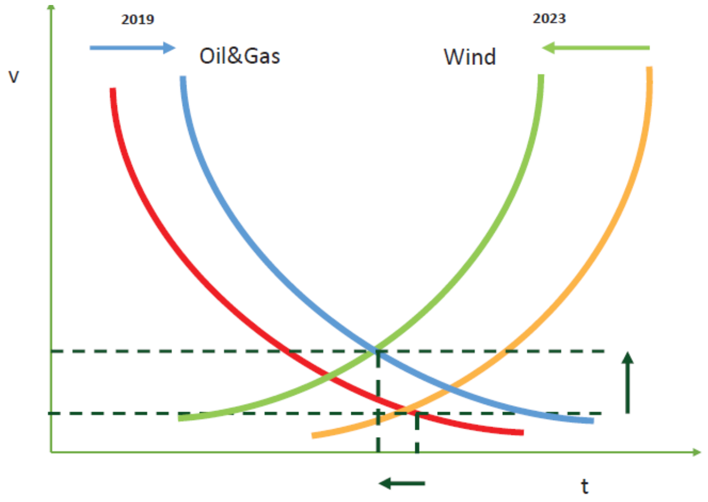

Figure 2 Speed of energy transition and potentially increase in total activities, copied from [1]

The Port of Den Helder's primary ambition with respect to offshore wind energy is to act as an operation and maintenance (O&M) hub for offshore wind farms (OWFs) [1] foreseen in the near-term (until 2023) and beyond. Besides acting as an O&M hub, the Port of Den Helder aims to participate in the development of wind farm sites by acting as a base for vessels that are within the size and depth constraints of the port.

Aside from offshore wind related activities, the Port of Den Helder acts as a collection point for three major offshore gas pipelines, transporting a large part of the natural gas from the North Sea to the main onshore gas infrastructure of N.V. Nederlandse Gasunie (the Dutch infrastructure and transportation company for natural gas). De Nederlandse Aardolie Maatschappij (NAM) operates a gas treatment plant, located in between the port of Den Helder and Kooyhaven. NAM processes the gas from several wells in the North Sea to standard delivery requirements of Gasunie gas transport grids.

The Netherlands Coastguard has its operational centre located in the Port of Den Helder. It is assumed that the role of the Netherlands Coastguard will be expanded when the offshore wind energy activities increase in the future.

Finally, the Royal Netherlands Navy has its home base at the Port Den Helder and uses a substantial part of the port, the Nieuwe Haven. It is foreseen that due to recent political decisions to increase defence spending, the activities of the Royal Netherlands Navy from the Port of Den Helder will remain the same or might even increase in the near future.

Future innovations for ports will have an influence on the layout and infrastructure. Innovations that are presently under development at ports (not specifically at the Port of Den Helder), and capable of affecting offshore wind O&M activities are:

- Automated shipping of wind turbine components for O&M, which could also make more efficient usage of ports [2]
- Optimised logistics where by just-in-time concepts could reduce the need for storage in the port and reduce the time that vessels occupy at quayside.

- Alternative vessel fuels, such as hydrogen, liquified biofuels or methanol, instead of marine diesel, changing the requirements for fuel storage and refuelling stations.

Although there is no specific mention of these innovations in the roadmap document, the Port of Den Helder has described and identified for further investigation in its strategy for sustainability document, [3] a number of the innovations mentioned above.

Description of the Port of Den Helder. From the layout of the Port of Den Helder (See Figure 3), direct sea access is available at *the Paleiskade*, which presently is occupied as an O&G offshore terminal, with three berth places, run by the energy logistics and supply company, Peterson. The *Nieuwe Diep north* quayside has a total of six multipurpose berth places (numbered 36 to 42 and together measuring 695 m in length), of which five are permanently assigned for offshore vessels. Beyond the *Moorman bridge*, *Het Nieuwe Diep south* has a quay length of 970 m, with a total of 13 smaller berth places (quays 43 to 55).

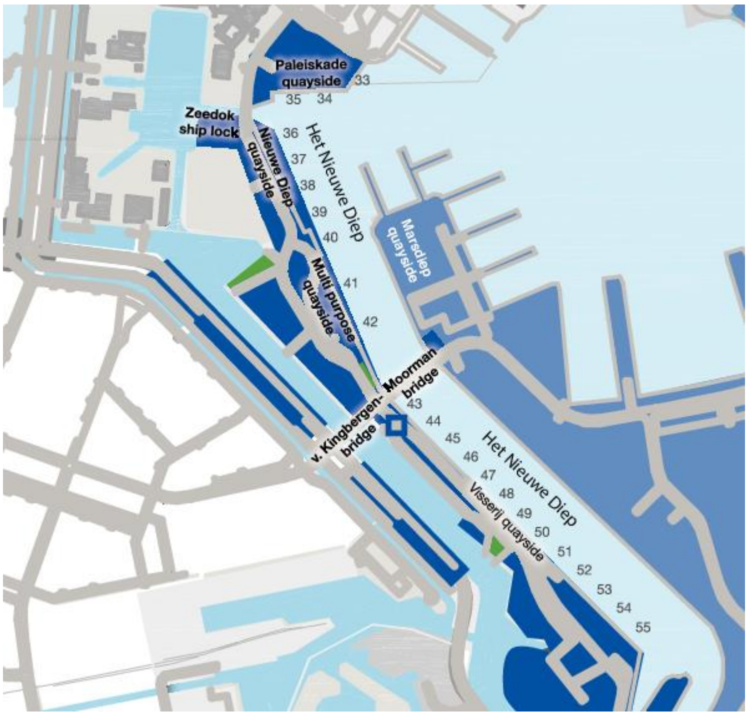

Figure 3 Layout and quays at Port of Den Helder [4]

Due to limitations of the *Moorman bridge* with a maximum width of 18 m for ships passing through, it will not be possible for ships wider than15 m to pass safely to the quays numbered 43 to 55. The depth of the port is 9 m at the sea side of the Moorman bridge, until quay 42. Beyond the Moorman bridge, from quay 43 and beyond, the depth of the port is 7 m.

The road map document mentions that the *Moorman bridge* might be replaced or be moved to a different location in the near future, making available the quaysides that are currently unavailable for large sea going ships. To use them though, it could be necessary to increase the depth at port for the quays 43 – 55.

Table 1 Summary of quay information at the Port of Den Helder

Name	**Direct sea access?**	**Number of quays**	**Quay numbers (#)**	**Quay length**	**Depth**
Paleiskade	Yes	3	33-35	240 m	9 m
Het Nieuwe Diep	Yes	5	36-40	495 m	9 m
Multipurpose quayside	Yes	2	41-42	200 m	9 m
Het Nieuwe Diep (beyond Moorman bridge)	No	13	43-55	970 m	7 m

Den Helder Airport, located about 5 km south of the port of Den Helder, is specially designated for helicopter operations, currently bringing technicians to and from oil rigs in the North Sea. As activity in oil fields will deplete in the North Sea in the future, alternate markets like offshore wind are being looked into. The use of helicopters as an alternative access vessel to transfer technicians to turbines is looked at in section 2.5.3.

1.3 Wind energy road map in the North Sea

In the report, “Wind Energy in Europe: Scenarios for 2030" [5], a wind energy road map is showing a substantial increase in offshore wind energy in the North Sea in presented. From Table 2, in the “central scenario”, it is seen that by 2030, about 50 GW of wind farms could be installed in the North Sea. In the “high scenario”, the installed capacity of wind farms in the North Sea adds up to 70 GW. The roadmap for offshore wind installations in the North Sea until 2030 per country are shown in Table 2 with a low, central and high scenario of growth.

Table 2 Offshore wind power cumulative capacity [GW] to 2030, from [1], countries around the North Sea.

	Low scenario	**Central scenario**	**High scenario**
United Kingdom	18.0	22.5	30.0
Germany	14.0	15.0	20.0
Netherlands	4.5	11.5	18.5
Denmark	3.4	4.3	6.13

The Netherlands

The vision for the Netherlands until 2030 for OWF development is currently well defined. Between 2020 and 2023, it is foreseen that the wind farm zones Borssele (~1400 MW), Hollandse Kust Zuid (~1400 MW) and Hollandse Kust Noord (~700 MW) will be built.

After 2023, the Hollandse Kust West (~1400 MW), Ten Noorden van de Waddeneilanden (~700 MW) and IJmuiden Ver (~4000 MW) wind farm zones will be developed. An additional wind farm of 900 MW capacity will be built at a location still to be decided. This results in a total offshore wind farm capacity in the Dutch part of the North Sea in 2030 of around 11.5 GW (see Table 3),

Table 3Table 3 Offshore wind farm development until 2030, totalling to 7 GW, in the Dutch North Sea [6]

Capacity	Wind Farm Zone	Shortest distance from the coast	Start of wind farm site decision	Year of tender	Year of commissioning
[GW]	[-]	[km]	[-]	[-]	[-]
1.4	HKW	51 (to Petten)	2018	2020/2021	2024/2025
0.7	TNW	56 (to Schiermonnikoog)	2019	2022	2026
approx. 4	IJV	53 (to Den Helder)	2020	2023-2026	2027-2030
approx. 0.9	TBD	-	-	-	-

The Port of Den Helder is competing with other ports to act as an O&M base for OWFs to be built after 2023. For some of these upcoming wind farms, the Port of Den Helder is closest to the wind farms centre location, see Figure 4.

However, while distance between port and wind farm is an important factor, it is not expected to be the deciding factor for the choice of an O&M port. Other factors such as quayside and warehouse space availability, proximity to onshore supply chain of spare part and component manufacturers will also play a role in developers choosing an O&M port.

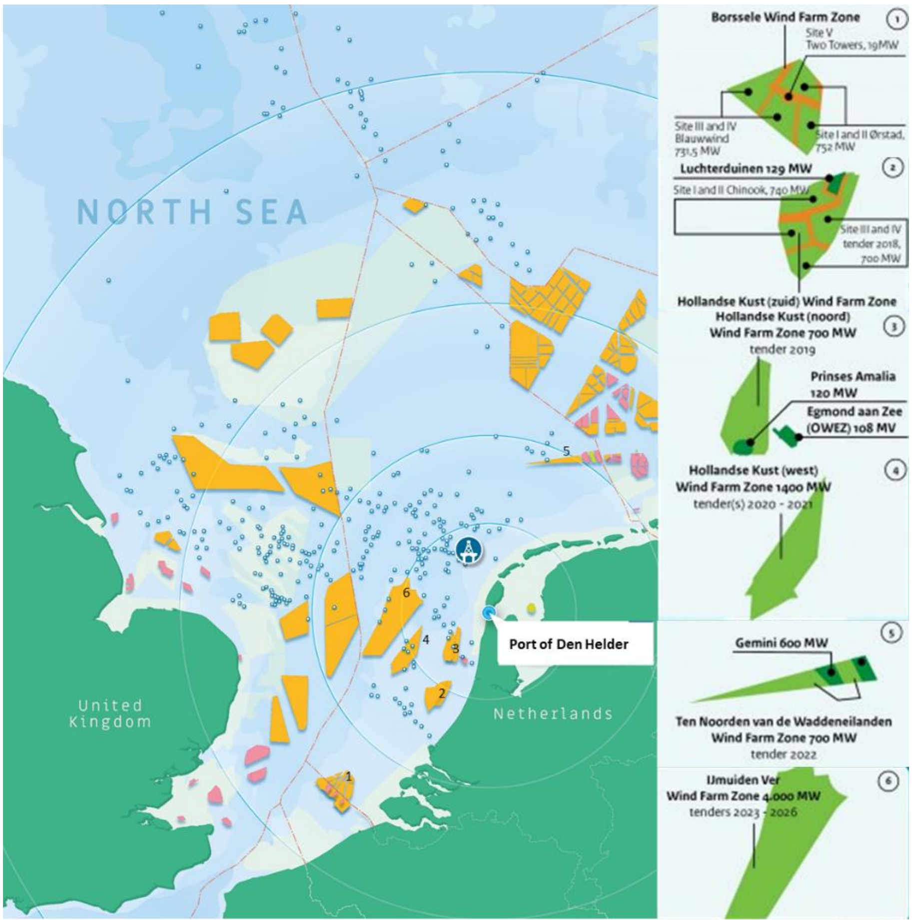

Figure 4 Offshore wind farm road map until 2030 for the Netherlands, UK and Germany, showing the central location of the Port of Den Helder

Beyond 2023, the projected development of offshore wind farms is based on scenarios in the future of the North Sea study [7] published by PBL Netherlands Environmental Assessment Agency. A scenario in the PBL study (see Figure 5) projects 60 GW of Dutch offshore wind energy capacity by 2050.

To realise this targeted capacity of OWFs in 2030 an uniform rate of installation of 1 GW per year until 2030 is envisioned by the Dutch Ministry of Economic Affairs and Climate Policy [8]. After 2030 there should be an increase in install capacity of 2 to 3 GW per year to reach the targeted capacity of 50 to 60 GW in 2050.

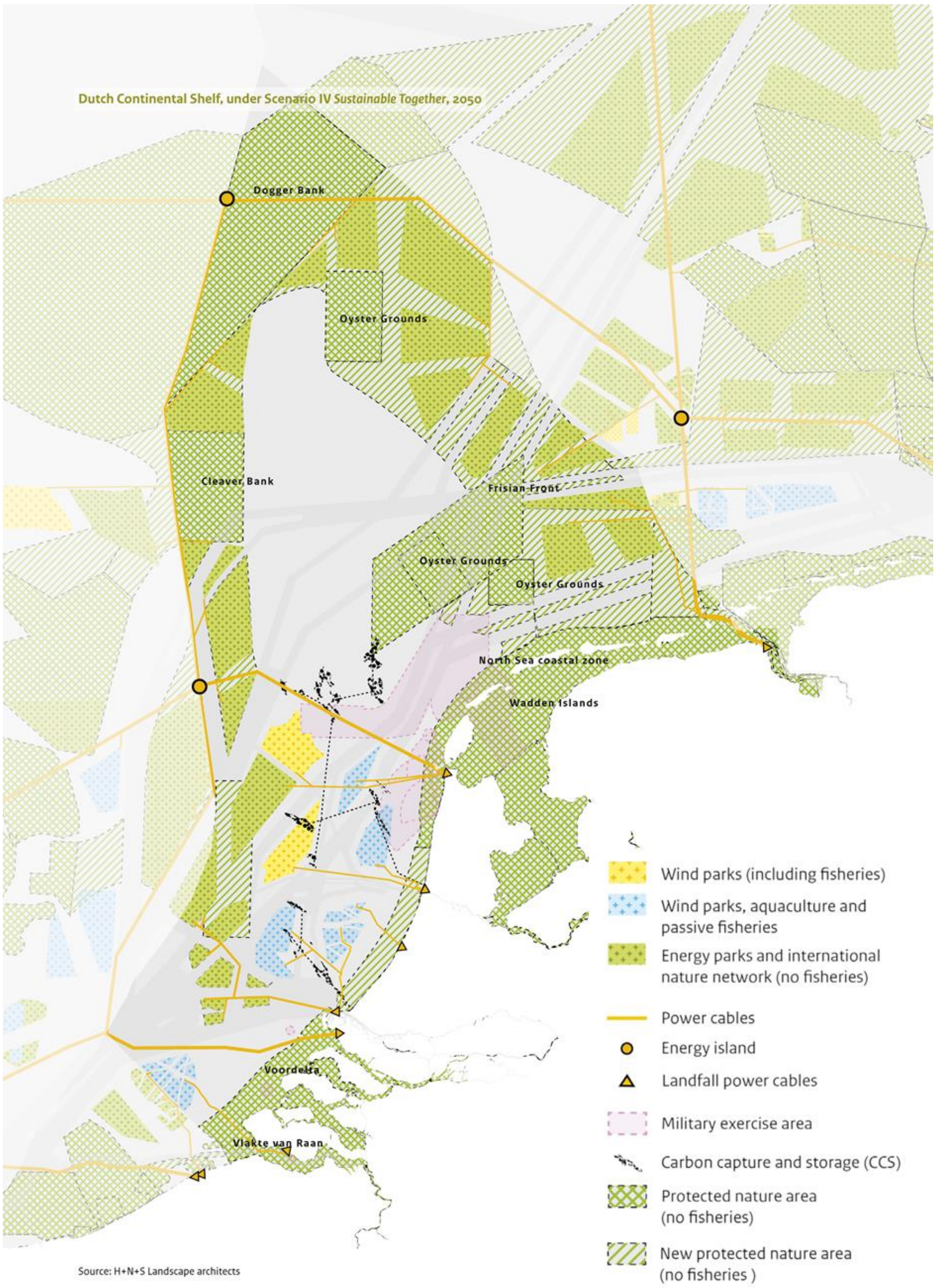

Figure 5 Projected development in the Dutch Continental Shelf, PBL study 2018 [7]

In the following sections, we divide the projected growth of OWFs into three development periods (refer section 2.4). At the end of each development period, the wind farm capacity in the Dutch part of the North Sea is estimated with some sensitivities in Table 7 and Table 8 of section 2.5.2.

