Vessel Supply Train Den Helder

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Summary

A new logistical concept, called ship to ship supply, that could improve the availability of Service Operation Vessels (SOV) in offshore wind farms is investigated. By supplying the SOV's at sea with supply vessels instead of sailing them back to port every 14 days, their workability is increased, reducing the wind farm's downtime, and increasing power production.

This report answers the main research question: is it possible to increase the yield and reduce the Operation & Maintenance costs of offshore wind farms by applying ship-to-ship supply of SOV's, following fixed schedules?

Secondary research questions are: what does the “Service Operations Vessel 2.0” need to be capable of” and “what are the possibilities for autonomous sailing of the supply vessels as a result of fixed timetable/ fixed route approach and what possibilities are opened up by combining more than one supply vessel through platooning?”

A consortium, with representatives from municipalities, private enterprises and governmental institutes developed scenarios to describe the existing state of the art, the ship-to-ship supply setup and variations of the ship-to-ship scenario using automation and drones for several logistical streams. The Port of Den Helder is chosen as the base port. Supply vessels will service two SOV's per supply run, representing a wind farm size that would have one owner.

During the initial workshop of the consortium, it became clear that the concept of platooning was not deemed beneficial for offshore application, as vessels could sail directly to their destinations in straight lines. This part of the study was therefore abandoned.

The scenarios were simulated using TNO's in-house developed software UWiSE, a discrete event based logistic simulation engine. The resulting costs for vessels, operations and personnel, and the yield availability of the serviced wind farms are analysed. The latter is directly correlated to the revenues of a wind farm, giving the possibility to determine the impact on the total project costs.

The evaluation of the baseline scenario and the basic ship-to-ship supply scenario show that the new logistical concept has a positive impact on both the yield availability of wind farms and the total project costs. While increasing the yield availability with 0.6%, the total costs of a project were reduced with 2.2%, or 24.3 million Euros annually.

Sensitivity analyses showed that the results remained positive towards the ship-to-ship supply concept for varying electricity sales prices, vessel costs and in different seasons. They also showed that the benefits increase if a larger number of SOV's is serviced by a supply vessel.

An economic analysis was done by the University of Antwerp to assess the potential benefits of automating the supply vessels. The method is generalised and used to evaluate the case study around the Port of Den Helder. It was found that autonomous vessels become favourable over conventional vessels if six or more

SOV's are serviced per supply vessel trip. Remote controlled vessels were not found to be economically attractive for this case study.

The application of drones further increases the benefits of the ship-to-ship supply concept. By using drones to take care of on-demand spare part shipments, delivering packages to oil/gas platforms and inspection of external parts of wind turbines the wind farm yield availability increased with 1.1%, while the costs were reduced by 10%.

The Dutch government has stated the ambition to have 70GW of offshore wind power installed in 2050. A projection is done towards the situation in 2050, using the ship-to-ship supply concept and the drone applications. Automation of supply vessels was not accounted for, since its impact could not be scaled like the other applications, due to the requirement of six SOV's to be serviced per supply run.

For the situation in 2050 the application of ship-to-ship supply of SOV's and drones could result in a 1%-increase in wind farm availability, while the total project costs are reduced with almost 12%.

The evaluated scenarios show that in the future SOV's should be equipped with ship-to-ship supply facilities, both for cargo and personnel. They should also be outfitted with one or more daughter craft, airborne drones and unmanned surface vessels.

The impact of port automation was assessed by the university of Antwerp by evaluating a case study around the port of Den Helder. The performance of conventional vessels is compared with that of automated vessels and road transport, to determine the most economic option for the expected cargo flow for Operations and Maintenance of offshore wind farms. Multiple vessel classes were assessed, as well as two different sailing regimes. The smallest conventional vessel is found to be the most economical solution, due to the relatively low cargo flow and the short distance between the logistical hub and the seaport. Furthermore, automation of the terminal does show promising results.

To provide the Port of Den Helder with guidelines for promising port infrastructure to support offshore wind O&M activities, an exploration was done by Royal Haskoning DHV. The trends show that in the future there will be a large need for shore power due to the electrification of various equipment and vessels. Concepts that could be beneficial are automated handling, remote pilotage, and automated mooring systems. If there is synergy with other industries, a roll-on-roll-off ramp could have a positive effect, despite the large investment costs.

Glossary

Terminology	Explanation
General setup	The input added on top of the model foundation to make it project specific but will be consistent in every evaluated scenario of this study, if not mentioned otherwise.
Maritime partners	Vroon, DHSS and Peterson, participants in the research consortium
Model foundation	A default input for the model that is used by TNO in O&M modelling. This default input contains: Subsystems of wind turbines, failure modes, corrective maintenance actions, scheduled maintenance actions, vessels, etc.
Yield availability	The energy produced by the wind farm relative to the hypothetical maximum amount of energy produced if the wind turbines would have no down time.

Abbreviation	Explanation
CTV	Crew transfer vessel
FCS	Fast crew supplier
LOA	Length overall (maximum ship length)
O&M	Operations and maintenance
OPEX	Operating expenses
S2SS	Ship to ship supply
SOV	Service operations vessel
UA	University of Antwerp
USV	Unmanned surface vessel

Contents

Appendix

1 Introduction

With the energy transition picking up speed, the pressure is on to increase the uptime of wind farms and reach the highest revenue against the lowest costs. To achieve optimal results, it is crucial to strike a balance between the added operational expenses and the additional revenue from wind farms of the future. The most promising approaches to reach this optimum involve implementing new methods and technologies that aim to increase yield while simultaneously reducing operating costs. This study focuses on the offshore wind business case, with a particular emphasis on Operations & Maintenance (O&M) activities for offshore wind farms as optimizing O&M activities hold the potential to enhance wind farm uptime and simultaneously minimize operational costs.

Currently wind farms, further from shore than approximately 25 km, are typically serviced by Service Operation Vessels (SOV's), sailing back to port every two weeks to exchange wind turbine technicians and to take in fuel, supplies, and spare parts. By exploring new logistic concepts and technologies to reduce the number of SOV port visits, it is possible to improve yield and reduce in operational costs This increases the effective working time of the wind turbine technicians, and therefore increases the SOV's production time in the wind farm.

Reducing the SOV's port visits can theoretically be done by reorganising the supply chains: by shifting the transfer function of goods and personnel from the SOV to *supply vessels*, the SOV can remain operational in the wind farm for a longer time. In this study it is investigated how supplying SOV's at sea can increase the wind turbine yield (more uptime) and reduce the O&M costs, by increasing the operational time of wind turbine technicians on SOV's in the offshore wind farm by assessing various operating methods. Two main variants are considered in this study:

1. "Radial" (point-to-point supply between SOV and harbour)
2. "Milk run" (circular route along multiple wind farms with multiple SOV's)

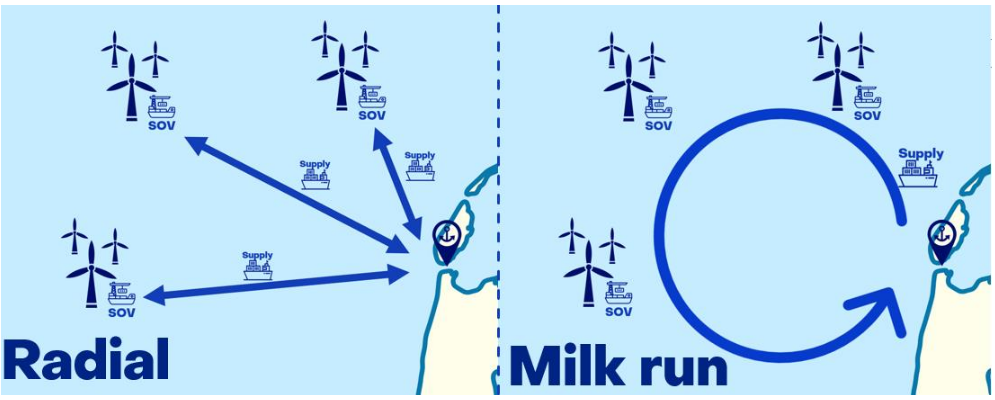

Figure 1: two variants of ship-to-ship supply

In addition to the main logistical methods, the concept of a “vessel train” is investigated, in which multiple vessels follow each other in a predetermined time schedule, addressing multiple fixed locations (SOV’s). This concept was developed for inland shipping under the Novimar project [1] and is also called *platooning*. For this concept, the “milk run” variant makes most sense. Figure 2 shows a schematic representation of this automated setup.

Besides the new logistical concepts, this study will investigate the potential benefits of using autonomous or remote-controlled vessels and helicopters and their effects on the wind farm yield and the O&M costs.

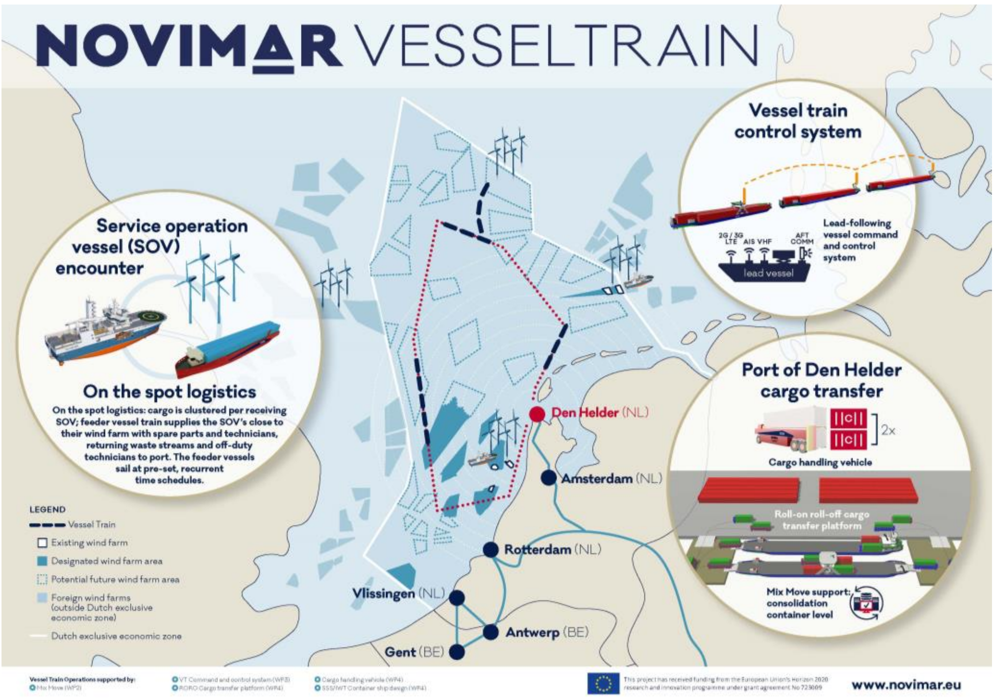

Figure 2: Illustration of the automated concept for supplying SOV’s at sea, based on the Novimar project.

In 2019 a study has been performed to explore the potential for the Port of Den Helder (PODH): what activities would be promising for the future and what infrastructure would be needed for the Port of Den Helder to position itself as a significant player as Operations & Maintenance port for offshore wind [2]. It concluded that great opportunities could emerge from the energy transition for the Port of Den Helder, under the condition that the port area would be further developed to increase the available area to 4-6 hectares. Advantages of the Port of Den Helder are the existing knowledge base, the availability of an airport and a strategic location towards the northern part of the Dutch North Sea, and the UK and German waters. Based upon these previous results, this study will consider the Port of Den Helder as base of operations, while the methodology that is developed is generic, so it is applicable to other ports.

1.1 Research methodology and report structure

During this research multiple workshops and interviews with smaller groups of the consortium partners were conducted. The purpose of both the workshops and the interviews was to validate methods, assumptions and to gather specific information required to properly model the O&M activities and the resulting energy production of the wind farms. This proved a powerful setup, resulting in significant changes to the initial logistic concepts that were evaluated throughout the project.

This introduction Chapter describes the general setup of the project, the consortium and the research questions that will be answered. It will also give the reader insight into the software tools that are used to evaluate the scenarios. In Chapter 2 the research approach and the evaluated scenarios are explained. The main research question is answered in Chapter 3, by comparing the existing state of the art and the ship-to-ship scenario. Chapter **Error! Reference source not found.** covers the effects of innovations on the Ship-to-ship s cenario, while Chapter **Error! Reference source not found.** provides a projection of the presented concepts onto 2050. In Chapter **Error! Reference source not found.** an e xploration into the envisioned required port infrastructure is shown, and finally the conclusions and recommendations are presented in Chapter **Error! Reference source not f ound.**.

1.2 Research questions

The goal of this project is to investigate if there are benefits to be expected of new logistic concepts and innovations on the operations and maintenance costs for offshore wind farms, by answering the main research question:

- Is it possible to increase the yield and reduce the Operation & Maintenance costs of offshore wind farms by applying ship-to-ship supply of SOV's, following fixed schedules?

Secondary research questions are:

1. With the findings from the main research question: what does the "Service Operations Vessel 2.0" need to be capable of?
2. What are the possibilities for autonomous sailing of the supply vessels involved because of this fixed timetable/ fixed route approach and what possibilities are opened for combining more than one supply vessel through platooning?

1.3 Starting point assumptions on considered logistical concepts

Logistical concepts

During Workshop 1 the working principle of the vessel supply train ("milk run" in combination with 'platooning') was explained to the consortium, including the theories that have been developed under the Novimar project. The discussion that followed, resulted in the common consensus that platooning would not be cost-effective for offshore logistics. The main reason for this consensus is that no benefits were identified of multiple vessels following the same fixed route. The reasoning is based on the following points:

1. For the Novimar platooning concept: early indications state that vessel marine crew costs, which is one of the key features to save money on by automation, is not an exceptionally large cost factor in the whole operational expenditure of seagoing vessels.

2. In all scenarios, it would be more cost-effective to have each ship sailing directly to its destination SOV, instead of all ships following a predetermined route along all service locations.

This shifted the attention mostly to the radial variant of ship-to-ship supply, although it is still investigated that supply vessels service more than one SOV. This brings the concept somewhere in between radial and milk run. This conclusion also triggered the decision to replace the Novimar vessel train concept with a two-part alternative: automated supply vessels and automated in-port logistics. Consortium partner *University of Antwerp (UA)*, previously involved in the Novimar project, has experience in modelling automated logistical streams. With the new focus on the radial ship-to-ship concept, UA's scope has changed from modelling Novimar contributions towards a focus on the business case contribution for offshore wind farms of automated supply vessels and automated in-port logistics. Automation in these two areas potentially increases the process efficiency in the whole supply chain, and through that, affect the wind farm yield and the O&M costs. .

Daughter craft for supply vessels
Due to the shift away from platooning, daughter craft for supply vessels were no longer deemed sensible, there is no longer a need for daughter craft sailing between supply vessels and SOV's are already outfitted with daughter craft. Supply vessel daughter crafts are therefore not further investigated in this study.

Helicopters
During normal operations, personnel and spare parts will be transported by vessels. In ad-hoc situations, it can be desirable for the offshore activities to have a faster response time. In these cases, it is an option to use helicopters for transport of personnel and (small) spare parts towards wind farms. As these logistical flows are considered similar for both logistical concepts, they are not considered in the calculations in this study.

1.4 Consortium partners and their roles in the project

This project was executed by a consortium of public and private entities, as specified in the table below.

Name	Type of organisation	Involved Department of the organisation	Role in the project
TNO	Research Institute	Wind energy group	Project Coordination Analysis logistic concepts in port and at sea; workshop hosting and participation; cost reduction impact of logistic concepts on offshore wind energy OPEX;
DHSS	Large Organization	Location Den Helder	DHSS is a large logistics provider in both offshore wind and oil/gas. DHSS provides important input on the logistical concepts and learns from the findings to prepare for future developments; workshop participation
DroneQ Robotics	Small and Medium-sized Enterprise (SME)	General	in the vessel train concept we also contemplate logistical streams by drone: spare parts delivered by drone to either wind turbine or SOV are contemplated; as a drone specialist, DroneQ will provide input and feedback; workshop participation; usage of drones in logistical concepts; analysing impact on regulations for air bound logistics.
Energie Beheer Nederland (EBN)	Public body	Advice & Innovation	With a potential shift from wind farms generating e.g. hydrogen, EBN will have an important role in overseeing network connections and logistical streams supporting those networks. Cash contribution; interested in findings, not participating actively;
Municipality of Den Helder	Public body	Harbour & Airport	as major stakeholder of Port of Den Helder the municipality will learn about potential future developments necessary for Port of Den Helder to be fitted adequately for the future; workshop participation