Germany
The vision for offshore wind farms in Germany is also quite concrete until 2030, with a total capacity of 15 GW. Most of the German OWFs will be installed in the North Sea and some of the locations that are further away from German coast might well be maintained by vessels from Dutch ports like Groningen seaports- Eemshaven or the Port of Den Helder.

United Kingdom
With the highest current offshore wind capacity, the UK also has the most ambition to install OWFs in the near future in the North Sea. UK installations are not only planned in the North Sea but also in the Irish Sea where a substantial capacity will be built. The UK also has the most developed plans for the Dogger Bank region, which is adjacent to the northernmost part of the Dutch economic zone of the North Sea. However, it is still under investigation what the best options are to install and maintain offshore wind farms in the Dogger Bank region.

Denmark
The road map of offshore wind energy in Denmark shows a smaller increase in installed capacity when compared with the other countries mentioned in Table 2. It is expected that by 2030 Denmark will increase its offshore wind capacity from 1300 MW (at the end of 2018) to 4300 MW. The projected locations for OWFs in the Danish part of the European Economic Zone are most probably not of interest for the Port of Den Helder.

1.4 Hydrogen landing, production and/or storage

If developments in offshore wind proceed as planned, new energy storage options will be required to ensure sufficient energy transport and to provide the flexibility to match the inherent intermittent production with the varying energy market demand. On the one hand, present demand for electricity will be insufficient to use all the electricity generated during high wind periods. On the other hand, by phasing out conventional, fossil fuel based power stations between 2030 and 2050, the electricity production from offshore wind will be insufficient to match the power demand during low wind periods.

Hydrogen production, from renewable energy sources, and storage may be a suitable option to harness the increase in electricity production during high wind periods. Likewise conversion of hydrogen back to electricity can solve the shortage of electricity supply during low wind periods. Additionally, by using the existing gas infrastructure, both onshore and offshore, hydrogen may potentially be used by and for industry, mobility and households.

Green hydrogen[1] (fully renewable based) or blue hydrogen[2] (natural gas based with CO_2 capture), can be produced both onshore and offshore. For large scale offshore production of green hydrogen, it is assumed that one or more energy islands, located near the wind farms, will most likely be necessary. Hydrogen related activities are discussed in detail in Chapter 4.

1.5 Seaweed cultivation

It is foreseen that seaweed production and cultivation (or biomass growth in general) in the North Sea may also require space and infrastructure for installation activities at the Port of Den Helder and for processing of crops for the energy as well as food industry in locations further inland (See Chapter 5).

1.6 Carbon Capture and Storage (CCS)

There is a study being performed on the possibilities of Carbon Capture and Storage (CCS) via one of the existing pipelines that currently lands in Den Helder. If this is a viable option, it is possible that the CO_2 will “arrive” by ship from remote CO_2 sources and be pumped into the CO_2 return pipeline at the Port of Den Helder, requiring space at the quay and other facilities. Due to the fact this CCS study is not yet complete, CCS options for the Port of Den Helder are not discussed in this report.

1.7 Education and employment

To improve the transition from O&G dominated activities in the Port of Den Helder to activities related to renewable energy in the future, an inflow of well-trained employees is a requirement. At Den Helder, several organisations are active in training and educating students for a career in offshore activities. Organisations like the Engineering (Techniek) Campus, Den Helder Training Centre (DHTC) and ROC Kop van Noord-Holland provide an excellent chance for educating and training (future) employees for pursuing a career in offshore renewable energy. The Royal Naval college (Koninklijk Instituut voor de Marine or KIM) is also located in Den Helder and currently provides a bachelor degree, while in the near future there are plans to introduce master courses that are open to non-military students and are relevant for offshore wind energy related activities. Located close to Den Helder, in Alkmaar, Hogeschool InHolland also provides useful education for offshore renewable energy related activities.

[1] Green hydrogen is obtained from renewable i.e. green energy sources. Through electrolysis, water is divided into its constituents hydrogen and oxygen
[2] Blue hydrogen is produced from natural gas, usually via steam-reforming, with carbon capture storage (CCS). Blue hydrogen has the potential of large-scale, CO2-lean hydrogen production with proven, high TRL technologies.

2 Offshore wind O&M scenario development

2.1 Introduction

As mentioned in section 1.3, Wind Europe's projection for offshore wind energy shows a substantial increase in offshore wind farms (OWFs) in the North Sea. The vision of multi GW OWFs in the North Sea presents an opportunity for Dutch (and other countries') ports to participate not only in the installation and commissioning of future OWFs, but also in their operation and maintenance (O&M). For the Port of Den Helder, its strategic location covering the southern[3] part of the North Sea, in between the ports of IJmuiden and Eemshaven, opens up possibilities to participate in the O&M of future OWFs in the North Sea.

In the following sections, based on future OWFs development in the North Sea, the involvement of Port of Den Helder in maintaining these future OWFs is quantified. Three development periods are defined in section 2.4 and in each of them, the projected growth of wind farm capacity in the Dutch part of the North Sea is identified. Next, a number of scenarios are created to identify the infrastructure requirements at the port.

Initially, a *reference scenario* is modelled (section 2.5.1) to compare the costs of performing O&M from different ports for OWFs until 2026. Next, a *baseline scenario* is modelled (section 2.5.2) to set a starting point for the infrastructure requirements at the Port of Den Helder in the development periods. Next, three further scenarios are modelled to study additional infrastructure and innovation needs at the port compared to the baseline scenario. They are:

- Impact of using helicopters from Den Helder Airport in assisting O&M vessels
- Impact of a large offshore energy island for performing OWF O&M activities
- Impact of automated shipping of wind turbine components on O&M costs

These additional scenarios are discussed in sections 2.5.3, 2.5.4 and 2.5.5. The estimation of infrastructure requirements in all the scenarios is made based on the movement, frequency and type of vessels, the number of O&M technicians needed to perform repair work in the wind farm and the warehouse and logistic areas required by spare parts at the port of Den Helder.

To quantify vessel movements, technician requirements and the necessary warehouse and logistic areas, detailed O&M simulations are run using ECN part of TNO's in-house simulation software ECN O&M Calculator (v 3.0) [9].

2.2 Modelling approach

This section describes the modelling approach followed by the ECN O&M Calculator[4] software package.

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[3] Boundary between southern part and northern part of the North Sea is a line between Scotland and Norway.
[4] Version 3.0 of the ECN O&M calculator software is used to run the O&M simulations.

ECN O&M Calculator is a time domain simulation tool which is used for modelling different O&M strategies and computing corresponding O&M key performance indicators (KPIs). The aim of this tool is to enable OWF developers and operators to have a fair estimation of the O&M costs depending on the wind farm characteristics and the chosen O&M resources (i.e. vessels, technicians, spare parts).

The software's main outputs are:

- Wind farm availability in time (%): The time availability may be interpreted as the technical availability; that is the time the turbines are technically able to produce energy.
- Wind farm availability in yield (%): The yield availability is based on production losses and reflects the additional losses when maintenance events can't be performed during periods with bad weather when wind speeds are usually high.
- Repair costs (M€/year): Repair costs can be defined as the sum of cost of materials, vessels, technicians and other fixed yearly costs.
- Revenue losses (M€/year): Revenue losses are the product of energy lost due to turbine unavailability and energy price per kWh. The energy price in all the simulations is assumed to be 5 c€/kWh.
- Total O&M effort (M€/year): The total O&M effort is defined as the sum of repair costs and revenue losses.

Additionally, more detailed output parameters reflecting the O&M effort and performance can be obtained such as the breakdown of the turbine, balance of plant (BOP) downtime, usage of vessels and technicians etc.

To find the best combination of resources (vessels and technicians) for an O&M strategy, optimisations are performed using ECN O&M Calculator. The optimised O&M strategy is obtained based on the following variables:

- Number and type of O&M vessels needed for yearly O&M
- Number of technicians needed for yearly O&M.

The optimisation objective is to minimise the total O&M effort (M€/yr), which accounts for both direct repair costs and wind turbine downtime losses.

An example of the optimisation for a sample wind farm (Hollandse Kust (Noord) Wind Farm Zone) is seen in Appendix B. Similar optimisation cases are performed for all the scenarios described in section 2.5.

2.3 Assumptions

Common assumptions which are applicable to offshore wind O&M scenarios in section 2.5 are listed below:

- Port of Den Helder mainly focusses on the O&M activities of constructed wind farms, and does not support the movement of large offshore wind farm components during their construction, as this would require mooring of large installation jack-up vessels[5] and large assembly spaces in the outer harbour. However, vessels for some support activities during wind farm construction are

[5] Typically with depth requirements of >6 m, and length overall (L.O.A) ~100 m

supported from the Port of Den Helder for activities such as seabed scans, core penetration tests, bathymetry investigations etc.
- Port of Den Helder warehouses store small wind turbine spare parts while larger components like gearboxes and wind turbine blades are expected to be stored at the ports where they are manufactured or installed (e.g. Esbjerg (Denmark), St. Nazaire (France)).
- For OWFs closer to shore (up to approx. 45 km from shore like Hollandse Kust Noord), access vessels like Crew Transportation Vessels (CTV), Surface Effect Ships (SES) and Service Operation Vessels (SOV) are considered for O&M.
- As OWFs in the future move further from shore, CTVs and SESs are not expected to be used for O&M. In the future, SOVs act as both an access vessel to individual turbines and a mothership to launch daughter crafts.
- In the energy island scenario (section 2.5.4), the use of a helicopter and ferry is explored for transporting technicians between the energy island and the onshore harbour. The SOV is assumed to transfer technicians every two weeks from the wind farm to the energy island, when the technician shift ends.

Assumptions related to creating an O&M model in ECN O&M Calculator are mentioned below:
- The system breakdown of a wind turbine is according to the RDS-PP (Reference designated system for Power Plants) taxonomy code, as published by VGB PowerTech [10] shown in Appendix C.
- The fault type classes of individual components and their associated repair classes for maintenance are shown in detail in Appendix D.
- Maintenance activities on Wind Turbine (WT) and Balance of Plant (BOP) structures can be divided into three groups:
  - Unplanned corrective maintenance (ucm): The fault type classes, maintenance category, maintenance description and application to a particular BOP or WT system can be found in Appendix D, Table 34.
  - Condition based maintenance (cbm): The fault type classes, maintenance category, maintenance description and application to a particular BOP or WT system can also be found in Appendix D, Table 35.
  - Calendar based maintenance (cal): The fault type classes, description and application to a particular BOP or WT system can be found in Table 36.
- An overview of the repair classes may be found in Appendix E. The actions listed as unplanned corrective maintenance are reactive maintenance or ad-hoc actions after a failure has occurred and hence these actions do not have a well-defined time interval; i.e., period between two repairs.

2.4 Development periods

To estimate the infrastructure requirements at the Port of Den Helder, we consider the following development periods for the growth of OWFs in the North Sea:
- Development period 1: 2019 (Present year) – 2030
- Development period 2: 2030 -2040
- Development period 3: 2040 -2050

For each of these periods, costs of vessels, technicians and wind turbine spare parts are assumed with an annual inflation rate of 2.5%. The resource costs are used as inputs to calculate and compare the O&M KPIs between various scenarios, and choose an optimum O&M strategy.

For the three development periods, a baseline scenario is first described to set a starting point for the calculation of infrastructure requirements for offshore wind O&M from the Port of Den Helder. After this, three additional scenarios are investigated. All the scenarios are described in section 2.5.

2.5 Scenarios

The estimation of infrastructure requirements for the Port of Den Helder in terms of vessel movements, technician requirements and warehouse and logistic area needs in each of the development periods is done using various scenarios. A short description of each scenario is listed below.

Table 4 Description of various scenarios to estimate offshore wind O&M infrastructure at PoDH

Scenario Name	Scenario Title	Description
Reference	Is O&M of WFs until 2026 beneficial from PoDH?	To compare O&M costs from Den Helder versus other Dutch ports for wind farms till 2026.
Baseline	Estimation of PoDH infrastructure needs for the three development periods	To set a starting point for infrastructure needs (i.e. quayside space, warehouse and logistic area) from vessel, technician, spare part movements at PoDH
Scenario 1	Impact of using helicopters from Den Helder Airport on O&M costs	To estimate the infrastructure needs at Den Helder airport, when a helicopter is used as an alternative access vessel to the SOV
Scenario 2	Impact of large offshore energy island for performing offshore wind O&M activities	To estimate the infrastructure needs of PoDH and Den Helder Airport when ferries and/or helicopters are used to transport technicians to the energy island
Scenario 3	Impact of automated shipping of wind turbine components on O&M costs	To define innovations and infrastructure needs in automated shipping and quantify its impact in reducing O&M costs.

2.5.1 Reference Scenario: Is O&M of OWFs until 2026 beneficial from PoDH?

The objective in this scenario is to evaluate the impact of distance between wind farm and port on annual O&M costs. First, the OWFs planned in the near future are identified. Netherlands Enterprise Agency (RVO) expects that aside from the OWFs currently built and operating, a further three OWFs [11] will be commissioned by 2026, which are:

- Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN): 700 MW
- Wind Farm Zone Hollandse Kust (West) (HKW): 1400 MW and
- Wind Farm Zone Ten Noorden van de Waddeneilanden (TNW): 700 MW

Some additional assumptions for the reference scenario are listed below.

- Wind farms in the Borssele zone are not expected to be maintained from Port of Den Helder. This is because they are much closer to ports on the Southern coast like Rotterdam and Vlissingen
- It is unlikely that O&M for the recently tendered Hollandse Kust (Zuid) Wind Farm Zone (HKZ) I and II will be maintained from the Port of Den Helder, as another base port has already been chosen for this purpose. It is likely that Hollandse Kust (Zuid) Wind Farm Zone (HKZ) III and IV, that will be developed

by the same developer as the sites I & II, will also follow suit and choose an O&M port other than Port of Den Helder.

For the three Dutch OWFs that can be maintained from the Port of Den Helder, some assumptions like wind farm capacity, distance(s) to port, wind turbine nominal power, number of turbines etc. are listed in Table 5 and Table 6.

Table 5 Wind farm assumptions for Hollandse Kust Noord (HKN), Hollandse Kust West (HKW) and Ten Noorden van de Waddeneilanden (TNW)

Wind farm	**Number of WTs**	**WT nominal power**	**WF Capacity**	**Water depth**
		[MW]	**[MW]**	**[m]**
Hollandse Kust Noord (HKN)	70	10	700	~30
Hollandse Kust West (HKW)	120	12	1440	25-35
Ten Noorden van de Waddeneilanden (TNW)	60	12	720	28-36

Table 6 Port distances for Hollandse Kust Noord (HKN), Hollandse Kust West (HKW) and Ten Noorden van de Waddeneilanden (TNW)

Wind farm	**Port option 1 for O&M**	**Distance WF to OM port 1**	**Port option 2 for O&M**	**Distance WF to OM port 2**
		[km]		**[km]**
Hollandse Kust Noord (HKN)	PoDH	45	IJmuiden	30
Hollandse Kust West (HKW)	PoDH	65	IJmuiden	55
Ten Noorden van de Waddeneilanden (TNW)	PoDH	150	Eemshaven	105

2.5.2 Baseline Scenario: Estimation of PoDH infrastructure needs for the three development periods

The baseline scenario considers North Sea's OWF development in three periods and the impact this development would have on vessel, crew and warehouse requirements at the Port of Den Helder. This scenario sets a starting point for the expected infrastructure requirement at the Port of Den Helder needed in the future.

Based on the projected offshore wind farm development of 60 GW until 2050 (Figure 5), Table 8 shows the capacity of OWFs in the three development periods that were earlier defined (Sensitivity 2). Another sensitivity (Sensitivity 1) is defined based on the input from stakeholders in the project consortium, where the total OWF capacity in the Dutch North Sea until 2050 was estimated more conservatively as 45 GW. Table 7 shows the wind farm capacity in development periods 1,2 and 3 for Sensitivity 1.

Table 7 OWF development in Dutch North Sea in development periods 1, 2 and 3 in Sensitivity 1

Development period (Sensitivity 1)	**Years**	**Total capacity (Dutch North Sea)**	**Capacity increase (Dutch North Sea)**
		[GW]	[GW]
Period 1	2018-2030	11.5	11.5
Period 2	2030-2040	26.5	15.0
Period 3	2040-2050	45.0	18.5

Table 8 OWF development in Dutch North Sea in development periods 1, 2 and 3 in Sensitivity 2

Development period (Sensitivity 2)	**Years**	**Total capacity (Dutch North Sea)**	**Capacity increase (Dutch North Sea)**
		[GW]	[GW]
Period 1	2018-2030	11.5	11.5
Period 2	2030-2040	33.5	22.0
Period 3	2040-2050	60.0	26.5

After estimating the OWF growth in the three development periods, the percentage of OWFs serviced from Port of Den Helder is listed in Table 9. The reasons for 30 and 50% of O&M of future wind farms being performed from the Port of Den Helder are mentioned below.

Table 9 Ratio of future OWFs serviced from Port of Den Helder

Development period	**Years**	**Percentage of O&M from Port of Den Helder**
Period 1	2018-2030	Between 30% and 50%
Period 2 (Sensitivities 1 & 2)	2030-2040	Between 30% and 50%
Period 3 (Sensitivities 1 & 2)	2040-2050	Between 30% and 50%

- The southern part of the Dutch North Sea contains major shipping lanes (Figure 6) and will therefore not be suitable for construction of multi GW OWFs. A large number of these OWFs until 2050 are expected to be built in the northern part of the Dutch North Sea, distancing them from ports like Rotterdam and Vlissingen.
- Since the Port of Den Helder is centrally located between ports of Amsterdam, IJmuiden and Eemshaven, there is an opportunity for Den Helder to capitalise on the expected future wind farm development in the more northern parts of the Dutch North Sea.
- Due to its location and the propensity of OWFs being built in the northern part of the Dutch North Sea, the Port of Den Helder can expect to compete to become the maintenance hub for somewhere between 30 to 40% of the OWFs belonging to the Dutch part of the North Sea. The sensitivity of 50% is studied to account for possible OWFs from the UK using the Port of Den Helder as hub. The maintenance of OWFs from the UK region of the North Sea presents an additional opportunity for the Port of Den Helder.
- No large difference in yearly costs while performing O&M from Den Helder, Eemshaven or IJmuiden is expected, especially as SOVs are expected to be used to maintain future (farther offshore) OWFs. Since they already provide accommodation for technicians, SOVs need the use of a port only once every two weeks for bunkering, exchanging technicians and spare parts.

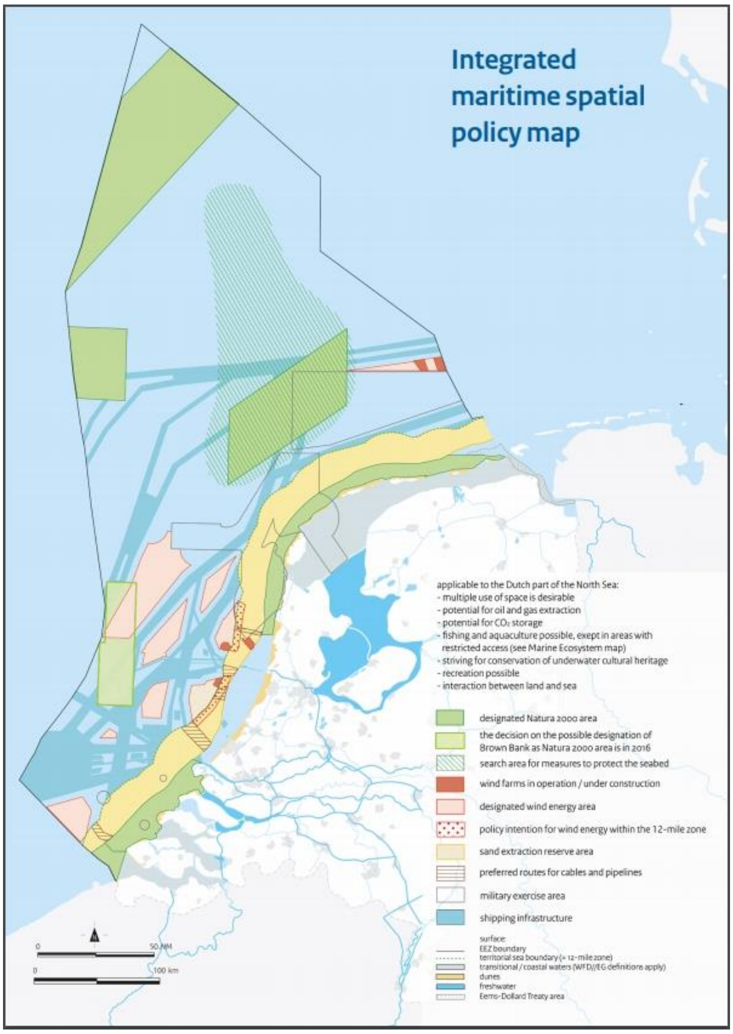

Figure 6 Offshore wind farm zones in Dutch part of the North Sea [12]

2.5.3 *Scenario 1: Impact of helicopters from Den Helder Airport on offshore wind O&M*

In addition to the use of O&M vessels, this scenario evaluates the impact of using helicopters as alternative access vessels for offshore wind O&M activities. The helicopter, modelled from Den Helder Airport (see Figure 7), is used only if the SOVs cannot access the wind farm and additional (urgent/ critical) maintenance needs to be performed. SOVs may be unable to access the wind farm either sue to being occupied with other work or due to unsuitable weather conditions.

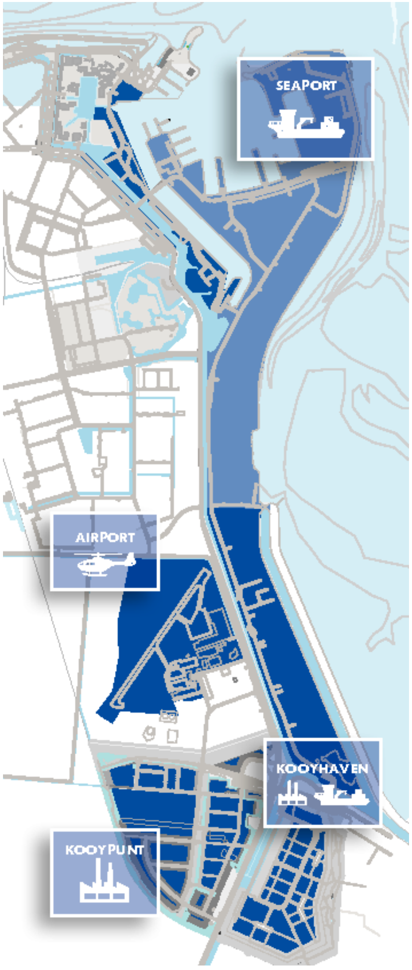

Figure 7 Helicopter launch point at Den Helder Airport (image courtesy of the Port of Den Helder)

2.5.4 Scenario 2: Impact of large offshore energy island to perform offshore wind O&M activities

In this scenario, the possibility of (multiple) large offshore energy island(s) and their impact on O&M of OWFs from the Port of Den Helder is investigated. From the "Future of the North Sea" study [7], it is estimated that between one and three offshore hub-islands will be constructed in the Dutch part of the North Sea by 2050, also supporting a power-to-gas (or hydrogen) production and storage infrastructure (three energy islands are shown in Figure 5).

During discussions in the workshops with partners in this project, the consensus was that probably only one energy island will be built between 2030 and 2040, as shown in Table 10.

Table 10 Number of offshore energy islands in future development periods

Development period	**Cumulative number of offshore energy islands**
Period 1 (2019-2030)	0 (no additional island)
Period 2 (2030-2040)	1 (additional island built)
Period 3 (2040-2050)	1 (no additional island)

2.5.5 Scenario 3: Impact of automated shipping of wind turbine components on O&M costs

In terms of infrastructure developments for automation at ports, research suggests that although automated ports are likely to be safer than human ones, the upfront capital expenditures will be quite high. Studies also highlight container ports as being ideal for automation, with some ports in Europe already starting to implement data collection and processing in order to set the required standards for port automation. [2]

Automated systems providing connections between warehouses on quayside and O&M vessels are expected to require large capital investments. However, the technology behind these automated systems is already seen as being quite mature. On the software side, the lack of data standardisation is seen as a challenge, given the integration a number of systems and interfaces such as gate operating software and computer vision to identify spare parts and components. [2]

In the earlier scenarios, SOVs are modelled to exchange technicians and spare parts at the Port of Den Helder once every two weeks. During these visits to port, besides the exchange of technicians and spare parts, routine services on the SOV such as cleaning, loading supplies and bunkering are carried out.

Innovations in automated transportation of spare parts and supplies between warehouse and quayside are expected to reduce handling times and exposure to weather. In this scenario, for development periods 2 and 3, a standard case is considered, where the SOV travels to port, takes six hours for exchanging technicians, spare parts, supplies and carrying out routine services. Next, two cases where this time is reduced by 25 % and 50% are considered, where the SOV only spends four and a half and three hours respectively at the port for the same activities.

It is not seen that this cycle time can be reduced by more than 50% since bunkering is likely to be a probable limiting factor, and no matter the innovation in the automated logistics, the refuelling time for SOVs ensures that it spends at least a certain amount of time during each visit to port.

Table 11 Reduction in SOV cycle time in development period 2 with automated logistics at port

Development period	**Time spent by SOV at port without automated shipping of spare parts and supplies (h)**	**Time spent by SOV at port with automated shipping of spare parts and supplies (h) (Case 1)**	**Time spent by SOV at port with automated shipping of spare parts and supplies (h) (Case 2)**
Period 2 (2030-2040)	6 hours per visit every two weeks	4.5 hours per visit every two weeks (assuming 25% cycle time reduction)	3 hours per visit every two weeks (assuming 50% cycle time reduction)
Period 3 (2040-2050)	6 hours per visit every two weeks	4.5 hours per visit every two weeks (assuming 25% cycle time reduction)	3 hours per visit every two weeks (assuming 50% cycle time reduction)

2.6 Vessels

The fleet of vessels expected to be used for O&M of OWFs in the North Sea is described in this section. As mentioned in section 2.4, the cost of these vessels in future development periods is assumed to increase from current day rates (see Appendix F) at an annual inflation rate of 2.5%. Some of the text in this section is sourced from ECN part of TNO's 2019 Offshore Wind Access report [13].

2.6.1 Crew Transfer Vessel (CTV)
CTVs (16-20 m in length) are stationed at the port after their daily trips to wind turbines in the OWFs. They are used to transfer technicians and small components to wind turbines. The CTVs specifications are listed in Table 38 in Appendix F.

2.6.2 Jack-up vessel
The transportation and hoisting of large components is done with a jack-up vessel. Since it can lift itself out of the water, a stable platform is created from which a large crane can be operated. The specifications of a jack-up vessel for O&M are given in Table 41 in Appendix F.

2.6.3 Cable laying vessel
For the replacement of cables within the wind farm, a cable laying vessel is used. It is assumed that the vessel has the necessary equipment to dig up and remove the failed cable, lay the new cable and bury it. During the repair action, the vessel stays inside the wind farm. Their specifications are given in Table 42 in Appendix F.

2.6.4 Diving support vessel
For inspection and repair under water, in case of foundations and scour protection, a diving support vessel is required. A diving support vessel is usually equipped with a Remotely Operated Vehicle (ROV). Specifications of the diving support vessel are given in Table 43 in Appendix F.

2.6.5 Helicopter
Helicopters can provide access to a wind turbine through the hoisting platform on top of the wind turbine nacelle or through the helideck on the substation. They are limited by the number of technicians and weight of spare parts that they can carry. In this study, a helicopter is used as an access vessel to transfer technicians to the turbine and as a mode of personnel transfer between the energy island and the onshore harbour (see section 2.5.3 and section 2.5.4). The specifications for a helicopter is listed in Table 44 in Appendix F.

2.6.6 Service Operation Vessel (SOV)
An SOV (with access gangway and/or daughter crafts) is located in the proximity of the wind farm. SOVs that are currently in operation in OWFs are being used as access vessels. They are also equipped with active or passive motion compensated gangways for technician and cargo transfer to the transition piece (TP) platform on the wind turbine. These vessels offer warehouse storage for smaller spare parts, accommodation for technicians to stay overnight, and act as access vessels for the wind turbines with the use of an access gangway. Using SOVs has the advantage that no working time is lost due to travel from the port. In the future though, it is expected that an SOV acts as a mothership for daughter crafts, which can be launched as alternative vessels for transporting technicians to the turbines.

Daughter crafts are connected using the boat landing on the midship of the SOV. In this study, the SOV is assumed to return to a port for service and exchange of wind turbine technicians every two weeks. The accessibility and cost details of this vessel type are included in Table 40 in Appendix F.

2.6.7 Surface effect ship (SES)

Like CTVs, SESs are stationed at the port after their daily trips to the OWFs. They are also used to transfer technicians and small components to the wind farm, and they are slightly larger in size compared to CTVs. SESs usually have a higher significant wave height (H_s) threshold compared to CTVs, which also make them more expensive. The accessibility and cost details of this vessel type are included in Table 39 in Appendix F.

2.6.8 Ferry vessels

In the future, when an energy island, acting as a O&M base for wind farms around it, is present in the North Sea (see section 2.5.4), ferries can be used for exchanging technicians between the island and onshore harbour. The specifications of a ferry are included in Table 45 in Appendix F.

3 Offshore Wind O&M scenario evaluation

Chapter 2 introduces expected developments in offshore wind in the coming few decades. Five scenarios related to the future of offshore wind O&M are defined in the previous chapter (see Table 4), along with modelling assumptions and inputs in terms of vessel costs and specifications. This chapter describes simulation results of the five scenarios, obtained from ECN O&M Calculator v3.0 software.

3.1 Reference Scenario: Is O&M of OWFs until 2026 beneficial from PoDH?

As mentioned in section 2.5.1, the objective of the reference scenario is to compare O&M costs from the Port of Den Helder with the corresponding O&M costs from other Dutch ports for wind farms till 2026. The wind farms until 2026 include the Hollandse Kust Noord (HKN) wind farm, Hollandse Kust West (HKW) wind farm and Ten Noorden van de Waddeneilanden (TNW) wind farm.

For the nearshore Hollandse Kust Noord (HKN) wind farm, the option of using CTVs from the ports of Den Helder and IJmuiden is investigated. For the other two wind farms, located further away, SOVs are modelled from ports for O&M. The O&M key performance indicators (KPIs) for the three wind farms are detailed in Table 12. For definitions of the O&M KPIs, see Table 13 or section 2.2.

Table 12 O&M KPIs of reference scenario

Wind farm	Strategy	O&M Port	Availability (%time, %yield)	Repair Costs (M€/yr)	Revenue Losses (M€/yr)	Total O&M Effort (M€/yr)	Cost per kWh (c€/kWh)
Hollandse Kust Noord[6]	CTV only	Den Helder	92.7 92.1	35.3	16.9	52.1	1.27
	CTV + Helicopter	Den Helder	93.6 93.3	37.1	14.4	51.7	1.32
	CTV only	IJmuiden	92.3 91.8	33.3	17.3	50.6	1.13
Hollandse Kust West	SOV[7]	Den Helder (bi-weekly)	94.0 93.3	83.7	27.0	110.7	1.56
	SOV	IJmuiden (bi-weekly)	94.4 93.9	84.5	24.9	109.3	1.56
Ten Noorden van de Wadden	SOV	Den Helder (bi-weekly)	95.2 95.1	51.3	10.9	62.2	1.69
	SOV	Eemshaven (bi-weekly)	95.1 94.9	51.45	11.28	62.73	1.70

Conclusions

- The use of “CTV only” option from IJmuiden is 1.5 M€/yr cheaper than the corresponding “CTV only” option from the Port of Den Helder in terms of total O&M effort (M€/year), which is marginal at ~3%.