Name	Type of organisation	Involved Department of the organisation	Role in the project
Coast Guard of The Netherlands	Public body	Policy maritime affairs	Operating innovative logistical concepts, each with their own specific potential impact on safety at sea, requires early involvement, input and feedback from Coastguard; workshop participation; analysing impact on regulations for air bound- and seabound logistics.
Maritime Emerging Technologies Innovation Park Noord-Holland (METIP)	Public body	General	as an innovation body, supporting new seabound technologies, METIP is very eager to learn about the vessel train concept and to bring their knowledge from related start-ups into the project; workshop hosting and participation; usage of drones in logistical concepts
OrangeBeak Penguin	Small and Medium-sized Enterprise (SME)	General	from large oil/gas related experience in logistical streams Orangebeak Penguin can make the connection between logistics for O/G and offshore wind. This is particularly relevant when Power to X wind farms will be built in the future, potentially connecting offshore wind farms to existing oil/gas infrastructure such as pipelines and underground storages; workshop participation
University of Antwerp	University	Faculty of Business and Economics	Modelling of automation concepts. Previous participant of the EU Novimar project.
Ontwikkelingsbedrijf NHN	Public body	General	as stimulator for economic activities in the northern part of Noord-Holland, the *Ontwikkelingsbedrijf* is very keen on bringing in their knowledge on technology developments as well as to learn from the other participants where developments are going; workshop participation; establishing future potential economic/ technical development directions
Peterson Den Helder BV	Large Organization	Energy Logistics	Peterson is a large logistics provider in both offshore wind and oil/gas. Peterson provides important input on the logistical concepts and learns from the findings to prepare for future developments; workshop participation

Name	Type of organisation	Involved Department of the organisation	Role in the project
Port of Den Helder	Public body	Management	With a large volume of offshore wind being foreseen in the working area of Port of Den Helder, the Port provides important input on the logistical concepts and learns from the findings to prepare for future developments and direct future investments; workshop participation and hosting
Ocean Winds Belgium Netherlands N.V.	Large Organization	General	As an operator/ developer of both offshore wind farms, Ocean Winds will provide important input and feedback for the project; analysing impact on business case
Vroon Offshore Services	Large Organization	Vroon Offshore Services B.V.	Vroon is a large logistics provider in both offshore wind and oil/gas. Vroon provides important input on the logistical concepts and learns from the findings to prepare for future developments; workshop participation

1.5 Tooling

TNO will model the O&M activities in this project in its in-house developed tool UWiSE (Unified Wind farm Simulation Environment), and specifically with the module O&M Planner.

TNO O&M Planner was developed based on TNO wind group's long expertise in O&M cost calculation and simulation tool: ECN O&M Tool (excel based tool), which has been widely used in offshore wind since 2005, followed by ECN O&M Calculator, which was a MATLAB based software major upgrade in functionality, in use from 2011. Both software tools, however, were not able to model increasingly complex features in O&M planning for large scale but also upcoming new technologies for offshore wind farms, such as floating wind farms, wind farm clustering, O&M resource sharing across multiple wind farms and hydrogen production. As a result, TNO has developed O&M Planner, software for long term O&M strategy evaluation studies, in use since 2020.

TNO O&M Planner is built on a discrete event based logistic simulation engine UWiSE (Unified Wind farm Simulation Environment). The software enables modelers to run simulations over multiple years, to calculate O&M costs, wind farm availability and energy production, while accounting for uncertainties based on weather input and component failure rates. The tool shows the impact on O&M KPIs of deploying various types and numbers of transport equipment such as vessels, helicopters and barges, each with their own weather limits of operation

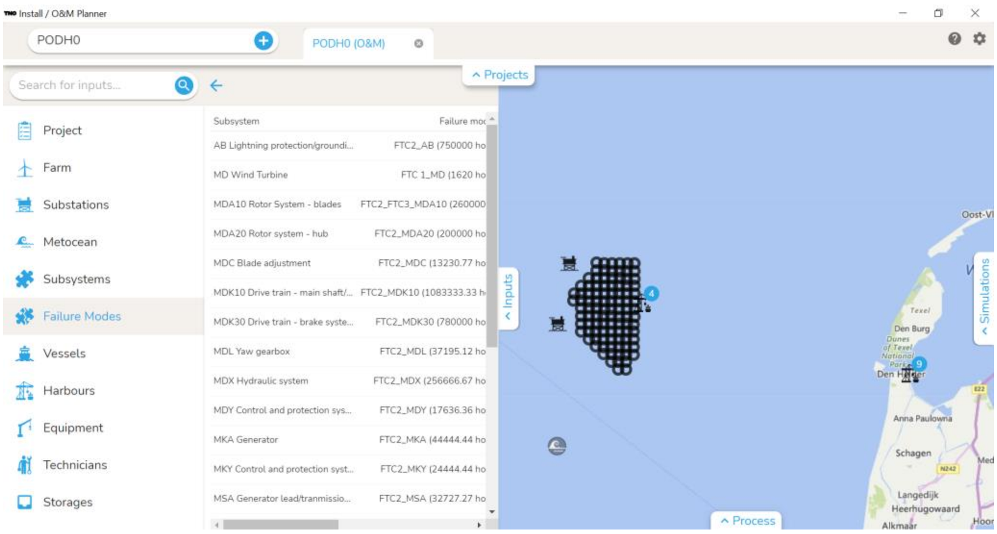

Figure 3 The user interface of TNO O&M Planner (Generic image, courtesy of TNO)

The software primarily aims to:

- Help wind farm operators optimize O&M choices between various transport modes, equipment, personnel and stock management options in terms of standard key performance indicators (KPIs) like produced energy, farm availability and repair costs.
- Perform scenario studies for an O&M project by varying the available resources (e.g., three crew transfer vessels vs. one service operation vessel).
- Provide an overview of maintenance actions planned and executed, the delays encountered (due to weather, personnel or vessel) and their associated costs.
- Provide insight into the causes of wind farm downtime per component failure mode and execution of scheduled maintenance activities.
- Evaluate the impact of innovative concepts (e.g., large component replacements with motion compensated cranes) on O&M KPIs

The University of Antwerp (UA) has developed software to determine the cost differences of automated logistics versus conventional logistics. The following paragraph is cited from their report. The full UA report is added as Annex I.

The study uses a comparison input-output methodology to analyze and compare the economic performance of the different vessel autonomy levels for the offshore transport part. Specifically, three scenarios are developed, analyzed, and assessed for this part. These are:

- *Economic feasibility of a conventional feeder vessel for offshore supply transport.*
- *Economic feasibility of a remote-controlled feeder vessel for offshore supply transport.*
- *Economic feasibility of an autonomous feeder vessel for offshore supply transport.*

The same approach is also applied to the second part (port logistics). However, only autonomous vessels are considered because remote-controlled vessels are unsuitable for inland port operations. The scenarios include:

- *Economic feasibility of road transport for inland port logistics.*
- *Economic feasibility of conventional barges for inland port logistics.*
- *Economic feasibility of autonomous barges for inland port logistics.*

In addition to these scenarios, the terminal investment analysis is also considered for both conventional and autonomous cases. The minimum terminal cost required per tonne is then used as the terminal rate in the terminal handling charge for both the offshore and port logistics parts.

2 Approach

This Chapter gives a general introduction, explaining how the research is done and how the models are set up. It also gives the reader an overview of the scenarios that are evaluated.

2.1 General setup

This section describes the assumptions that are made, starting with the model foundations. These are a set of default values and settings that are embedded in TNO's modelling software and that are used in all the evaluated scenarios. Project-specific assumptions are provided next for costs, wind farm location selection, harbour selection, oil/gas platforms, vessels and on-demand logistics.

2.1.1 Model foundation

All scenarios make use of a default set of inputs and assumptions, which is referred to as the model foundation. This model foundation consists of a chosen set of wind turbine types, failure modes, corrective and scheduled maintenance actions, transport modalities, warehouse stocks, etc.

2.1.2 Costs

In this study the 2023 price levels are used for vessels, electricity, technicians, etc. Inflation is not considered in calculating future scenarios. The resulting differences in costs between the scenarios are shown relative to the costs of the baseline scenario.

2.1.3 Electricity price

The electricity sales price has been set to 45 €/MW as a representative market price.

2.1.4 Base port

The base port chosen for this study is the port of Den Helder, as it is close to the wind farms and the Port of Den Helder is a partner in the project. It is not expected that all wind farm locations in Dutch territorial waters will be serviced by Den Helder but the general methodology in this study will also be applicable for other ports in the Netherlands.

2.1.5 Wind farms

This study aims to get insights into the operations and maintenance cost developments in the year 2030 when indeed wind farms will be operational further from shore. The situation is chosen where offshore wind farms *Nederwiek, Lagelander, IJmuiden Ver* and *Hollandse Kust West* are operational, as planned by the Dutch government. This represents a situation where 18 GW is operational at distances from shore larger than 25 km, using logistical concepts as considered in this project. The wind farm locations are shown in Figure 4.

To keep computational costs manageable, a 1.5 GW wind farm is modelled, and the results are extrapolated to 18 GW. The 1.5 GW size is chosen as wind farms are generally split up into zones of roughly that size and awarded to developers. From earlier experience within TNO it is known that this method of extrapolation gives sufficient accurate results.

Each 1.5 GW wind farm is modelled as 100 Wind turbines of 15 MW. These turbines are modelled at the general position of *IJmuiden Ver,* since the distance between *IJmuiden Ver* and the Dutch coast is similar to the average distance from the coast to the mentioned wind farm locations.

Figure 4 The outline of the wind farms chosen for this study. The figure is edited from RVO [3]

The layout of the modelled wind farm is shown in Figure 5. The wind turbines are evenly distributed in the region set by the government as *IJmuiden Ver* [4]. The North-West part of *IJmuiden Ver* is used, though it has to be noted that the exact shape is not completely similar to that of *IJmuiden Ver*.

2.1.6 Oil/gas platforms

In this study analysis of the combined logistics between windfarms and oil and gas platforms is desired. Seven oil/gas platform are located around *IJmuiden Ver*. Two platforms located in the west of *IJmuiden Ver* are considered for the simulations. Similar to the extrapolation of the wind farms, two platforms are modelled in detail and the findings are then extrapolated. For the full 18 GW wind farm, this results in 24 oil/gas platforms that are used in the simulations.

In an earlier study by *North Sea Energy*, TNO investigated the potential of collaboration of wind farms and oil/gas platforms [5]. The vessels that are used for wind farms can be used to deliver packages to the platforms. Using data from *Peterson*, the frequency of these deliveries was set to 18 times per year per platform. The deliveries were simulated as maintenance actions for the platforms, with the corresponding frequency.
The *North Sea Energy* study found no other significant benefits for synergising the wind energy O&M activities with oil/gas platform activities [5].

Figure 5 The layout of the 1.5 GW wind farm that is used for the simulations.

2.1.7 Vessels

For the modelled 1.5 GW wind farm, the following vessel types are used in the model foundation: jack-up vessels, diving support vessels and helicopters. These vessels can be short-term leased when needed.

The vessel types that are added for this study are SOV's with daughter craft (DC) and on-demand supply vessels. The specifications of these vessels are shown in Table 1. These specifications are provided and verified by the maritime partners. An example of an SOV would be the *VOS Stone* of Vroon, as can be seen in Figure 6. Other vessel types that are added for specific scenarios will be described in the relevant sections of this report.

Vessels	Unit	SOV	Daughter craft	On-demand supply vessel
Average transit speed:	Knots	12	10	10
Passenger Capacity		30	8	12
Weather limit: Significant Wave Height	m (Hs)	2.5	1.5	2.5
Weather limit: Wind Speed at 10 m	m/s	20	15	20
Day Rate Working	kEur	40	n.a	30
Day Rate Waiting	kEur	40	n.a	30

Table 1 Vessel specification for the general scenario. The specifications are provided by Vroon, Peterson and DHSS

Figure 6 An example of an SOV: The VOS Stone of Vroon [6]

2.1.8 On-demand spare parts

An extra logistical stream of on demand spare parts was added to all scenarios. On-demand spare parts are parts that are not present in the general stock of an SOV and would therefore normally not be resupplied. These spare parts therefore need to be transported to the SOV when needed.

Four types of replacement maintenance actions are specified in the model foundation, that only involve an SOV as vessel. These four maintenance actions represent different magnitudes of replacements. It is assumed that the two maintenance actions with the longest duration require on-demand spare parts, as they would likely entail parts that are too large to be a part of the SOV's regular supply. For the two shorter maintenance actions it is assumed that the required spare parts are already present on the SOV.

The frequencies of the four maintenance actions are determined from the simulations. From these frequencies it is calculated that the two longer maintenance action comprise 54% of the replacements that are done by SOV's, so consequently on-demand spare parts are considered to be required for 54% of the replacement actions.

For the very large maintenance actions that require a jack-up vessel the on-demand spare parts are not considered. It is assumed that the jack-up vessel brings the spare parts from port.

2.2 Baseline scenario (Existing state of the art)

In this scenario the existing state of the art is investigated. The SOV's will go back to base port every 14 days. During each port call the wind turbine technicians are exchanged and provisions, supplies and fuel are resupplied. The marine crew will be changed periodically.

It is assumed that the SOV will stay in port for 24 hours. The average distance of the wind farms in this study is approximately 70 km. Seven hours travel time for a round trip is therefore added to the time period that the SOV is unavailable to service its wind farm: a total of 31 hours. No extra features are added to the general setup for this scenario.

2.3 Ship-to-ship supply scenario (S2SS)

The main logistical concept in this study is the ship-to-ship supply scenario, in which the SOV's will not return to base port frequently. They will remain in their wind farms and will be resupplied at sea by supply vessels and crew transfer vessels. For this scenario multiple logistic streams are determined:

- Wind technicians,
- Marine crew,
- Provisions including drinking water,
- Spare parts
- Fuel

Wind turbine technician crews are exchanged every two weeks. A fast ship with a high weather workability is used to transport them to the SOV. For example, a Fast Crew Supplier (FCS) [6] could be used, as shown in Figure 7.
The marine crew is changed every eight weeks. This duration is averaged from the various responses of multiple consortium partners. This marine crew change is combined with the wind technician crew. To accommodate both personnel groups, a larger FCS is used, as shown in Figure 8. This larger FCS replaces the smaller FCS every fourth crew supply run. Throughout this report the two types of FCS are distinguished as *small FCS* and the *large FCS*. Note that these vessel types are selected based on their crew capacities. This report does not go into further detail to determine the optimal vessel types.

Figure 7: Example of a Fast Crew Supplier; the Damen 2206 [image courtesy of Damen]

Figure 8 Example of a larger Fast Crew Supplier; the Damen 3307 [image courtesy of Damen [7]]

The supply of provisions (including drinking water), spare parts for wind turbines and fuel are assumed to be combined into one supply vessel. It is assumed that this supply vessel visits the SOV's every four weeks. An example of a suitable supply vessel in shown in Figure 9. It is assumed that this ship type is also used for the on-demand spare parts.

Figure 9: The VOS patriot: An example of a suitable supply vessel. [8]

The specifications for the vessels used for these logistical streams are shown in Table 2.

Table 2 vessel specifications

Vessels	Unit	Supply vessel	Small FCS	Large FCS
Average transit speed:	Knots	10	30	30
Passenger Capacity	Pax	12	40	80
Weather limit: Significant Wave Height	m	2.5	1.75	1.75
Weather limit: Wind Speed at 10 m	m/s	Transit: 20 Working: 10	20	20
Day Rate Working	kEur	30	20	30
Day Rate Waiting	kEur	30	20	30
Ship length (LOA)	M	84	27	27

2.3.1 Fixed schedule

Supply vessels can service multiple SOV's per trip. Since servicing wind farms of multiple owners could lead to disputes due to prioritisation, it is assumed for the S2SS scenario that a supply vessel services two SOV's per supply run. These two SOV's service a total of 1.5 GW of wind turbines, which is the expected wind farm size for a single owner around 2030. It has to be noted that future WTG's are being designed to require less maintenance. That trend could result in SOV's covering larger areas with more WTG's. This has not been considered in this study.

It is assumed that FCS's will not service multiple SOV's per trip for personnel transport, since "waiting" or "detour" time for personnel is quite sensitive and could lead to resting hours on board of the SOV which is undesired. Attending multiple SOV's is investigated as a sensitivity analysis (see results in Section 2.3.2). This study does not further investigate the optimum balance between ship size, travel time and costs.

With these assumptions, the resulting fixed schedule for a 1.5 GW wind farm is:

- One supply vessel that sails every 4 weeks,
- Two small FCS's that sail every 2 weeks for wind turbine technicians
- Two large FCS's that sail every 8 weeks, replacing the two small FCS's for both marine crew and wind turbine technicians

2.3.2 Sensitivity Analyses

Multiple sensitivity analyses are done to test the robustness of the results. These analyses are done for the comparison between the existing state of the art scenario and the ship-to-ship supply scenario. The following parameters were varied for these analyses:

- Electricity price;
- Vessel day rate;
- Seasons throughout the year;
- Number of SOV's serviced per supply vessel run.

Electricity sales price: the electricity sales price is highly volatile. Since the scenarios balance reduced losses due to non-operational wind turbines with increased operational costs, the electricity sales price can have a large impact.

Vessel costs: the vessel cost that are used in this study are estimated with input from the consortium members. Due to numerous reasons these vessel costs could vary, making it important to understand the influence on the results.

Season-dependency: conditions on the North Sea substantially differ between the summer and the winter. It was suggested that for this reason, ship-to-ship supply might not be beneficial during winter seasons. To determine if ship-to-ship-supply is still beneficial during the winter period, both seasons were evaluated separately.

Number of SOV's serviced per supply vessel run: to check the benefits of the milk run concept for the resupplying SOV's, the number of SOV's per supply trip was varied. From this method the impact on the yield availability of the wind farms could not be calculated and it therefore focusses on the difference in vessel costs.