[6] Although in the reference scenario for HKN wind farm, CTVs are used to compare O&M impact from different ports, an optimisation study for HKN (See Appendix B) shows a SES will be more beneficial. Therefore, in the baseline scenario results (Section 3.2), SES is seen ideal for O&M of HKN than a CTV.
[7] SOV acts as both an access vessel and a mothership for daughter crafts

- The use of a helicopter from Den Helder increases availability and reduces revenue losses for a nearshore wind farm like Hollandse Kust Noord (HKN). The total O&M effort is now closer (<1 M€/yr) to the "CTV only" option from IJmuiden.
- As OWFs move further offshore, SOVs are the preferred mode of access, making the choice of port less significant (<1% for Ten Noorden van de Waddeneilanden wind farm[8] (TNW)).
- For OWFs that will be built in the northern part of the Dutch coast after 2026, the Port of Den Helder, due to its central location, can act as a possible choice of O&M port. Although its central location is advantageous, it will most likely not be the deciding factor for developers for an O&M port. Other factors such as weather and wind conditions at port, quayside and warehouse space availability will also play a role in developers choosing a port.

3.2 Baseline Scenario: Estimation of PoDH infrastructure needs for the three development periods

As described in section 2.5.2, the results from this scenario set a starting point for necessary future infrastructure developments at the Port of Den Helder, following the growth of offshore wind O&M activities.

Results for development period 1
For Hollandse Kust Noord (HKN) wind farm, from the optimisation study seen in Appendix B, the optimal O&M strategy is with the use of a single SES with 20 technicians. The optimised strategy for Hollandse Kust West (HKW) wind farm is with the use of two SOVs, each providing access to individual wind turbines besides acting as a mothership for a small number of daughter crafts (See Table 13 below).

Table 13 O&M KPIs of Hollandse Kust West (HKW) wind farm with 2 SOVs and 45 technicians.

Strategy	**2 SOV, 45 technicians**	**Description**
Availability (% time, % yield)	94.0 93.3	(%time: period without downtime; %yield: ratio of energy produced relative to 20 years without shut down of turbines
Repair costs (M€/year)	83.7	Cost of materials, vessels, technicians and other fixed yearly costs in performing yearly O&M
Revenue losses (M€/year)	27.0	Product of energy lost due to turbine unavailability and energy price per kWh
Total effort (M€/year)	**110.7**	Sum of repair costs plus revenue losses
Cost of energy (€/MWh)	1.56	Repair costs divided over number of kWh produced

Table 32 and Table 33 from the optimisation study in Appendix B also compare the results for various strategies of vessels and technicians for Hollandse Kust West (HKW) wind farm and Ten Noorden van de Waddeneilanden (TNW) wind farm.

Table 14 lists the vessel and technician requirement for the O&M of OWFs in development period 1. For wind farms where SOVs are used for O&M, the number

[8] The accuracy on O&M effort is approximately +/- 1 M€ (+/- 2%), due to the stochastic process of failure modelling and inherent variability in the weather data, although running a large number of simulations (~300) compensates for this uncertainty to some extent.

of technicians from the simulation results is multiplied by two. This is to account for a new batch of working technicians that would be needed after every two weeks when a new shift starts. The working time for each batch of technicians is 12 hours per day for 14 days in a month. This equals 168 working hours per technician per month, which is equivalent to the monthly hours of an full time equivalent (FTE) as defined in the study by TKI wind op zee on *Employment analysis of various activities in the Dutch offshore wind sector* [14].

Table 14 Vessel and technician requirement for OWFs in development period 1

	Wind farm	**Type of vessel**	**Number of vessels**	**Number of technicians**
Development period 1 (Present year -2030)	HKN	SES	1	20
	HKW	SOV (with daughter crafts)	2	45 (*2)
	TNW	SOV (with daughter crafts)	1	30 (*2)
	IJV	SOV (with daughter crafts)	4	60 (*2)

Results for development period 2 and 3

For development periods 2 and 3, simulations are run using ECN O&M Calculator to find an optimised O&M strategy, in a process similar to the analysis in Appendix B. Resulting vessel and technician numbers from the simulations are listed in Table 15 and Table 16. A distinction needs to be made between results in the two tables.

Table 15 shows just the additional wind farm capacity and vessel and technician needs during a single development period. Table 16 shows up until each development period, the cumulative wind farm capacity and vessels and technicians that are needed.

Besides the expected number of SOVs operating from the Port of Den Helder, Table 15 and Table 16 also show the possibility for operating a SES vessel to maintain a nearshore wind farm like Hollandse Kust Noord (HKN).

Furthermore, with the construction of a large number of OWFs close to Den Helder, a number of support vessels are also expected to be present at the Port of Den Helder, taking part in offshore wind site preparation activities like seabed scans, core penetration tests, bathymetry investigations etc.

From the number of vessels, technicians and spare parts needed in each development period, infrastructure requirements at the Port of Den Helder in terms of quayside, warehouse and logistic spaces are estimated below.

Table 15 Additional vessel, technician need for OWFs in development period 2 and 3

Development periods	**WF capacity (additional)**	**Vessels required (additional)**	**Number of technicians (additional)**	**SOVs from PoDH (30% of total O&M vessels)**	**SOVs from PoDH (50% of total O&M vessels)**
Period 1 (2019-2030)	11.5GW	1 SES, 7 SOV	290	2 SOV; 87 techs	4 SOV; 145 techs
Period 2 (Sens 1) (2030-2040)	15GW	14 SOV	310	4 SOV; 93 techs	7 SOV; 155 techs
Period 2 (Sens 2) (2030-2040)	22GW	17 SOV	410	5 SOV; 123 techs	9 SOV; 205 techs
Period 3 (Sens 1) (2040-2050)	18.5GW	16 SOV	382	5 SOV; 115 techs	8 SOV; 191 techs
Period 3 (Sens 2) (2040-2050)	26.5GW	18 SOV	490	5 SOV; 147 techs	9 SOV; 245 techs

Table 16 Cumulative vessel and technician need for OWFs in development period 2 and 3

Development periods	**WF capacity (cumulative)**	**Vessels required (cumulative)**	**Number of technicians (cumulative)**	**SOVs from PoDH (30% of total O&M vessels)**	**SOVs from PoDH (50% of total O&M vessels)**
Period 1 (2019-2030)	11.5GW	1 SES, 7 SOV	170	2 SOV; 87 techs	4 SOV; 145 techs
Period 2 (Sens 1) (2030-2040)	26.5GW	21 SOV	600	6 SOV; 180 techs	11 SOV; 300 techs
Period 2 (Sens 2) (2030-2040)	33.5GW	24 SOV	700	7 SOV; 210 techs	12 SOV; 350 techs
Period 3 (Sens 1) (2040-2050)	45GW	37 SOV	982	11 SOV; 295 techs	19 SOV; 491 techs
Period 3 (Sens 2) (2040-2050)	60GW	42 SOV	1190	13 SOV; 357 techs	21 SOV; 595 techs

Infrastructure requirements (Quayside space)

From the O&M vessel requirements at the Port of Den Helder in Table 15 and Table 16, the frequency of vessel movements and quayside needs at the port in the three development periods are listed in Table 17. The length overall (L.O.A) of an SOV is assumed as approximately 80 m, and each SOV is modelled to visit the port after a shift of 2 weeks. Although the size of spare parts on an SOV may increase owing to larger wind turbines, it is unclear whether this will have an impact on the size of an SOV itself in the future. The sensitivity with 50% of total O&M vessels (in Table 15 and Table 16) is used to calculate vessel frequency to set an upper limit for the quayside spatial needs at the Port of Den Helder.

In addition to the frequency of SOV movement, a SES for maintaining nearshore wind farms and additional support vessels for preparation activities during the construction of OWFs can be expected from the Port of Den Helder. Based on discussions with the Port of Den Helder, there are two support vessels that presently visit the port, with a frequency of about one visit per week. These support vessels perform activities such as seabed scans, core penetration tests and bathymetry investigations. An estimate for the increase in visits by support vessels corresponding to the increase in OWFs is accounted for in Table 17.

Table 17 Frequency of future vessel movements and quayside requirements at PoDH

Development periods	SOVs from PoDH (50% of O&M vessels)	Frequency of SOV movement at PoDH	Other vessels at PoDH	Quayside requirement at PoDH
Period 1 (2019-2030)	4 SOV; 145 techs	1 SOV once every 3-4 days	1 SES (~200 trips/yr.); 2-4 SVs (support vessels), once per week[9]	Up to 1 quay for SOV; Up to 1 quay for SES, SVs
Period 2 (Sens 1) (2030-2040)	11 SOV; 300 techs	1 SOV once every 1-2 days	1 SES (~200 trips/yr.); 4-6 SVs (support vessels), one visit per week each	Up to 1 quay for SOV; Up to 1 quay for SES, SVs
Period 2 (Sens 2) (2030-2040)	12 SOV; 350 techs	1 SOV once every 1-2 days	1 SES (~200 trips/yr.); 4-6 SVs (support vessels), one visit per week each	Up to 1 quay for SOV; Up to 1 quay for SES, SVs
Period 3 (Sens 1) (2040-2050)	19 SOV; 491 techs	One to two SOV's per day	1 SES (~200 trips/yr.); 8-10 SVs (support vessels), one visit per week each	1-2 quays for SOV; 1-2 quays for SES, SVs
Period 3 (Sens 2) (2040-2050)	21 SOV; 595 techs	One to two SOV's per day	1 SES (~200 trips/yr.); 8-10 SVs (support vessels), one visit per week each	1-2 quays for SOV; 1-2 quays for SES, SVs

Infrastructure requirements (Warehouse and logistic space)

The warehouse floor area per turbine is obtained from discussion with the project partners on equivalent warehouse areas at other O&M ports for Dutch OWFs. Research shows that an O&M base for the Borssele 1 and 2 wind farms at Vlissingen, being built by Ørsted, has a size of 2100 m^2 to support approximately 75 turbines [15]. When scaled to the number of turbines in the development periods 2 and 3, the logistic areas at Vlissingen are comparable to those from Table 18.

The warehouse area only accounts for storing “non-large” spare parts such as pitch and yaw motors, battery packs, control systems and sliprings. The storage and transportation of large spare parts such as blades, gearboxes and generators is expected to happen from their manufacturing ports (e.g. Esbjerg or Saint Nazaire).

The warehouse and logistic space requirement for each development period at the Port of Den Helder is shown in Table 18.

[9] This is a rough estimate, based on two support vessels presently visiting PoDH with a frequency of about one visit per week, performing construction related activities of wind farms like seabed scans, bathymetry investigations etc

Table 18 Warehouse and logistic space requirement at PoDH for each development period

Development periods	**Period 1 (2019-2030)**	**Period 2 (2030-2040)**	**Period 3 (2040-2050)**	**Description**
WF capacity (additional)	11.5GW	22GW	26.5GW	Assumed (Refer Table 7)
Share of spare parts at PoDH	30%	30% to 50%	30% to 50%	Assumed (Refer Table 9)
Share of WFs serviced from PoDH (additional)	3.45 GW	6.6 to 11 GW	8 to 13.3 GW	Product of WF capacity and share of spare parts at PoDH
Rated Power per WTG	10 MW	15 MW	15 MW	Rated power of WTs modelled in each development period
Number of WTG (spares supported from PoDH)	345	440 to 733	533 to 883	Ratio of share of WFs serviced from PoDH and rated power per WTG
Warehouse area per WTG	12 m^2	12 m^2	12 m^2	Estimate of warehouse area based on discussions with PoDH, includes walkways etc along with spaces for forklifts to operate
Warehouse area per development period	4140 m^2	5280 to 8800 m^2	6400 to 10600 m^2	For storage of components only
Office and crew facilities	1250 m^2	2500 m^2	2500 m^2	Office of 25*50 m^2 assumed in 2030, added 2500 m^2 offices assumed by 2040 and 2050
Gross space requirement (warehouse space including logistic areas)	10780 m^2	15600 m^2 to 22600 m^2	17800 to 26200 m^2	Sum of warehouse area and office & crew facilities is multiplied by factor of two to account for walkways, parking, access roads, onshore manoeuvring etc
Space requirement adjacent to quay	2250 m^2	2250 m^2	-	Assumed that one quay space required until 2030 and one extra until 2050
Warehouse plus logistic area needed per development period	13030 m^2	17850 to 24850 m^2	17800 to 26200 m^2	Sum of logistics space and space needed adjacent to quay
Total warehouse plus logistic area needed	**1.3 hectares**	**3.1 to 3.8 hectares**	**4.9 to 6.4 hectares**	Sum of warehouse plus logistic area per development period

Conclusions
From Table 17, up to one quay with direct sea access until development period 2, and an increase to two quays thereafter can handle the frequency of SOVs for offshore wind O&M from the Port of Den Helder. Additionally, up to two quays may be needed by 2050 for SES and support vessels (SVs) to perform other offshore wind related activities. Given that quays 36 to 42 are presently being used for offshore vessels, with medium occupancy rates, in the short term (until 2030), the quayside requirement for offshore wind activities seems sufficient. However, as the infrastructural need for maintaining OWFs increases in development periods 2 and 3, it is expected that further investment in quays would be necessary. The location of possible new quaysides is not explored in this report.

A warehouse to store wind turbine spare parts (excluding large spare parts like blades, gearboxes and generators) and space for logistic areas such as office facilities, walkways, parking facilities, access roads and onshore manoeuvring is accounted for. The overall space requirement for logistics increases from an estimated 1.3 ha in 2030 to between 4.9 and 6.4 ha in 2050.

Finally, the baseline results from Table 17 also shows a required labour force of 600 offshore technicians working in offshore wind O&M by 2050. Besides direct employment of O&M technicians at sea, there will also be indirect jobs created in the primary and secondary labour markets at Den Helder. There will also be a need for onshore crew that operate and maintain trucks, warehouses and other infrastructure on the port.

3.3 Scenario 1: Impact of helicopters from Den Helder Airport on offshore wind O&M

As described in section 2.5.3, in this scenario, the impact on O&M costs of a helicopter as an alternative access vessel in addition to SOVs is investigated. The movement of helicopters in this scenario is translated into space requirements at Den Helder Airport. The O&M KPIs for development period 2 is in Table 19.

Table 19 O&M KPIs with use of helicopter as an alternative access vessel in development period 2

Development period 2 (2030-2040) (Sensitivity 1): 15 GW capacity increase		
Strategy	14 SOV, 0 helicopter	14 SOV, 1 helicopter
Availability (% time, % yield)	94.3 94.1	94.4 94.1
Repair costs (M€/year)	616.3	614.7
Revenue losses (M€/year)	208.1	202.7
Total effort (M€/year)	**824.4**	**817.4**
O&M Cost of energy (€/MWh)	0.95	0.95

There is a slight increase in availability, owing to the possibility of wind turbine access using a helicopter. This reduces revenue losses by 5.4 M€/yr. Also, the repair costs are lower, because of lesser work performed by the SOV overall[10]. In all, a reduction of ~7 M€/yr is seen with the use of an additional helicopter.

[10] Results from the detailed excel output of ECN O&M Calculator show 25 lesser round trips by the SOV when an additional helicopter is modelled as an alternative access vessel

Table 20 shows the impact of two additional helicopters in development period 3.