2.4 Innovations

In addition to the basic sea-to-sea supply concept this study also investigates the benefits of innovations to further increase the wind farm yield and decrease the operational costs. Two concepts are evaluated: automated supply vessels and drones.

2.4.1 Automated supply vessels

Autonomous vehicles have gained prominence in recent years and are increasingly being explored across various fields to assess their suitability and applicability. Although during the writing of this report, there are no fully autonomous vehicles used as accepted technology that are allowed on roads or seaways, it is anticipated that this could take flight in the period towards 2030. In the meantime, successful tests have been executed with remote controlled survey vessels by Fugro (see Figure 10), showing that the first step towards autonomous vessels is within reach. It must be noted that legislation is not yet on-par with the technological development which could delay the implementation.

Figure 10: Fugro Blue Shadow

As sub-assignment for this research, the University of Antwerp developed a mathematical model describing the expected economic performance of automated supply vessels in the scope of this project. Two levels of automation are considered: remote controlled and fully autonomous. The costs involved with both options are evaluated for the parameters specified in this project (e.g., distances, supply run frequencies, etc.) and compared to the costs of a conventional supply vessel.

A second area that is modelled by the University of Antwerp is automation of the in-port logistics and terminal equipment. Results on both areas of automation are shown in Section 6.2.

2.4.2 Drones

The application of unmanned transportation modalities such as airborne drones and Unmanned Surface Vessels (USV) are investigated. The modelled specifications of these unmanned modalities are shown in Table 3. The specifications are provided by partner *DroneQ* except the day rates of the seaborne drone; these rates were estimated.These vehicles are remotely operated from a control room. This control room can be located on shore, or on a vessel (e.g., an SOV).

Drone specifications	Unit	Airborne drone	Unmanned Surface Vessel (USV)
Average transit speed:	Knots	45	10
Weather limit (in transit): significant wave height	m (Hs)	N.a.	2.5
Weather limit (in transit): wind speed at 10m height	m/s	13	30
Day Rate Working	kEur	1.2	10
Day Rate Waiting	kEur	1	10
Cargo capacity	kg	15	1,000
Range (in- and outbound combined)	km	120	3,000

Table 3: The specifications for the vessels used in the drone scenarios.

Three applications for unmanned transportation modalities are investigated:

- On-demand spare parts
- Offshore handling of oil/gas platforms
- External inspection of wind farm subsystems like rotor blades, towers or foundations

On-demand spare parts

Now a large vessel is used to supply on-demand spare parts. It is assumed that these on-demand spare parts are too large to be transported by airborne drones. Therefore, USV's are used to deliver these parts to the SOV's. These USV's will be loaded in the Port of Den Helder.

Offshore handling of oil/gas platforms

In a previous study done by the consortium *North Sea Energy*, synergy between the offshore wind energy field and the oil/gas industry was identified [5]. Handling of packages for oil/gas platforms could be a function that could be performed by an SOV. This logistical stream could also be taken on by drones, instead of the SOV (or its daughter craft). From a study of DHSS, the median weight of package bundles to oil/gas platforms around *IJmuiden Ver* is 13 kg [9].This would mean that 50% of the package bundles could be delivered by airborne drone and the other 50% will have to be delivered by a USV. The drone and USV would be stationed at an SOV.

External inspection of wind farm subsystems
Small inspections of wind turbine blades, tower exteriors and foundation exteriors are frequently performed. Typically, the need for large component exchange is found in earlier inspections and then degradation is monitored. For external subsystems this could be done partially by USV and partially by an airborne drone. A specialist technician is needed to control the drone and inspect the turbine. The subsystems that are inspected by these are: blades, hub, blade adjustment and tower structure. This USV could be stationed at an SOV or within the wind farm.

All unmanned transportation modalities are at least partly remote controlled and are not completely autonomous yet. This was deemed not feasible yet by the consortium partners before 2030.

2.5 2050 Outlook

In all the previous scenarios the focus has been on the expected status of offshore wind in the Dutch territorial waters in 2030. It is important to test the robustness of the solutions also for the further future. To see how the ship-to-ship supply case would be cost-effective in the further future, an extrapolation is done towards 2050. The Dutch government expects 70 GW of offshore wind power to be installed at that time. Because technology is expected to develop in a rapid pace, this 2050 outlook comprises the sea-to-sea supply concept and all innovations that are found to be beneficial from the previous sections as fully applied technology in 2050.

In a study performed by TNO in 2019, a share of 30% to 50% is considered as feasible share for the Port of Den Helder [2] for the O&M activities for offshore wind power in the Northern North Sea. Based on the aforementioned expectation of 70 GW installed offshore wind power, this results in roughly 30 GW (43%) that could be serviced from the Port of Den Helder.

For this simulation, a wind farm is defined at the location of *Nederwiek,* consisting of 100 Wind turbines of 15 MW and two offshore oil/gas platforms. This wind farm is extrapolated to 30 GW and to 40 oil/gas platforms. A location further out into the sea is chosen since the average distance will increase with the larger amount of wind farms in 2050. The location and layout of the offshore wind farm and oil/gas platforms is shown in
Figure **11**.

Figure 11: Layout of the wind farm at the location of Nederwiek.

The results from this scenario will be indicatively only, as there are many factors that could greatly influence the global energy market and therefore the resulting situation in 2050.

2.6 Summary of scenarios

An overview of the scenarios and the different levels of modelling input is shown in Figure 12.

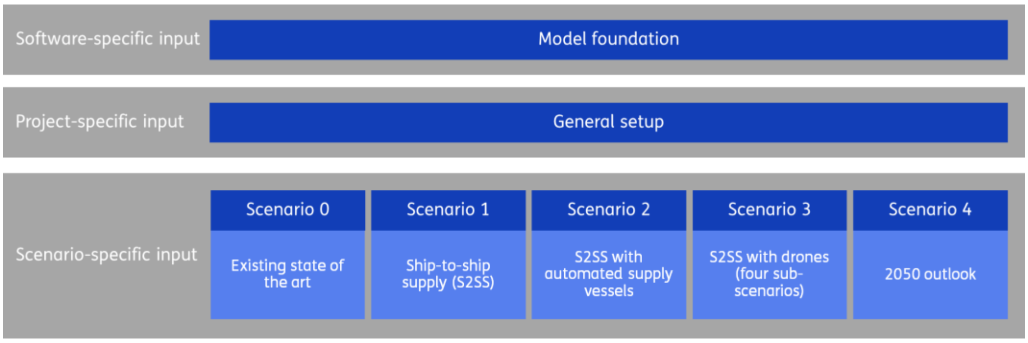

Figure 12: overview of scenarios

3 The effects of Ship-to-Ship supply towards wind farm-bound SOV's

To assess if ship-to-ship supply can positively influence the yield of wind farms and reduce the O&M costs Scenario 0 and Scenario 1 have been evaluated and the results were compared. Both scenarios were evaluated with 100 simulations, while using historic weather data from ten different years and ten different seeds for randomised events. This was done to ensure the results are statistically justified.

3.1 Results

3.1.1 Overall results

The comparison of ship-to-ship supply versus the existing state of the art of SOV returning to port every 14 days, results in a net cost reduction of 2.2%. The results are shown in Figure 13 and Table 4.

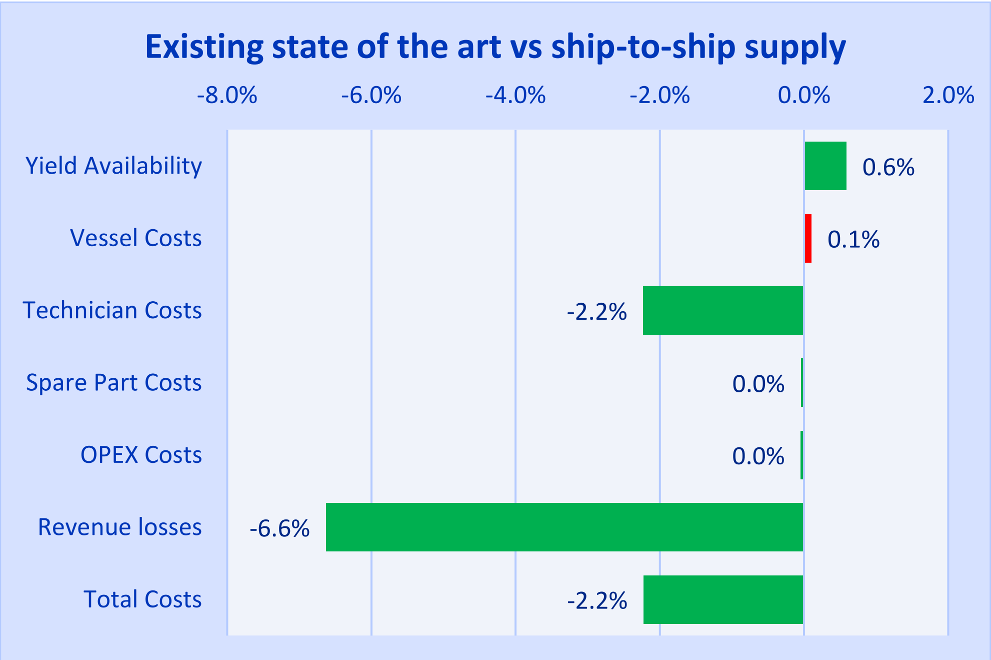

Figure 13 The existing state of the art scenario compared with the ship-to-ship supply scenario.

For relative comparison only	Unit	Existing State of the art	Ship-to-ship supply	Δ [%]	Δ [M€/year]
Yield Availability*	[%]	91.9	92.4	0.6%	
Vessel Costs	[M€/year]	521.6	522.1	0.1%	0.5
Technician Costs	[M€/year]	37.0	36.2	-2.2%	-0.8
Spare Part Costs	[M€/year]	94.7	94.7	0.0%	0.0
OPEX Costs	[M€/year]	729.5	729.2	0.0%	-0.3
Revenue losses	[M€/year]	361.2	337.2	-6.6%	-23.9
Total Costs	[M€/year]	1090.7	1066.4	-2.2%	-24.3

Table 4 The Existing State Of The Art scenario compared with the Ship-to-Ship Supply scenario.

The net result of ship-to-ship supply compared to today's state of the art of SOV's returning to port every 14 days, is a reduction in the Total project costs of over 2%. Explanation for this reduction lies in the shorter response time on failures and planned maintenance actions, leading to higher energy production as the combined effect of higher yield availability and reduced energy losses due to repair time despite of the slightly increased vessel cost.

The yield availability represents the energy that is produced by the wind farm, relative to the hypothetical maximum amount of energy produced if the wind turbines are always operational. The revenue loss is the monetary loss of the energy that is not produced during the periods that the wind farm is not or less operational. The yield availability and the revenue loss are therefore correlated.

3.1.2 Resulting vessel costs

The costs per vessel type are shown more in detail in Table 5. The vessels used in the model foundation are not given as their cost is similar in both scenarios.

Costs per vessel	Unit	Existing State of the art	Ship-to-ship supply	Δ [%]	Δ [M€/year]
Supply vessel	[M€/year]	0	10		10
Fast crew supplier	[M€/year]	0	13		13
On-demand vessel	[M€/year]	37	36	-2.5%	-1
SOV	[M€/year]	266	248	-6.8%	-18
Total Vessels	**[M€/year]**	**522**	**522**	**0.1%**	**0.5**

Table 5: detailed vessel costs for the status quo scenario compared with the ship-to-ship supply scenario.

The ship-to-ship supply method results in slightly higher vessel costs, but also increases the availability of the wind farm, leading to reduced revenue losses. The higher vessel costs are caused by the larger number of vessel movements that are required for resupplying the SOV's. The benefits of ship-to-ship supply can be seen as a trade-off between increased vessel cost and reduced energy loss. Additionally, the cost of technicians is reduced in the ship-to-ship supply scenario, due to reduced delay time during maintenance activities. An increase in spare part cost is noticed, since the increased wind turbine availability implies longer uptime, which in turn shortens the throughput time until the next failure.

The ship-to-ship supply vessels are not used in the existing state of the art scenario; hence they have no costs attributed to them. The SOV cost is reduced in ship-to-ship supply scenario as the SOV does not have to go back to port every 14 days. Also, a reduction for the on-demand vessel is seen. This can be attributed again to the reduced delays in maintenance activities with the result of less breakdowns and less on-demand spare parts being required.

3.1.3 Weather implications

The S2SS scenario is built on the idea that supply vessels and personnel vessels will follow a fixed schedule. An aspect that could affect the ability to follow this schedule that cannot be controlled is the weather. To get an indication of the impact of weather circumstances on the logistical streams in the S2SS scenario, it was investigated how often the supply vessels and FCS's were delayed for more than one day due to the weather. This is shown in Table 6. In almost a quarter of the cases, supply vessels are delayed for more than one day. For the FCS this occurs less frequently, due to their higher weather workability. These numbers are significant enough that it is advisable to ensure there is sufficient storage of supplies, fuel etc. on SOV's to have a buffer.

	Supply vessel	**FCS**
Occurrences of delays (>1 day)	23%	16%

Table 6 Percentage of occurrences of longer than a day delay due to the weather for different logistic streams.

3.1.4 Port calls

For the investigation of the required port functionalities in Chapter **Error! Reference source not found.** it is important to know the number of port calls of the vessels in both scenarios. From an earlier study by TNO in 2019 [2] the Port of Den Helder is expected to service 30% to 50% of the total O&M activities of the Dutch wind energy sector in 2030 and 2050. It is assumed that wind farms are only serviced as a whole.

For the situation in 2030 it is therefore chosen that six wind farms of 1.5 GW are serviced by the Port of Den Helder, resulting in 9 GW, or 42% of the Dutch wind energy sector. For the situation in 2050 20 wind farms are considered, resulting in 30GW of installed wind power, or 43%.

Each port call comprises a round trip between a wind farm and the harbour. In the case of an SOV this represents one port call for resupplying. For the other vessel types this represents a supply run.

It must be noted that the on-demand spare parts only consider the larger spare parts, that would not be part of the normal stock on SOV's. It is therefore the same for both scenarios.

As expected, the total number of trips, and therefore port calls, increase when changing to the S2SS scenario. The results are shown in Table 7 for one year of operations. This is a direct result of separating the logistic streams of cargo and personnel.

	Existing State of the art			**Ship-to-ship supply**		
	1.5 GW	**9 GW**	**30 GW**	**1.5 GW**	**9 GW**	**30 GW**

SOV with Daughter Craft	52	312	1040	0	0	0
Supply Vessel (Fuel, etc)	0	0	0	13	78	260
Small FCS (Wind technicians)	0	0	0	39	234	780
Large FCS (Wind technicians and Marine crew)	0	0	0	13	78	260
On-demand vessel	69	414	1380	69	414	1380

Table 7 Annual port calls for the existing state of the art and the ship-to-ship supply scenarios.

3.2 Sensitivity analyses

Sensitivity studies are performed to see how robust the overall findings are when major input parameters are changed. Does ship2ship supply still result in a net cost reduction of 2.2% in comparison with today's regular practice of SOV's returning to port every 14 days?

The sensitivities studied are:
- Electricity sales price
- Vessel day rates
- Seasonal deployment summer vs winter
- Number of SOV's served by one supply vessel

3.2.1 Electricity sales price

Three different electricity sales prices were used to determine the influence of energy pricing on the base case comparison:
- 34.7 €/MWh (-23%)
- 45 €/MWh (base price)
- 53.7 €/MWh (+19%)

The base price is in line with current electricity sales price level in 2023. The two variations 53.7 €/MWh and 34.7 €/MWh are taken as maximum and minimum and originate from a whitepaper from TNO [10] as potential energy pricing in 2030.

In Figure 14 and Table 8 the results of this variation of the electricity sales prices are shown. Even with the lowest electricity sales price the ship-to-ship supply scenario is beneficial.

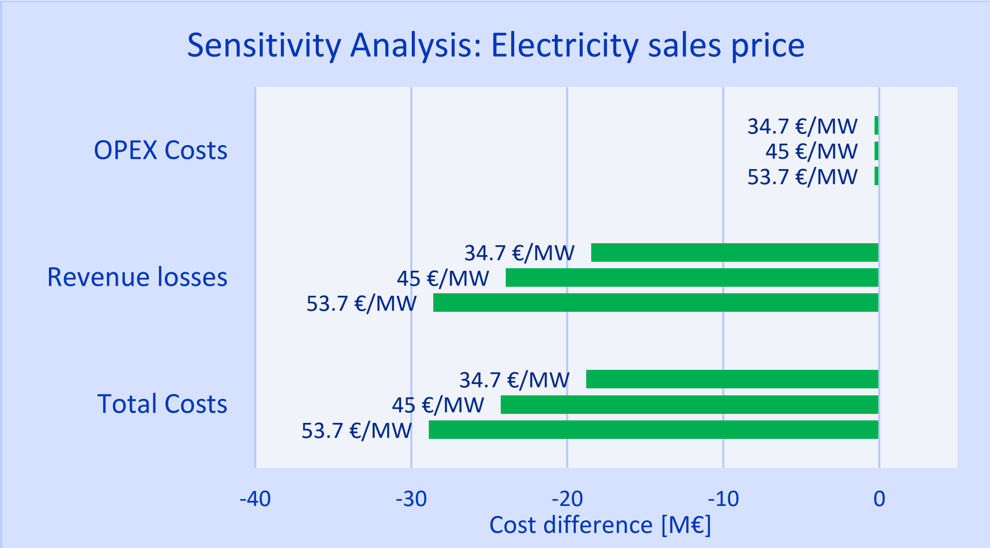

Figure 14: Sensitivity of electricity sales prices on the business case

	Unit	34.7 €/MWh			45 €/MWh			53.7 €/MWh		
		Existing state of the art	Ship-to-ship supply	Δ [%]	Existing state of the art	Ship-to-ship supply	Δ [%]	Existing state of the art	Ship-to-ship supply	Δ [%]
OPEX Costs	[M€/year]	729	729	0.0%	729	729	0.0%	729	729	0.0%
Revenue losses	[M€/year]	279	260	-6.6%	361	337	-6.6%	431	402	-6.6%
Total Costs	[M€/year]	1,008	989	-1.9%	1,091	1,066	-2.2%	1,160	1,132	-2.5%

Table 8: Sensitivity of electricity sales prices on the business case

It has to be noted that the yield availability of wind farms is not affected by the variation of the electricity sales price.