Table 20 O&M KPIs with the use of additional helicopter as an alternative access vessel in development period 3

Development period 3 (2040-2050) (Sensitivity 1): 18.5 GW capacity increase		
Strategy	17 SOV, 0 helicopter	17 SOV, 2 helicopter
Availability (% time, % yield)	94.8 94.5	95.0 94.8
Repair costs (M€/year)	930.8	941.6
Revenue losses (M€/year)	236.6	220.3
Total effort (M€/year)	**1167.4**	**1161.9**
O&M Cost of energy (€/MWh)	1.16	1.18

In development period 3, with a fleet of 17 SOVs as primary access vessels, two additional helicopters are used for O&M with an average frequency of 208 round trips per year. An increase in availability is seen with the two helicopters. There is however, an increase in repair costs. Overall, there is an annual saving of 5.5 M€.

Table 12 in the reference scenario shows, an annual reduction of 1.64 M€ with the use of a helicopter for Hollandse Kust Noord (HKN) wind farm.

Infrastructure requirements

Infrastructure requirements and frequency of the helicopter as an alternative access vessel is in Table 21.

Table 21 Infrastructure requirements and frequency of the helicopter as an alternative access

Development periods	**WF capacity (overall)**	**Number of vessels (and helicopters) needed at PoDH (overall)**	**Number of round trips per helicopter**	**Freq. of helicopter movement at Den Helder Airport (per helicopter)**	**Number of touch down & lift-off areas needed**	**# storage/ hangar spots needed at Den Helder Airport**
Period 1 (2019-2030)	11.5GW	1 SES; 7 SOV; 1 helicopter	240 round trips	Once every 1-2 days	One	One
Period 2 (Sens 1) (2030-2040)	26.5GW	21 SOV; 1 helicopter	280 round trips	Once every 1-2 days	One	Two
Period 2 (Sens 2) (2030-2040)	33.5GW	24 SOV; 2 helicopters	300 round trips	Once every 1-2 days	One	Two
Period 3 (Sens 1) (2040-2050)	45GW	37 SOV; 3 helicopters	208 round trips	Once every 1-2 days	One	Three
Period 3 (Sens 2) (2040-2050)	60GW	42 SOV; 3 helicopters	230 round trips	Once every 1-2 days	One	Three

Conclusions

- With helicopters as alternative access vessels, there is no decrease in the number of SOVs for offshore wind O&M in the three development periods. The frequency of SOV movement and quayside spatial needs at the Port of Den Helder are the same as in the baseline scenario (See section 3.2 conclusions).
- There is an obvious need for storage or hangar spots at the Den Helder Airport for up to three helicopters used for offshore wind O&M by 2050 (see Table 21).

3.4 Scenario 2: Impact of large offshore energy island to perform offshore wind O&M activities

Offshore energy islands are expected in the North Sea by 2050 [7] with functions that might include:

- Area for a warehouse for small wind turbine spare parts
- Accommodation for technicians and end-of-shift technician transfer
- Quayside for O&M vessels and landing pads for helicopters to transfer technicians.

In this scenario, SOVs use the offshore energy island instead of onshore ports for technician and spare part exchange once every two weeks. This has a dual impact on the Port of Den Helder:

- The port may be used as a hub to transfer technicians and spare parts to the island by ferries or helicopters
- The range of wind farms serviced by technicians from the energy island can be much larger than in previous scenarios, where only 45 to 60 GW of OWFs were maintained by vessels from the Port of Den Helder. This increase in range of may also include OWFs from UK part of the North Sea.

Infrastructure requirements

The infrastructure requirements for development period 1, will not change from baseline scenario (section 3.2) since no offshore energy islands are expected to be built. Infrastructure needs for development periods 2 and 3 are estimated with two modes of technician transfer to the energy island from the onshore harbour.

<u>Use of ferries for technician transfer:</u>

The O&M results with ferries (with a technician capacity of 60) in development periods 2 and 3 are in Table 22. By 2050, the use of two ferries is seen almost every day. With a length overall (L.O.A) of around 30 m, two ferries in 2050 can be handled from a single quay at the Port of Den Helder.

Although this is a reduction in quayside needs when compared with the baseline scenario (section 3.2) for offshore wind O&M vessels, the movement of vessels for maintenance of facilities on the energy island is not accounted for. The list of activities for the maintenance of the energy island is expected to be significant, and could be another potential line of business interest for Port of Den Helder.

Table 22 O&M KPIs with ferries for technician transport to the offshore energy island

Development periods	**WF capacity (cumulative)**	**Number of technicians transported from PoDH (50% of total traffic)**	**Number of ferries from PoDH (cumulative)**	**Frequency of ferry movement from PoDH**	**Quayside required at PoDH**
Period 2 (Sens 1) (2030-2040)	26.5GW	300 techs	1	5-6 times every two weeks per ferry	Up to 1 quay
Period 2 (Sens 2) (2030-2040)	33.5GW	350 techs	1	5-6 times every two weeks per ferry	Up to 1 quay
Period 3 (Sens 1) (2040-2050)	45GW	491 techs	2	8-9 times every two weeks per ferry	Up to 1 quay
Period 3 (Sens 2) (2040-2050)	60GW	595 techs	2	10-11 times every two weeks per ferry	Up to 1 quay

Also, this scenario calculates infrastructure needs based on 50% of technician transfers for an estimated development of 45 GW to 60 GW of wind farms until 2050. In reality, as mentioned earlier, both the share of technician transferred from the port and the number of OWFs they maintain could be higher. The conclusions on infrastructure needs in this scenario should be seen as a conservative estimate.

Use of helicopters for technician transfer:
The O&M results with helicopters (with a technician capacity of 8) for technician transfer in development periods 2 and 3 are in Table 23.

By 2050, five helicopters are required almost every day and Den Helder Airport will be used quite intensively if all technician transfers are made using helicopters. It is therefore more likely that a combination of ferries and helicopters are used for transferring technicians to and from the offshore energy island.

Table 23 O&M KPIs with helicopters for technician transfer to the offshore energy island

Development periods	**WF capacity (cumulative)**	**Number of techs transported from PoDH (50% of total traffic)**	**Number of helicopters from PoDH (cumulative)**	**Frequency of helicopter movement from PoDH (for each helicopter)**
Period 2 (Sens 1) (2030-2040)	26.5GW	300 techs	3	12-13 times every two weeks
Period 2 (Sens 2) (2030-2040)	33.5GW	350 techs	3	14-15 times every two weeks
Period 3 (Sens 1) (2040-2050)	45GW	491 techs	4	15-16 times every two weeks
Period 3 (Sens 2) (2040-2050)	60GW	595 techs	5	14-15 times every two weeks

Conclusions

- Either helicopters or ferry vessels can be used to transfer offshore wind O&M technicians between onshore ports and the offshore energy island. This will increase the number of port calls for ferries and hangar space requirement at Den Helder airport (see Table 22 and Table 23).
- An energy island would reduce the number of port calls for SOVs. This reduction is not easy to quantify, since for wind farms that are closer to the shore than the energy island, it is possible that SOVs transfer technicians back at the onshore port. The number of port calls for the SOV is not expected to decrease to zero.
- There could be an increase in vessels required to maintain island infrastructure from the Port of Den Helder. With the increase in ferries to transfer technicians and the increase in other vessels to maintain the island, it is unclear whether the reduction in SOV activity would have a net positive or negative impact of the port calls from the Port of Den Helder.

3.5 Scenario 3: Impact of automated shipping of wind turbine components on O&M costs

Automated shipping of wind turbine components from warehouses onto vessels can be expected to reduce cycle times of SOVs at ports (see section 2.5.5). Table 34 and Table 35 show the impact of reducing cycle times (by 25% and 50%) at port for SOVs in development periods 2 and 3 with the use of automated shipping of spare parts and other supplies.

Table 24 O&M KPIs for development period 2 with the use of automated shipping of spares.

Development period 2 (2030-2040) (Sensitivity 1): 15 GW			
Strategy	14 SOV, 6 hours at port	14 SOV, 4.5 hours at port	14 SOV, 3 hours at port
Availability (% time, % yield)	94.4 94.1	94.3 93.9	94.4 94.1
Repair costs (M€/year)	616.3	609.86	608.0
Revenue losses (M€/year)	208.1	208.38	204.5
Total effort (M€/year)	**824.4**	**818.5**	**812.5**
O&M Cost of energy (€/MWh)	0.95	0.93	0.93

Table 25 O&M KPIs for development period 3 with the use of automated shipping of spares

Development period 3 (2040-2050) (Sensitivity 1): 18.5 GW			
Strategy	17 SOV, 6 hours at port	17 SOV, 4.5 hours at port	17 SOV, 3 hours at port
Availability (% time, % yield)	94.8 94.5	94.8 94.6	95.1 94.8
Repair costs (M€/year)	930.8	932.0	935.6
Revenue losses (M€/year)	236.6	232.17	224.4
Total effort (M€/year)	**1167.4**	**1164.16**	**1159.9**
O&M Cost of energy (€/MWh)	1.16	1.16	1.16

In both periods, the reduction in cycle times of SOVs at port lead to a marginal decrease in total annual O&M effort, by increasing availability and reducing revenue losses. The savings in both development periods are only of the order of 1% of the annual O&M effort.

4 Hydrogen activities

4.1 Introduction

There is a trend globally towards investigating the use of hydrogen as an energy carrier, thus supporting the energy transition by adding storage and flexibility into the energy system [16] [17]. Global, European and national organisations have released reports and roadmaps on how to effectively integrate hydrogen in the current and future energy systems.

Production of green[11] hydrogen from offshore wind energy could play a key role in this transition. Especially in the Netherlands, with the vision of nearly 12 GW of offshore wind capacity by 2030 and with targets of up to 60GW in 2050 [7], the potential to produce green hydrogen is significant. To reach the 60 GW goal the energy conversion to hydrogen is seen as inevitable because the insufficient electricity transport capacity upgrade and due to the required flexible and reliable energy supply. Therefore many hydrogen related development activities are expected to start in the near future.

Many key players in the Dutch natural gas market are participating in projects and studies related to the role and use of hydrogen within their systems. Several initiatives have been already developed or proposed concerning production, storage, transmission and distribution of hydrogen [18] [19]. Additionally, it may have an important role as an energy carrier, as described in the study *TenneT and Gasunie infrastructure outlook 2050* [20].

As synergy among various stakeholders is needed, the Port of Den Helder potentially has a unique role, given its proximity to the developments in offshore wind described above, and to existing gas transport infrastructure (see Figure 8). The import and (or) local production of hydrogen could have a substantial positive impact on the activities in and around the Port of Den Helder.

The options for hydrogen related activities in Den Helder are:

1. Production of offshore blue[12] hydrogen from natural gas, and its transport to Den Helder using existing gas pipeline(s).
2. Production of offshore green hydrogen from offshore wind power plants, and its transport to Den Helder using existing gas pipeline(s).
3. Production of blue hydrogen onshore using natural gas from the North Sea, and pumping back CO_2 via existing gas infrastructure.
4. Production of green hydrogen onshore using electricity from offshore wind farms.

[11] Green hydrogen is obtained from renewable or “green” energy sources. Through electrolysis, water is divided into its constituents namely, hydrogen and oxygen.
[12] Blue hydrogen is produced from natural gas, usually via steam-reforming, with carbon capture storage (CCS). Blue hydrogen has the potential of large-scale, CO2-lean hydrogen production with proven, high TRL technologies

Figure 8 Existing gas transport pipelines near Den Helder [21]

Since this study focuses on offshore wind related activities, the following section looks at green hydrogen production using offshore wind as the energy source.

4.2 Offshore production of green hydrogen

Scenarios analysed by Gasunie and TenneT [20] indicate the necessity of hydrogen production near renewable energy supply units, thereby relieving the electrical grid, reducing onshore congestion and thus avoiding curtailment.

Offshore hydrogen production is seen as a viable option to extend the life of existing oil and gas (O&G) platforms which would otherwise be decommissioned. Figure 9 shows that close to half of the existing platforms are expected to be decommissioned before 2027, and the remainder after 2027.

The possibilities for offshore production of green hydrogen include

- retrofitting of electrolysers that produce hydrogen onto existing O&G platforms (which will otherwise be decommissioned);
- installation of electrolysers on energy island(s) where facilities required for the O&M of OWFs and infrastructure to export electricity to shore are additionally available [22]; (or)
- installation of electrolysers inside wind turbine support structures, creating the so called hydrogen wind turbine [23].

While all of these options include reuse of the existing gas pipeline infrastructure, the first option also reuses the existing O&G platforms in the North Sea [24] [25].

However, it is probably not realistic to expect that existing platforms can provide sufficient space for large scale green hydrogen production facilities. For alkaline electrolysers [16], the required space is around 90-100 m^2 per MW installed while for PEM electrolysers it is ~20 m^2 per MW installed [24] [26].

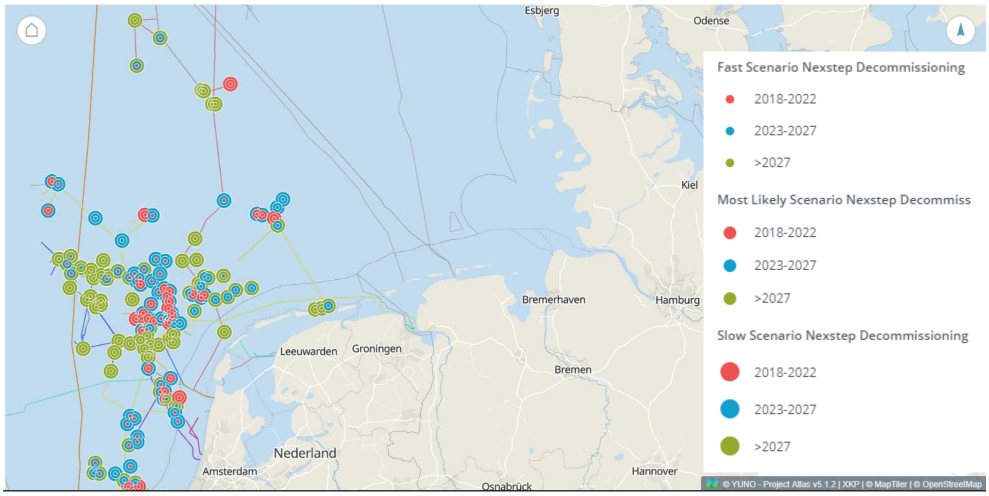

Figure 9 Decommissioning of oil and gas infrastructure over the next decades [11]

For example, assuming 500 MW from the planned IJmuiden Ver wind farm is used for hydrogen production, offshore hydrogen conversion using PEM electrolysers would require a 10,000 m^2 facility. Also, a PEM electrolyser weighs around 17 tons for a 1.25 MW system [27], making retrofits of existing platforms unfeasible.

In all three options i.e. offshore production on energy island, retrofit of existing platforms and hydrogen wind turbines, the hydrogen produced offshore may be transported through existing pipelines to the Port of Den Helder. The pipelines may be used as is or may be upgraded with composite linings inside the existing steel pipe. From Den Helder the hydrogen produced may undergo further treatment and transmission to the main Gasunie grid where it may be utilised stored.

4.3 Onshore production of green hydrogen

When large scale offshore hydrogen production is not feasible, another option is to build and operate onshore electrolysis plants in suitable locations such as Den Helder, with its current gas infrastructure. However to produce green hydrogen onshore, it would be necessary to transmit offshore wind electricity to shore. This would require a new large scale electricity connection between the OWFs and the Port of Den Helder. According to the infrastructure outlook study in 2050 by TenneT and GasUnie [20], there are presently no plans to strengthen the high voltage grid in the north of Noord-Holland to import offshore wind power into the grid. However technically it would be feasible to strengthen and expanding the high voltage grid to Den Helder.

Figure 10, Hydrogen grid, figure 2 from [20]

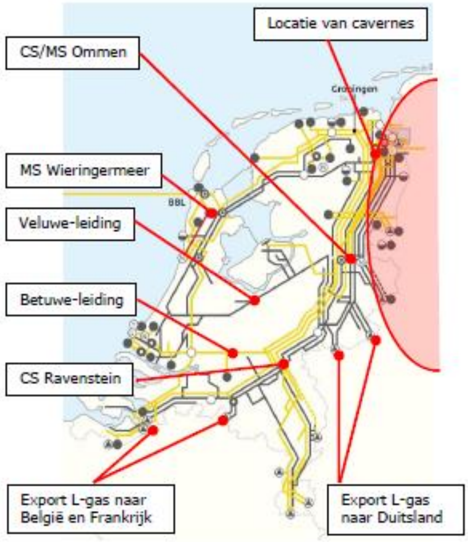

Figure 11 Gas infrastructure in Netherlands figure 9 from [28]

4.4 Transmission of hydrogen to Gasunie grid

To facilitate hydrogen import and/or production in Den Helder, improvements in transport infrastructure to the load centres and/or storage locations are necessary. A DNV-GL study on hydrogen infrastructure [28] describes how the present gas infrastructure could be used for hydrogen with the adjustment of some components such as compressors. However, the energy transport capacity of hydrogen would be significantly lower than that of natural gas[13] due to its lower energy density (approx. 30%).

The infrastructure outlook study in 2050 by TenneT and GasUnie [20], shows that Den Helder is in a strong position with regard to existing infrastructure, with grid nodes in Julianadorp (closest point) and connections to Wieringermeer, Beverwijk and Bergermeer, where Underground Gas Storage (UGS) already exists for seasonal gas storage (see Figure 10 and Figure 11).

4.5 Utilisation of Hydrogen in (Port of) Den Helder

The Port of Den Helder could potentially also use (part of) the produced and/or imported hydrogen in the harbour or in the city of Den Helder. Both the Netherlands Coastguard and the Royal Netherlands Navy have shown interest in reducing their CO_2 footprint by in powering part of their fleet with hydrogen. It is also conceivable that wind farm O&M vessels may be powered by hydrogen. The vessels powered by hydrogen fuel will require fuel cells to convert hydrogen back into electricity [29].

Other local options could be, for example, data centres at Wieringermeer, that have substantial energy requirement. Another example is hydrogen-powered public transport cars, facilitated by infrastructure for refuelling and compressed or cryogenic liquid hydrogen storage in the harbour, bearing in mind that larger

[13] 12 MJ/NM^3 for H_2 versus 35 MJ/NM^3 (NM^3 = Normal cubic meter) for Groningen NG, [28]

storage facilities would be required than at present due to the lower power density of hydrogen.

4.6 Impact and requirements for the Port of Den Helder

All potential activities related to hydrogen will have impact on the layout of the Port of Den Helder.

- **Offshore hydrogen production:** To support future offshore electrolyser plants, quayside space and storage to must be made available. Given the expectation that current oil and gas-related activities will be reduced and platforms decommissioned (as predicted in Figure 9), the conclusion is that the existing oil and gas facilities in the port are sufficient to support offshore electrolyser plants.
- **Hydrogen treatment:** For treatment of hydrogen before entering into the gas transport infrastructure of Gasunie, the gas treatment facility of NAM may be used. This is located just south of the harbour, and is connected to three pipelines that transport natural gas from the North Sea. With a capacity of 92 million m^3 of natural gas per day, approximately 10 billion m^3 of natural gas is processed here every year [30]. From Den Helder, NAM supplies the gas to Gasunie [31] via the blending station and compressor station located at Middenmeer (see Figure 11 and 12). The NAM gas treatment facility is capable of performing the hydrogen treatment required. Also it would be a large opportunity to extend the usage of the knowledge and permit space of the gas treatment facility.
- **Hydrogen production onshore** will have the largest footprint of all hydrogen-related activities at the Port of Den Helder, with the degree of impact depending on the chosen technology. For instance, a 1 GW wind farm with a capacity factor of 50% could produce more than 200 tons of hydrogen daily, or close to 80,000 tons annually. This could power more than 40,000 cars (5kg/car) per day, and could also be translated into vessel-related demand.

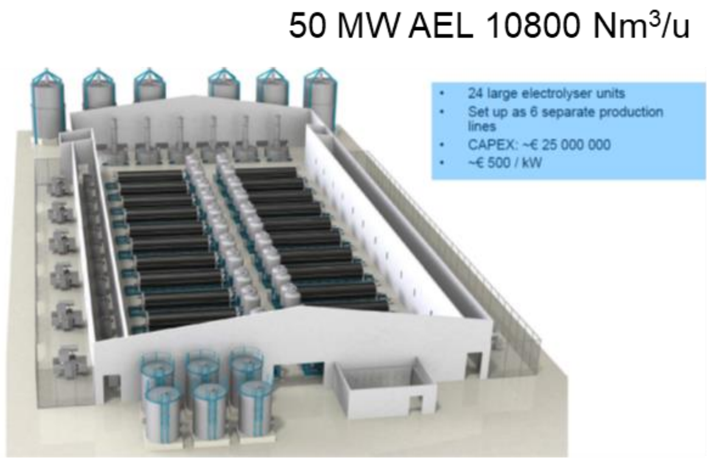

Figure 12 Footprint of a 50MW Alkaline electrolyser

Presently the NAM investigating the opportunity to produce blue hydrogen in Den Helder using natural gas from offshore production platforms, and storing the striped CO_2 from the reforming process[14]. Currently, the space near NAM facilities is

[14] It is also investigated whether it is possible to provide CO_2 to green houses in the Wieringermeer nearby.

sufficient for a first pilot, although for the next phase with a substantially higher capacity of production, a CO_2 return pipe line back to an O&G platform will be required. This could either be an existing natural gas pipeline or a new one.

Storage of hydrogen is crucial for the future as hydrogen is an energy carrier and should have possibilities to be stored or utilized on demand. At the Port of Den Helder, compressed hydrogen could be stored in hydrogen tanks to cover for demand in relation to various port activities. In the future cryogenic storage at minus 252 ºC may be an option.

Large scale storage could be an option at underground gas storage (UGS) facilities near Alkmaar and Bergermeer [32]. There are no current examples of hydrogen storage in natural gas UGS facilities, although no problems on tightness and hydraulic integrity were reported in past projects looking into hydrogenous town gas storage in porous formations. Salt caverns could also be used, the closest located in the province of Groningen. Finally, the transmission system and pipelines could provide a certain flexibility and storage capacity.

Hydrogen could bring up many new activities and job opportunities in the Den Helder area, since new markets will be created and existing ones (e.g. public transport) may transform towards hydrogen-related activities.

Finally, an important aspect that should be taken into account is safety. Hydrogen is a high caloric gas that would be treated in a massive scale, thus special consideration must be given to designing process in activities involving hydrogen.

Employment opportunities would be created by installation and O&M of future hydrogen electrolysis power plants and hydrogen storage facilities. Additionally, people would be also needed for the transformation of the gas treatment and transmission facilities, as well as the O&M of those facilities. Indirect employment opportunities would also be created by offshore hydrogen-related activities, if the production were to be done offshore instead of onshore.

Training, education and safety activities would be necessary to carry out the work required. The Port of Den Helder already offers opportunities for on- and offshore training and safety courses. Existing training facilities could be extended or new facilities built for hydrogen-related operations.

5 Seaweed activities

Another potential development from which the Port of Den Helder could benefit is the large-scale cultivation of seaweed. Technical designs for large-scale cultivation are available including 2-D substrate and automatic seeding, harvesting and transport to shore. Figure 13 is an example of seaweed farming on a 2-D substrate.

Figure 13 Example of seaweed farming with 2-D substrate

The main activities related to seaweed cultivation at port are to harvest, transport and store the seaweed before moving it to a processing facility. In the transport and storage phase, the Port of Den Helder could be used as a hub for the import and storage of wet seaweed before its dispatch to processing facilities further in land.

Wet seaweed comprises 12% dry seaweed matter, meaning that about eight tonnes of wet seaweed is required for each ton of dry matter [33]. It is estimated that 3 m^3 of storage volume is required by each ton of wet seaweed, translating to 25 m^3 per ton of dry matter [34].

From discussions with experts on seaweed and biomass from TNO, it is estimated that an area of 81 km by 81 km (or 6,561 km^2) can produce substrate seaweed of approximately 1 million tonne dry weight when cultivated in one layer.

If 1 GW of OWFs in the future are expected to support the growth of sea weed, the area of the wind farm can be calculated as 200 km^2 by assuming a wind farm power density of 5 MW/km^2 for the wind farm.

Assuming a usable area[15] of around 50% in the wind farm for seaweed farming, this gives an area of 100 km^2. This translates to more than 15,000 tonnes of dry seaweed, for which storage requirements are described in Table 31

Table 26 Storage requirements for dry weed at PoDH

Per GW of wind farm	
Tonnes of dry seaweed per GW of WF (t)	15,000
Storage need per tonne of dry seaweed (m^3)	25
Storage need for dry seaweed per GW WF(m^3)	**375,000**
Height of storage tank (m)	20
Area of storage tank (m^2)	18,750
Circular tanks of diameter 60 m	
Area covered by each tank(m^2)	2827
Number of tanks required	7
Storage area required for 6 tanks near port (m^2)	**16,962**

To store seaweed harvested from one GW of OWFs in cylindrical storage tanks, a footprint of approximately 170 m by 100 m is estimated. A supply chain is expected to develop, in which the seaweed is moved from storage tanks to production facilities that use the raw material to manufacture various products.

Seaweed farming is seen as a space intensive activity, hence the spatial requirement of 17,000 m^2 would be better placed away from the port of Den Helder, where the need for warehouse storage and logistics areas for offshore wind O&M activities may take precedence.

[15] Rough estimate, based on possible safety/clearance areas needed around wind turbines for movement of vessels etc. An earlier study by ECN [38] suggests there is a need for co-development of legal standards between policy makers and industry for producing seaweed in wind farms offshore.

6 Employment and education

For the Port of Den Helder to play an important role in the energy transition, it is necessary that the required work force is available. In July 2019, a report was published by TKI Wind op Zee on *Employment analysis of various fields of activities in the Dutch offshore wind sector* [14]. The important recommendations from this report on employment, education and training are:

- To facilitate additional research into studies that output a detailed competency overview required for offshore wind energy activities. Such an overview will increase the alignment between the education sector and the needs of industry.
- The offshore wind industry should develop a human capital plan, to absorb an influx of working professionals and students into the offshore energy sector.
- The alignment between industry and educational organisations should be increased so that relevant courses can be developed and supplied.

Den Helder is home to a number of qualified educational organisations that could support educational needs by providing excellent opportunities for training of future renewable energy employees in the offshore renewable energy industry. They are:

- The Engineering (Techniek) Campus,
- ROC Kop van Noord-Holland,
- Royal Netherlands Navy college and
- Den Helder Training Centre (DHTC)

The TKI study [14] reports that for the operation (management, planning and analysis) of a 1 GW wind farm consisting of 74 turbines, approximately 11 full time equivalent (FTE) employees are needed. For wind turbine maintenance, including structural inspection, approximately 30 FTE (0.48 FTE per wind turbine) are required. Besides this, it is expected that 15 more FTE are needed for operating O&M vessels such as SOVs. In all, for a 1 GW wind farm of 74 wind turbines, (each turbine rated at 13.5 MW[16]) approximately 60 FTE may be employed.

In this study we calculate that the work force for an OWF of 700 MW (TNW) will be around 60 FTE (Table 14), which is in line with the employment numbers from the TKI study. Table 27 shows expected employment numbers in the development periods from the baseline O&M scenario, assuming an overall installed capacity in 2050 of 45 GW and 60 GW (refer Table 7 and Table 8).

Table 27 Direct employment at Port of Den Helder in development periods 1, 2 and 3

Employment at PoDH	**Development Period < 2030**		**Development Period 2030- 2040**		**Development Period 2040- 2050**	
[FTE]	30%	50%	30%	50%	30%	50%
Baseline Scenario (Sensitivity 1); 45 GW until 2050	87	145	180	300	295	491
Baseline Scenario (Sensitivity 2); 60 GW until 2050	87	145	210	350	357	595

[16] average of 12 and 15 MW

In addition to the direct employment shown in Table 27, the total labour force depending on the offshore wind energy activities will be larger. Onshore activities, supporting the direct activities like e.g. maintenance and other supportive functions will be required.

7 Conclusion and recommendations

The main conclusion based on the analysis in this study is that the energy transition offers great opportunities for the Port of Den Helder and that:

- the Port of Den Helder is well positioned as an operations and maintenance (O&M) hub for future offshore wind farms (OWFs). The port's central location in relation to future offshore wind development and the availability of a fully equipped helicopter base are very strong advantages in Den Helder's value proposition. Another advantage is the presence of offshore maintenance supply chains at Den Helder;
- Studies indicate a possible increase in offshore wind capacity to 60 GW by 2050 in the Dutch Continental Shelf of the North Sea. OWF installations will grow at a rate of ~1 GW per year until 2030, when the total installed capacity is expected to be 11.5 GW. After 2030, studies predict a possible further growth rate of ~2 to 3 GW per year until 2050. The volume of O&M activities needed to support such a large number of wind farms will most likely not be handled by a single port. A combined effort by several specialised and well positioned ports is more likely to occur;
- this study confirms that the Port of Den Helder can potentially contribute to the O&M activities for OWFs in the northern part of the Dutch Continental Shelf and that it is also well positioned for some of the adjacent OWFs on the British Continental Shelf;
- O&M simulations indicate a significant growth in offshore wind related vessel movements at the Port of Den Helder. The number of SOV visits gradually increases to a maximum of ~550 annual movements by 2050, with an average of 1 to 2 SOV visits every day. Additionally, it is expected that nearshore wind farms such as Hollandse Kust Noord (HKN) could be maintained using SESs from the Port of Den Helder, with ~200 annual port visits. An increase in number of port visits of support vessels to ~1 per day is expected. Support vessels perform work related to the development and construction of OWFs such as seabed scans, core penetration tests, bathymetry investigations etc.
- The increase in port visits mentioned above do not account for vessel movements in other activities at the Port of Den Helder, such as
  - H_2 bunker services;
  - CO_2 capture-transportation and storage services;
  - Seaweed cultivation activities;
  - Ferry services to (and the maintenance of) a future offshore energy island. However, regular SOV movements at the port may reduce in this case as some OWF O&M activities will be performed at the offshore energy island.

It should be mentioned that these opportunities do not automatically lead to guaranteed success for the Port of Den Helder. It will be necessary for the Port of Den Helder to position itself as a strong partner to OWF operators and O&M service contractors to be successful in the offshore wind energy business. All offshore wind related service vessels require ISPS-certified quaysides with direct access to open waters, sufficient working space for logistic handling and sufficient storage space and warehouse facilities. The present port facilities allow for limited scale of offshore wind activities. In the Port of Den Helder's roadmap, future investments are identified for the development of additional quaysides and working space, to accommodate the predicted growth in infrastructure.

It is expected that existing oil & gas (O&G) activities will start declining in the North sea, while new offshore wind activities will soon begin. From 2023, most of the upcoming OWFs are planned in the proximity of the Port of Den Helder. A scenario in this study shows that the influence of distance between the port and wind farm is not very significant as compared to the total annual O&M cost. Port distance from the OWF will therefore not have a strong influence on the choice of the O&M port.

Quayside needs for offshore wind O&M
The movement of O&M vessels increase from one SOV every 3 to 4 days in 2030 to around two SOVs per day in 2050. In terms of quays needed for SOVs, up to one quay until 2030 would suffice. By 2050, this would have to increase to two quays due to the increase in SOV port calls. SESs and support vessels involved in OWF development and construction may also require up to two dedicated quays by 2050.

Warehouse for WT spares and logistic space requirement
Based on discussions with the Port of Den Helder and Royal HaskoningDHV, a consultant to the Port of Den Helder, the logistic space requirement includes spaces for a warehouse for small to medium wind turbine spare parts, office and crew facilities, walkways, parking spaces, access roads and onshore manoeuvring areas. This study estimates that approximately 1.3 ha of logistic space by 2030 is required at the Port of Den Helder. This requirement could increase to between 4.9 and 6.4 ha by 2050. This estimate is strongly influence by the number of wind farm operators and O&M contractors that operate OWFs from the Port of Den Helder and the cooperation between them with regard to sharing spare parts and equipment. It is recommended to have the warehouses for spare parts in the proximity of the quays used by SOVs.