Conclusion is that even when the sales prices of electricity drop to low values, there is a reduction in LCOE of 1.1% This is lower than the base case ship2ship supply scenario because of the reduced upside of producing more energy. When electricity sales prices go up to base case of EUR 45/MWh (net result on total project costs -/-2.2%) or even higher at EUR 53.7/MWh (net result on total project costs -/- 2.5%) the reduction on total project costs is stronger.

3.2.2 Vessel costs

As the benefits of the ship-to-ship supply scenario relies heavily on the trade-off between vessel costs and the yield availability (revenue losses), the sensitivity the results to varying vessel costs is important. In Figure 15 and Table 9 the results are shown of a variation of the vessel costs by varying the vessel day rates with 20% in both positive and negative direction.

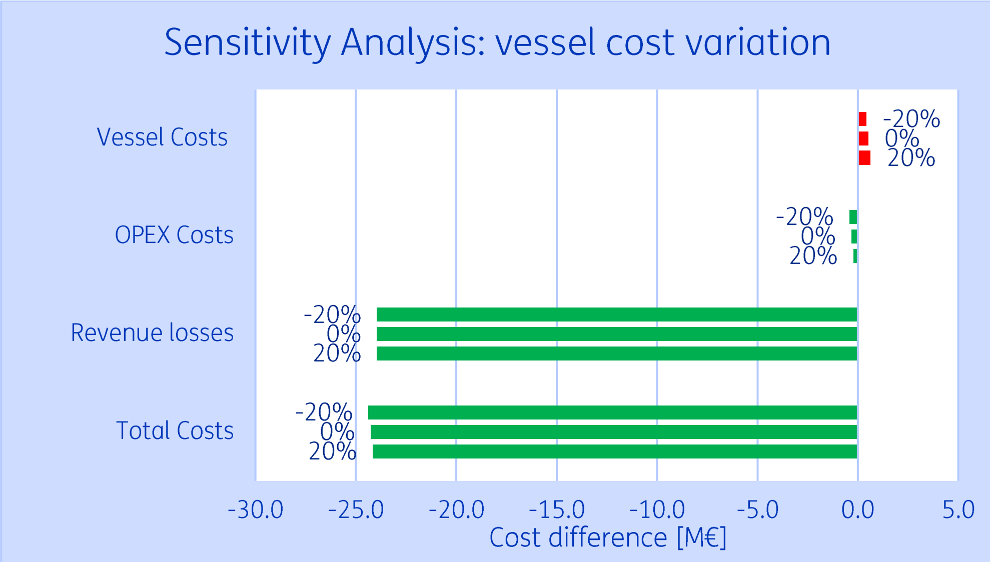

Figure 15: Sensitivity of the vessel cost on the business case.

		-20%			0%			+20%		
	Unit	Existing state of the art	Ship-to-ship supply	Δ [%]	Existing state of the art	Ship-to-ship supply	Δ [%]	Existing state of the art	Ship-to-ship supply	Δ [%]
Vessel Costs	[M€/year]	417	418	0.1%	522	522	0.1%	626	627	0.1%
OPEX Costs	[M€/year]	625	625	-0.1%	729	729	0.0%	834	834	0.0%
Revenue losses	[M€/year]	361	337	-6.6%	361	337	-6.6%	361	337	-6.6%
Total Costs	[M€/year]	986	962	-2.5%	1,091	1,066	-2.2%	1,195	1,171	-2.0%

Table 9: Sensitivity of the vessel cost on the business case.

Even with the 20% increased vessel cost the ship-to-ship supply scenario is beneficial and leads to a reduction of the total project costs of 2%. Since the vessel cost difference between the two cases is relatively small, the impact is marginal.

3.2.3 Season-dependency

In this sensitivity study the seasons are explicitly split in summer-only and winter-only data. The resulting sensitivity analysis on season-dependency is shown in Figure 16 and Table 10. Only 60 simulations were done per season due to the reduced amount of available weather data.

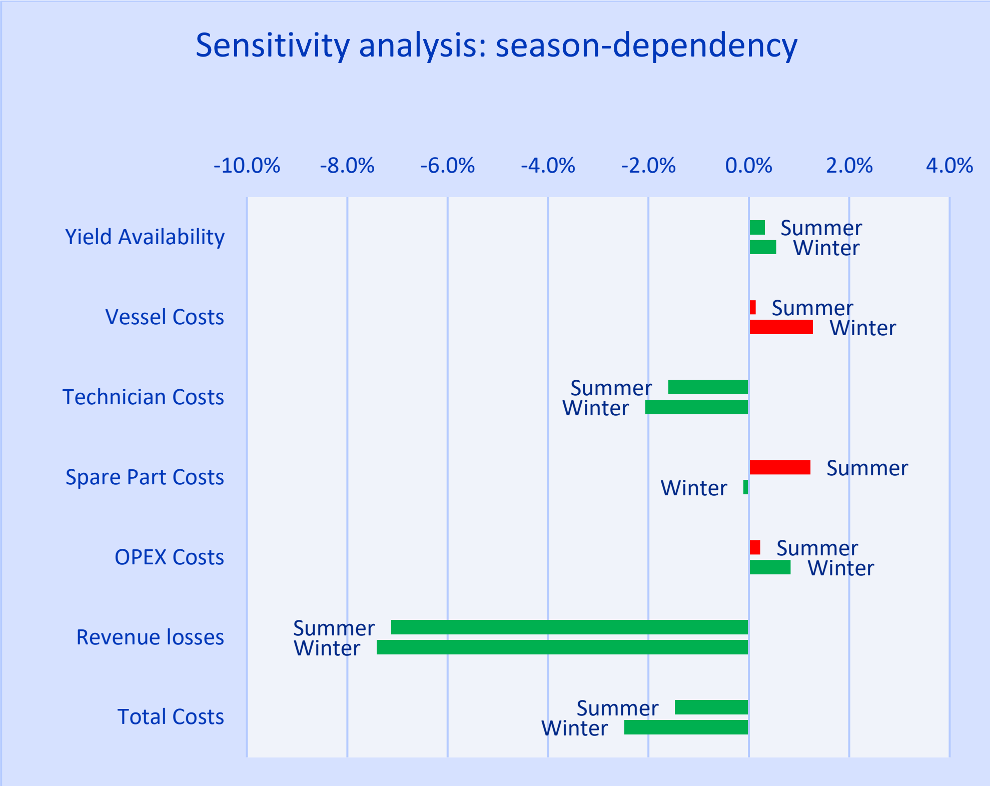

Figure 16 Seasonal sensitivity on the business case.

		Summer			Winter		
	Unit	Existing state of the art	Ship-to-ship supply	Δ [%]	Existing state of the art	Ship-to-ship supply	Δ [%]
Yield Availability	[%]	94.0	94.3	0.3%	90.4	90.9	0.5%
Vessel Costs	[M€/year]	517	518	0.1%	524	530	1.3%
Technician Costs	[M€/year]	35	35	-1.6%	40	39	-2.1%
Spare Part Costs	[M€/year]	95	96	1.2%	93	93	-0.1%
OPEX Costs	[M€/year]	724	725	0.2%	732	739	0.8%
Revenue losses	[M€/year]	218	203	-7.1%	492	456	-7.4%
Total Costs	[M€/year]	942	928	-1.5%	1,225	1,194	-2.5%

Table 10 Seasonal sensitivity on the business case.