Den Helder Airport
Den Helder Airport is a valuable asset to the Port of Den Helder. Wind farm operators that plan O&M using technician transport by helicopters will see a strong advantage in operating from Den Helder, owing to its proximity to the airport. Results show that when helicopters act an alternative access vessel, annual O&M costs are reduced. Using helicopters will also not reduce the number of port calls for SOVs. Other ports might have similar access to airports, e.g. airport Eelde for Groningen seaports-Eemshaven or Schiphol airport (or Den Helder Airport) for the Port of IJmuiden, but additional travel time needs to be accounted for. The effect of increased automation in the airport should be investigated.

Energy Island
The presence of one or more energy island(s) will inevitably change the way that OWFs are operated and maintained. It is to be expected that (some) warehouses and logistics spaces would be moved from the onshore ports to the energy island(s). In that case, the role of the harbour would shift from a logistics hub to a ferry harbour for personnel to and from the energy island(s). However, even when an energy island is used, it is expected that vessels such as SOVs would still use the harbour for e.g. bi-weekly crew transfer or refuelling (unless a (hydrogen) fuelling station is created at the energy island). Other business opportunities for ports are expected to arise such as the maintenance of facilities on and the provision of supplies to the energy island.

Innovations in automated shipping at moving towards *Port 4.0*
Conclusions on innovations and automation in ports are less obvious. This study shows that automated shipping and improved logistics may not have a large influence on yearly O&M costs. However a report from McKinsey [2] shows cost improvements of 25 to 55 % of the operating cost in the harbour, largely due to port automation and the application of *Port 4.0*.

In terms of infrastructure developments, automated systems providing connections between warehouses on quayside and O&M vessels are expected to require large capital investments, particularly on the software front, as data standardisation is seen as a potential challenge.

Hydrogen related activities
While the *Kop of Noord-Holland* will not be used to land electrical energy from offshore wind farms, the existing gas infrastructure such as transport pipelines to shore, treatment facilities and connections to the main gas transport grid, gives Den Helder a very strong position. The largest gas transport pipelines from the Dutch North Sea come to shore just south of Den Helder. The gas treatment plant of NAM between the sea harbour and the Kooyhaven, is the largest gas treatment facility around the North Sea. Hydrogen production could also happen offshore on refurbished, otherwise decommissioned, oil and gas production platforms, or on future energy islands in the North Sea (to be built after 2030), or indeed onshore at new conversion facilities in the Den Helder area.

Fuelling installations for hydrogen as a marine fuel should be installed in the harbour, not only for the offshore wind farm vessels, but also for the Netherlands Coastguard and the Royal Netherlands Navy. (Underground) hydrogen storage may be necessary to enable fast refuelling, e.g. 100 tons in 1 hour[17]. The storage space should be capable of storing in the order of a hundred ton of hydrogen in order to refuel several vessels per week

Maritime biomass – Seaweed
If future offshore wind farms (built after 2023) include facilities for seaweed harvesting, the Port of Den Helder also has an excellent position to transport the wet biomass to a facility onshore for further processing for the food and/or bio-energy industry. Quayside requirements for biomass transportation vessels at this location should be investigated.

Employment
The offshore wind energy activities will lead to a substantial demand in work force. In the period till 2030 this could grow to 145 FTEs directly involved in the operations and maintenance of offshore wind farms. The work force could grow till 2050 to 500 – 600 FTEs depending on the total number of wind farms supported from the Port of Den Helder, see Table 27. Additionally there will be a substantial work force required onshore to support the offshore activities.

Challenges
As mentioned above the advantages of location and *Port 4.0* innovations have a relatively small influence on the total cost for operating an offshore wind farm. This

[17] The assumption is that 1 SOV will use 4 tons of diesel a day and is refuelled every 14 days.

means that the Port of Den Helder should also be *"the Port to be"* based on other qualifications, like good organisation, sound regulations and easy/fast procedures to set up wind farm service centres.

The lack of standardisation in implementing automated systems and integration of systems is a danger for being a front runner in port automation.

Due to the fact that the installation of wind farms is done from other harbours on the Dutch coast, the choice for Port of Den Helder as O&M hub may not be obvious.

Further investigations

- In the transition from oil & gas to renewables, the decrease in activities for oil & gas may be slower than the increase in activities for offshore wind. This can lead to substantial growth in activities in the near future and needs to be studied in more detail.
- Changes to layout of the port in terms of possible new locations for additional quaysides and warehouses needs to be investigated
- The effect of an energy island after 2030 and 2040 on the usage of the Port of Den Helder could be substantial. Especially if vessels use hydrogen as a fuel with a fuelling station on the energy island, it is unsure how many port calls the vessels will make at the Port of Den Helder.
- In terms of fuelling infrastructure, the coast guard plans to renew their fleet in a couple of years with hydrogen while other vessels still use marine diesel, the fuelling requirements of various offshore stakeholders in the future needs to be studied.
- Data standardisation at ports which will be part of technologies that attempt to automate current processes and move towards *Port 4.0* should be investigated.

8 Bibliography

[1] *Port of Den Helder; Routekaart,* Port of Den Helder, 2017.

[2] C. Fox, S. Gailus, L. Liu and L. Ni, “The future of automated ports,” McKinsey and Co, 2018.

[3] “Ambitiedocument Duurzaamheid – Port of Den Helder,” Port of Den Helder, Den Helder, 2019.

[4] P. o. D. H. Seaport, “Brochure port of Den Helder,” Den Helder.

[5] “Wind energy in Europe:Scenarios for 2030,” Wind Europe, 2017.

[6] E. Wiebes, “Offshore Wind Energy Roadmap 2030,” Minister of Economic Affairs and Climate Policy, The Hague.

[7] J. Matthijsen, E. Dammers and H. Elzenga, “The future of the North Sea: The North Sea in 2030 and 2050: a scenario study,” PBL Netherlands Environmental Assessment Agency, The Hague, 2018.

[8] “Energy Agenda: Towards a low-carbon energy supply,” Ministry of Economic Affairs, Netherlands.

[9] M. Asgarpour and R. van de Pieterman, “O&M Cost Reduction of Offshore wind farms - A novel case study,” ECN, Petten, 2014.

[10] “VGB PowerTech: “Guideline Reference Designation System for Power Plants, RDS-PP; Application Explanations for Wind Power Plants,” VGB 116 D2, 2007.

[11] “Offshore Wind Energy,” RVo, 2019. [Online]. Available: https://english.rvo.nl/subsidies-programmes/offshore-wind-energy.

[12] “Policy Document on the North Sea 2016-2021,” Netheralnds ENterprise Agency.

[13] B. Hu, H. Stumpf and W. v. d. Deijl, “Offshore Wind Access 2019,” ECN part of TNO, Petten, 2019.

[14] E. Knol and E. Coolen, “Employment analysis (2019-2023) of various fields of activities in the Dutch offshore wind sector,” TKI Wind op Zee, July 2019.

[15] “Ørsted Starts Building Borssele O&M Base,” Offshore wind biz, 13 December 2018. [Online]. Available: https://www.offshorewind.biz/2018/12/13/orsted-starts-building-borssele-om-base/.

[16] F. Birol, “The Future of Hydrogen,” IEA, 2019. [Online]. Available: https://www.iea.org/hydrogen2019/.

[17] “Hydrogen Roadmap Europe,” FC:H: Fuel Cells and Hydrogen, Luxembourg, January 2019.

[18] “Waterstofprojecten,” Gasunie, [Online]. Available: https://www.gasunie.nl/expertise/thema-waterstof/waterstofprojecten.

[19] “Power2Gas: Elektriciteit omzetten in waterstof,” Stedin, [Online]. Available: https://www.stedin.net/over-stedin/duurzaamheid-en-innovaties/een-nieuw-energiesysteem/power2gas.

[20] "Infrastructure Outlook 2050: A joint study by Gasunie and TenneT on integrated energy infrastructure in the Netherlands and Germany," Gasunie, TenneT.

[21] "North Sea Energy Atlas," 2019. [Online]. Available: https://www.north-sea-energy.eu/atlas.html.

[22] "Roadmap for development of offshore grid in 2024-2030 period," TenneT, 27 03 2018. [Online]. Available: https://www.tennet.eu/news/detail/roadmap-for-development-of-offshore-grid-in-2024-2030-period/.

[23] "Werking waterstofmolen," Hygro, [Online]. Available: https://hy-gro.net/nl/werking-van-de-waterstofmolen.

[24] C. J. Jepma, "Towards sustainable energy production on the North Sea - Green hydrogen production and CO2 storage: onshore or offshore?," 2018.

[25] "De eerste waterstofmolen voor duurzame brandstof komt in Nederland," Lagerwey, 18 October 2017. [Online]. Available: https://www.lagerweywind.nl/blog/2017/10/18/eerste-waterstofmolen-duurzame-brandstof-komt-nederland/.

[26] "Hydrogenics: Enabling a utility scale renewable hydrogen solution, with the smallest footprint," [Online]. Available: www.hydrogenics.com/wp-content/uploads/HyLYZER_600_3MW.pdf?hsCtaTracking=5a6d839a-3849-47c9-93b7-193092745c35%7Ca663eb3d-ad8f-479d-bb67-512aaf6fe906.

[27] "SILYZER 200 High-pressure efficiency in the megawatt range," [Online]. Available: https://assets.new.siemens.com/siemens/assets/public.1524044774.8063d38e3aca74d2a0bcc307fcef435ced002103.silyzer200-broschure-en.pdf.

[28] A. v. d. Noort, "Verkenning waterstofinfrastructuur," DNV GL, November 2017.

[29] "Fuel Cell Applications for Marine Vessels: Why Fuel cells make sense," Ballard.

[30] "NAM: Locaties en activiteiten," [Online]. Available: https://www.nam.nl/gas-en-oliewinning/locaties-en-activiteiten.html#iframe=L21hcHMvZGVmYXVsdC8.

[31] "The transmission network," Gasunie transport services, [Online]. Available: https://www.gasunietransportservices.nl/en/network-operations/the-transmission-network.

[32] "The effects of hydrogen injection in natural gas networks for the Dutch underground storages," Ministry of Economic Affairs, 2017.

[33] S. W. K. van den Burg, A. P. van Duijn, H. Bartelings, M. M. van Krimpen and M. Poelman, "The economic feasibility of seaweed production in the North Sea," Aquaculture Economics & Management, 2016.

[34] A. Wortel, W. Huijgen and J. van Hal, "Storing and refining seaweed," ECN, 2014.

[35] W. Veenstra, "Royal Netherlands Navy's Future Fleet Capabilities: A Continuation of Rational Thinking," NETHERLANDS DEFENCE ACADEMY, Breda, 2016.

[36] "Unmanned autonomous (aerial) vehicles for maritime applications," Maritime Knowledge Centre, NLDA, TNO and TU Delft, 2019.

[37] M. d. Jong, *Memo M&ABZ1111N001F01,Offshore wind @ Port of Den Helder,* Royal HasKoning , 2018.

[38] F. Groenendijk, “North-Sea-Weed-Chain: Sustainable seaweed from the North Sea; an exploration of the value chain,” ECN, Petten, 2016.

[39] “Esvagt Njord arrives in North Sea ahead of Christening,” 4c offshore, 16 September 2016. [Online]. Available: https://www.4coffshore.com/windfarms/esvagt-njord-arrives-in-great-yarmouth-ahead-of-christening-nid4461.html.

9 Signature

Petten, 31st of July 2019

M. Langelaar

Head of department

ECN part of TNO

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A Workshops with project partners

During the course of the project, several workshops and discussions were held between TNO and the project stakeholders including the Royal Netherlands Navy, CHC Helicopters, Netherlands Coastguard, Den Helder Support Service (DHSS) and Peterson. The workshops were held to discuss and identify future innovations that would complement the infrastructure needs at the Port of Den Helder. The main issues foreseen by each stakeholder are as follows:

CHC Helicopters

- Helicopters are very efficient in transportation of workforce to and from offshore work locations. Main advantages are longer hands on tools time and living onshore of the work force.
- Helicopters have a wider operating window than walk to work vessels; they can transfer passengers in higher sea state, thus increasing availability. The impact of using helicopters on O&M costs is discussed in section 2.5.3
- Hydrogen or electric power is not likely to be a helicopter's energy source in near future. Usage of biofuels might be possible to reduce the CO_2 footprint in the future.
- Den Helder Airport can be a commuter airport when the workforce lives in UK or Denmark.

Den Helder Support Service (DHSS)

- It is an option to free up one of the 3 existing gas pipelines to CCK Den Helder and use the existing gap pipeline infrastructure to tie-in and transport hydrogen.
- It is expected that offshore wind O&M will be performed directly from port or from small and large O&M hotel islands.
- Autonomous sailing / mooring and logistics of supplies are envisioned in the future. This may reduce harbour time, which for larger vessels is at present 5 to 8 hrs.
- Supply of replacement blades, just-in-time, by roll-on roll-off vessels or to jack up locations offshore.
- Green hydrogen could be fuel for SOVs. The effect on bunkering time is unknown, but at present bunkering occurs at up to 70 tons/hr.

Royal Netherlands Navy

- Hydrogen fuelling infrastructure is foreseen for the Navy's new fleet of vessels, with possible fuelling stations at Kooyhaven. However, for larger vessels with longer ranges in the future, marine diesel is seen as an option for fuel with alternatives of methanol and ammonia, rather than hydrogen.
- Innovation in remote data diagnostics is seen after 2024. For this, the introduction of unmanned vehicles is expected, as well as centralisation in intelligence support with new types of contracts between the ministry of defence (MoD) and the industry [35].
- Knowledge sharing and training of personnel is also seen as an important activity for the Navy, to be achieved by developing links with technical universities and applied science universities.

Netherlands Coastguard

- The coastguard is experiencing a large upscaling of activities planned due to offshore wind development. Coastguard staff will be expanded in the coming period from 55 to 70, and later to 90 persons.
- The forecast is that there will be fewer operational oil and gas platforms, but the reduction will be compensated by the increasing number of offshore wind farms.

These activities mean that the current vessel fleet of the coastguard will be replaced in the near future:

- An emergency towing vessel (ETV) is always available for the coastguard and is stationed at the Port of Den Helder. The ETV is on a ten year lease. Due to the increase in offshore wind activities, the coverage area for this ETV will be insufficient.
- There are two standby patrol vessels; one is currently stationed at the Port of Den Helder. The age of these vessels is greater than 20 years, and they will be replaced.
- In the future, a large patrol vessel (Length overall > 80 m) is expected to be permanently on coastguard duty. There are also discussion about additional new vessels. These new vessels could potentially be fuelled by hydrogen at fuelling stations similar to those required by the Navy.
- In terms of future innovations, drones are foreseen on all coastguard vessels, along with autonomous sailing. Also, innovations in longer use-cycles for autonomous vessels including ASVs (Autonomous Surface Vessels) and AUVs (Autonomous Underwater Vessels) is foreseen [36].

Peterson

Peterson has combined many of their operations on the North Sea in the Port of Den Helder since 2010. In the past Peterson had several operational hubs in several harbours in The Netherlands. For efficiency reasons Peterson centralised the operations and warehouses in the Port of Den Helder resulting in a state of the art logistics and supply hub. Peterson is mainly active in Oil & Gas industry but is also involved in offshore supply operations for offshore wind farms from Port of Den Helder for UK wind farms.

The technological improvements in logistics and maintenance support for O&G will be crucial in the support for the offshore wind energy support activities. The efficiency steps include sharing of logistic services, warehouses as well as supply ships.

Petersons expectations are that the O&G activities will continue, depending on the price of oil and gas, and that wind activities will benefiting from the supply and logistics “infrastructure” that is present in and around the Port of Den Helder.

Improvements of the logistics and supply technology, including Port 4.0 innovations, will stay and be important to keep Port of Den Helder attractive for offshore wind related activities.

B Optimisation of O&M Strategy (an example)

This section describes an example of optimising an O&M strategy. The chosen wind farm is the relatively nearshore Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN). The control variables for the optimisation are the number and type of vessels and number of technicians.

An initial estimate is made for the O&M strategy for the 700 MW wind farm which will be located around 45 km from Den Helder. First, a single CTV, with 20 technicians is chosen for performing O&M from Port of Den Helder. The O&M key performance indicators (KPIs) for this initial choice is in Table 28 below.

Table 28 O&M KPIs for Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN) with a single CTV and 20 technicians

Strategy	**1 CTV, 20 technicians**
Availability (% time, % yield)	92.7 92.1
Repair costs (M€/year)	35.3
Revenue losses (M€/year)	16.9
Total effort (M€/year)	**52.1**
O&M Cost of energy (€/MWh)	1.27

The wind farm availability (time based and yield based) in this case is ~93%. A breakdown of the downtime shows that a large contribution to this is downtime due to the impact of bad weather on the transportation vessels (~32%) (See Figure 14). This is a result of the CTV’s relatively low wave height threshold of 1.5 m, leading to low accessibility.

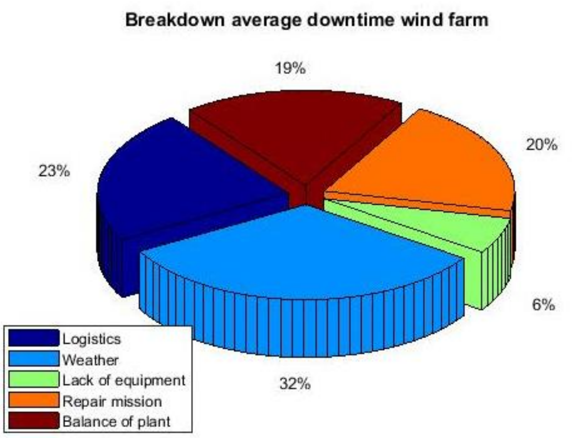

Figure 14 Downtime breakdown for Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN) with a single CTV and 20 technicians

To reduce this downtime due to bad weather, a more expensive SES with a wave height threshold of 2.0 m is modelled. With the SES, the time based availability of the wind farm increases to 94.1%, and the total annual O&M effort reduces to 48.60 M€ (See Table 29).

Table 29 O&M KPIs for Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN) with a single SES and 20 technicians

Strategy	**1 SES, 20 technicians**
Availability (% time, % yield)	94.1 93.7
Repair costs (M€/year)	35.2
Revenue losses (M€/year)	13.4
Total effort (M€/year)	**48.6**
O&M Cost of energy (€/MWh)	1.24

For this case, a breakdown of the downtime shows that although the downtime due to bad weather has decreased, the downtime due to lack of equipment contributes to about 4% (See Figure 15).

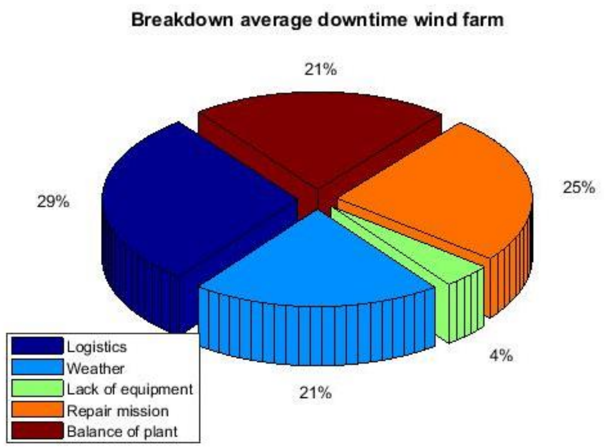

Figure 15 Downtime breakdown for Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN) with a single SES and 20 technicians

In order to reduce this, the number of SESs is increased to 2. Table 30 shows the simulation results for this case.

Table 30 O&M KPIs for Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN) with a single SES and 20 technicians.

Strategy	**2 SES, 20 technicians**
Availability (% time, % yield)	94.1 93.8
Repair costs (M€/year)	38.2
Revenue losses (M€/year)	13.2
Total effort (M€/year)	**51.4**
Cost of energy (€/MWh)	1.25

There is hardly an increase in wind farm availability. An analysis of the downtime shows that the contribution of downtime due to lack of equipment and technicians are now both insignificant (< 1%) (See Figure 16). However, the cost of an additional SES adds to repair costs and the total annual O&M effort are higher in the case with two SES.

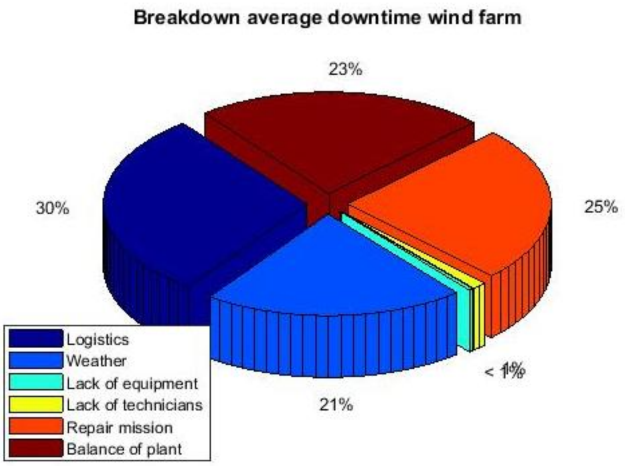

Figure 16 Downtime breakdown for Hollandse Kust (Noord) Wind Farm Zone, Site V (HKN) with two SESs and 20 technicians

Comparing the results of the three cases, the option with the lowest total effort and cost of energy is with the use of a single SES and 20 technicians (See Table 31).

Table 31 O&M KPIs for optimisation cases of Hollandse Kust (Noord) Wind Farm Zone, (HKN).

Strategy	**1 CTV, 20 techs**	**1 SES, 20 techs**	**2 SES, 20 techs**
Availability (% time, % yield)	92.7/92.1	94.1/93.7	94.1/93.8
Repair costs (M€/year)	35.3	35.2	38.2
Revenue losses (M€/year)	16.9	13.5	13.2
Total effort (M€/year)	52.1	**48.6**	51.5
Cost of energy (€/MWh)	1.27	1.24	1.25

Results for optimisation for the other OWFs considered in the reference scenario are in Table 32 and Table 33.

Table 32 O&M KPIs for optimisation cases of Wind Farm Zone Hollandse Kust (West) (HKW).

Strategy	**2 SOV, 50 techs**	**2 SOV, 45 techs**	**3 SOV, 45 techs**
Availability (% time, % yield)	93.3/93.0	94.0/93.3	94.5/94.2
Repair costs (M€/year)	84.6	83.7	111.9
Revenue losses (M€/year)	28.6	27.0	23.4
Total effort (M€/year)	113.2	**110.7**	135.4
Cost of energy (€/MWh)	1.58	1.56	2.06

Table 33 O&M KPIs for optimisation cases of Ten Noorden van de Waddeneilanden (TNW)

Strategy	**1 SOV, 45 techs**	**1 SOV, 36 techs**	**1 SOV, 30 techs**
Availability (% time, % yield)	95.2/95.0	95.4/95.2	95.2/95.1
Repair costs (M€/year)	55.6	52.7	51.3
Revenue losses (M€/year)	11.2	10.6	10.9
Total effort (M€/year)	66.8	63.3	**62.2**
Cost of energy (€/MWh)	1.84	1.74	1.69

Similar optimisation cases are performed for all the scenarios described in sections 3.2 to 3.5.

C RDS-PP taxonomy code

Turbine system breakdown

- MDA10 - Rotor system – blades
- MDA20 - Rotor system – Hub
- MDC - Blade adjustment
- MDK10 - Drive train - main shaft/bearing
- MDK30 - Drive train - brake system
- MDL - Yaw gearbox
- MDX - Hydraulic system
- MDY - Control and protection system turbine
- MKA - Generator
- MKY - Control and protection system generator
- MSA - Generator lead / transmission cables
- MST – Transformer
- MUD - Machinery enclosure
- UMD - Turbine structure / tower
- XA - Heating, ventilation, air conditioning
- XM - Crane system
- AB - Lightning protection / grounding
- MD - Remote Resets

Balance of Plant system breakdown

- Transformer
- Foundation/ Scour protection
- Cables within wind farm

D Fault type classes of all scenarios

Table 34, Table 35 and Table 36 shows the definition of generic fault type classes and their assignment to certain systems of the wind turbine and balance of plant.

Table 34 Unplanned corrective fault type classes

Fault type class ID	**Maintenance category**	**Description**	**BOP system**	**WT system**
FTC1	Remote reset (only downtime, no visit)	no crew, Repair = 2 hr, no costs	Transformer	MD
FTC2	Inspection and small repair inside	small crew, Repair = 4 hr, consumables	Transformer	AB, MDA10, MDA20, MDC, MDK10, MDK30, MDL, MDX, MDY, MKA, MKY, MSA, MST, MUD, UMD, XA, XM
FTC3	Inspection and small repair outside	small crew, Repair = 8 hr, consumables	Foundation	MDA10
FTC4	Replacement small parts (< 2 MT) internal crane	small crew, Repair = 8 hr, low costs	Cables	MDA10, MDA20, MDK10, MDX, MDY, MSA, MUD, UMD, XA, XM
FTC5	Replacement small parts (< 2 MT) internal crane	small crew, Repair = 16 hr, low costs		MKY, MST
FTC6	Replacement small parts (< 2 MT) internal crane	large crew, Repair = 16 hr, medium costs		MDA10, MDA20, MDC, MDK10, MDK30, MKA
FTC7	Replacement small parts (< 2 MT) internal crane	large crew, Repair = 24 hr, medium costs		UMD
FTC8	Replacement small parts (< 2 MT) internal crane	large crew, Repair = 24 hr, high costs		MKY, MST
FTC11	Replacement large parts (< 100 MT) large external crane	large crew, Repair = 24 hr, medium/high costs		MDC, MDK10
FTC12	Replacement large parts (< 100 MT) large external crane	large crew, Repair = 40 hr, medium/high costs		MDA20, MDL
FTC13	Replacement large parts (< 100 MT)	large crew, Repair = 40 hr, very high costs		MDA10, MKY, UMD

	large external crane			

Table 35 Condition maintenance fault type classes

Fault type class ID	Maintenance category	Description	BOP system	WT system
FTC9	Remote reset (only downtime, no visit)	no crew, Repair = 2 hr, no costs	Transformer	MD
FTC10	Preventive replacement small parts (< 2 MT) internal crane	large crew, Repair = 16 hr, medium costs		MDL

Table 36 Calendar-based fault type classes

Fault type class ID	Description	BOP system	WT system
FTC1	Remote reset	Transformer	Transformer
	Regular maintenance		MD
	Large WT maintenance		MD

E Repair classes of baseline scenario

This appendix gives an overview of the type of maintenance and time interval per repair class (Table), followed by the maintenance phases per RPC ().

Table 37 Repair classes (RPC) for baseline scenario

Generic name	**Type of maintenance (ucm[18], cbm[19], cal[20])**	**Time interval**
Remote reset	ucm	
4h Inspection/small repair inside	ucm	
8h Inspection/small repair outside	ucm	
8h Replacement parts (< 2MT)	ucm	
16h Replacement parts (< 2MT)	ucm	
24h Replacement parts (< 2 MT)	ucm	
24h Replacement parts (< 100 MT)	ucm	
40h Replacement parts (< 100 MT)	ucm	
4h BOP transformer repair	ucm	
48h BOP transformer repair	ucm	
8h BOP Foundation/scour protection	ucm	
32h BOP cable replacement	ucm	
8h Replacement pitch motors (<2 MT)	cbm	5 years
16h Replacement yaw motors (<2 MT)	cbm	5 years
42h (for entire wind farm) BOP preventive maintenance	cbm	2 years
24h WT preventive maintenance	cal	1 years
48h WT preventive maintenance	cal	5 years[21]
60h Transformer preventive maintenance	cal	1 year

[18] Unplanned corrective maintenance
[19] Condition based maintenance
[20] Calendar based maintenance
[21] replacing 24h WT maintenance for the years that 48h preventive maintenance is planned

F Vessel information

Table 38 Specifications of the crew transfer vessel

Crew transfer vessel CTV	
Specification	**Value**
Significant wave height Hs max at transfer	1.5 m
Max wind speed V max at transfer	12 m/s
Travel time to turbine	Depending on distance from port to WF
Maximum nr of technicians	12
Mobilisation time	0 h
Maximum weight payload	2000 kg
Day rate Cost[22]	3000€
Mob + demob costs	0
Vessel draught	2m

Table 39 Specifications of the surface effect ship

Surface effect ship SES	
Specification	**Value**
Hs max at transfer	2 m
V max at transfer	12 m/s
Travel time to turbine	Depending on distance from port to WF
Maximum crew size	12
Mobilisation time	0 h
Maximum weight load	3000 kg
Day rate Cost	7500€
Mob + demob costs	0

Table 40 Specifications of the service operation vessel

Service operation vessel (with access gangway & daughter crafts)	
Specification	**Value**
Hs max at transfer	3.5 m
V max at transfer	17 m/s
Travel time to turbine	Depending on distance between turbines in WF
Maximum crew size	40[23]
Mobilisation time	0 h
Maximum weight load	20000 kg
Day rate Cost	50000€ (converted to annual yearly cost)
Mob + demob costs	0
Vessel draught	5m
Length overall (L.O.A)	80m
Example of vessel	Esvagt Njord

[22] Current day rate estimate. Inflation rate of 2.5% per annum is used to calculate day rates in the future development periods
[23] Technician capacity reference link [39]

Table 41 Specifications of the O&M jack-up vessel

Jack-up vessel		
Specification	**Value**	**Remarks**
Hs max at transfer	2.0 m (positioning)	Average wave height limit
V max at transfer	10 m/s (hoisting)	This limit refers to the maximum allowed wind speed for technicians working in the turbine and refers to wind speed at hub height.
Travel time	Depends on port to WF distance	Based on a transit speed of 8 knots.
Mobilisation time	720 h	*Estimate* Depends heavily on market condition *Assumption* Travel time included in mobilisation time
Day rate	100 k€/day	*Estimate* Depends heavily on market condition
Mob + demob costs	350 k€/mob	*Estimate* Depends heavily on market condition
Vessel draught	6.5m	
Cost during travel	-	Included in Mob + demob cost

Table 42 Specifications of the cable laying vessel

Cable laying vessel		
Specification	**Value**	**Remarks**
Hs max	1.5 m	*Estimate* Only relevant when laying cables
V max	Not relevant	Modelled as 25 m/s
Travel time	Depends on port to WF distance	Based on a transit speed of 12 knots.
Mobilisation time	720 h	*Estimate* Depends heavily on market conditions
Day rate	75 k€/day	*Estimate* Depends heavily on market conditions. Waiting cost is 75% of working cost
Mob/demob costs	450 k€/mob	*Estimate* Depends heavily on market conditions
Vessel draught	6m	
Cost during travel	75 k€/day	Based on the assumption that in total one day of travel is needed; travel costs equal the day rate

Table 43 Specifications of the diving support vessel

Diving support vessel		
Specification	**Value**	**Remarks**
Hs max	2.0 m	*Estimate ; biggest driver is current: only at dead tide = like 4 hrs/day at change of tide*
V max	Not relevant	Modelled as 25 m/s
Travel time (one way)	Depends on port to WF distance	Based on a transit speed of 16 knots.
Mobilisation time	360 h	*Estimate* Depends heavily on market conditions
Day rate	75 k€/day	*Estimate* Depends heavily on market conditions (Waiting cost is 75% of working cost)
Mob/demob costs	150 k€/mob	*Estimate* Depends on market conditions

Table 44 Specifications of the helicopter

Helicopter		
Specification	**Value**	**Remarks**
Hs max at transfer	10.0 m	No wave height limit for helicopter access
V max at transfer	20 m/s	Access can be performed up to 20 m/s, however for work in the nacelle, the limit is 12 m/s. For access to BOP components the limit is 20 m/s.
Maximum crew size	8	
Mobilisation time	8 h	*Estimate* Depends on market conditions
Mob/demob costs	6 k€/mob	*Estimate* Depends on market conditions
Cost during travel	6 k€/trip	*Estimate* (one time back and forth, including fuel costs)

Table 45 Specifications of the ferry vessel

Ferry vessel		
Specification	**Value**	**Remarks**
Hs max	3.5 m	*Estimate*
V max	Not relevant	Ferry transfers crew to the energy island, hence wind speed during transfer is not relevant
Maximum crew size	60	*Estimate*
Day rate	10 k€/day	*Estimate* Depends on market condition
Length overall (L.O.A)	30m	*Estimate*