The benefits of ship-to-ship supply are even larger for the winter-only scenario than for the summer-only scenario. This is due to the higher average wind speeds and therefore wind farm yield during the winter season. Even though the vessel costs have increased, the larger reduction of the revenue losses compensates for this effect. It is very important to aim for the highest availability of wind farms during the period with most wind.

3.2.4 Number of SOV's serviced per supply vessel run

In the base scenario a supply vessel only services two SOV's in one supply run, following the assumption that those two SOV's are serving one wind farm with one owner. In today's wind turbines, we see an aim in the designs to reduce the OPEX and maximise the uptime due to the paramount effect of energy yield on the business case. This could lead to a reduced

number of SOV’s per GW of offshore wind farm. One SOV could potentially cover the full 1.5GW concession size we have assumed. It could even be possible that one SOV covers offshore wind farms of more than one owner. In that case the spare part consumption and potentially the number of wind turbine technicians per SOV would go down.
To determine the effect of servicing multiple SOV’s per supply vessel run the number of SOV’s is varied. The cost of the supply vessel per SOV for different number of SOV’s per supply runs is shown in Figure 17 and Table 11.

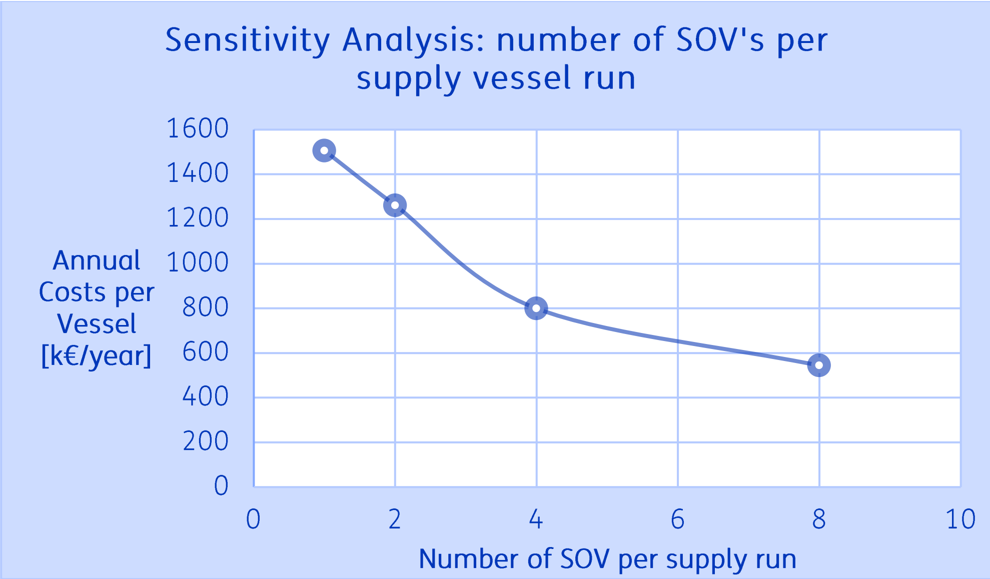

Figure 17 The vessel cost per SOV for different number of SOV’s per supply vessel run

Number of SOV per supply run	Unit	1 SOV	2 SOV’s	4 SOV’s	8 SOV’s
Cost/vessel	[k€/year]	1,506	1,262	800	544

Table 11 The vessel cost per SOV for different number of SOV’s per supply vessel run

It is clear increasing the amount of SOV’s serviced in a supply run will decrease the total costs. The effect on the whole scenario is shown in Figure 18 and Table 12.

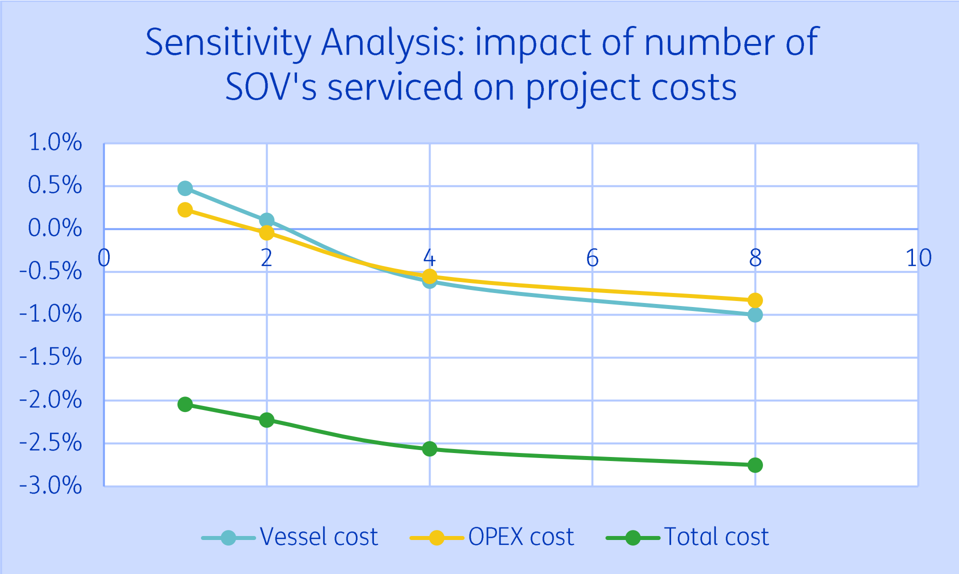

Figure 18 The sensitivity of the number of SOV's per supply run on the business case.

	Unit	Status quo	1 SOV	Δ [%]	2 SOV	Δ [%]	4 SOV	Δ [%]	8 SOV	Δ [%]
Vessel Costs	[M€/year]	522	524	0.5%	522	0.1%	518	-0.6%	516	-1.0%
OPEX Costs	[M€/year]	729	731	0.2%	729	0.0%	725	-0.6%	723	-0.8%
Total Costs	[M€/year]	1091	1068	-2.0%	1066	-2.2%	1063	-2.6%	1061	-2.8%

Table 12 The sensitivity of the number of SOV in a supply run on the business case.

By attending more SOV's per supply run, the benefits of ship-to-ship supply increase. This will of course also increase the complexity of the logistic system as multiple wind farm owners are likely serviced per supply run. The impact on the availability of the wind farm could not be modelled using different SOV's due to the extrapolation method. This could be determined in a future study.

If a supply vessel would service more SOV's in one run, it should have enough capacity to resupply all these ships. Especially the fuel capacity of the supply vessel is considered as a limiting factor. An SOV needs 150-200 tonnes of fuel per month and supply vessels are legally limited to a maximum fuel capacity of 999 tonnes. A Higher fuel capacity would require a different ship classification. Due to this limit, a supply vessel can supply up to five SOV's per supply run. No further investigation was done to the limits caused by spare parts, provisions and drinking water in this study.

Energy islands have been mentioned as potential future development in the North Sea. Large fuel storage for supply vessels on energy hubs could be used in the future to alleviate the fuel capacity bottleneck. This is however not in the scope of this study. Studies performed for the North Sea Wind Power Hub, looking at the effects of an energy island for offshore wind, have not shown significant impact on cost reductions on OPEX or LCoE [12].

3.3 Conclusion

Using the ship-to-ship supply concept instead of the conventional method of sailing the SOV's back to port is found to be beneficial for the wind farm yield and the total project costs. The performed sensitivity analysis shows that the concept is still beneficial while key parameters are varied. What is also shown as a promising next step is to attend more SOV's per supply vessel run, which results in a larger example of the milk run principle. This will however require the collaboration of wind farm owners, which is currently not often done, due to potential disputes over priority.

The ship-to-ship supply concept required the transfer of goods and personnel between vessels. It is not yet widely accepted that this can be done safely, nor are the circumstances in which this could happen agreed upon. Further research and developments into methodologies and technologies to make these transfers safe and fast are required to ensure adaptation by the industry. While large scale solutions exist for personnel transfer (e.g. the *Ampelmann* platforms), this is not yet widely used in smaller applications or in the transfer of goods.

4 The effects of innovations

Research has been done to answer the secondary research questions.

1. With the findings from the main research question: what does the "Service Operations Vessel 2.0" need to be capable of?
2. What are the possibilities for autonomous sailing of the supply vessels involved because of this fixed timetable/ fixed route approach and what possibilities are opened for combining more than one supply vessel through platooning?

Innovations can further increase the wind farm yield and decrease the operational costs. The concepts that were introduced in Section 2.4 were evaluated and compared with the basic sea-to-sea-supply scenario to assess their potential. For each innovation 100 simulations were evaluated, based on ten historical weather years and ten seeds for randomised technical failures.

4.1 Service Operations Vessel 2.0

Because TNO in this chapter has not yet created the overview of all the foreseen required functionalities of the future (beyond 2030) Service Operation Vessel, this topic will be described further in Chapter Error! Reference source not found..

4.2 The effects of supply vessel automation

University of Antwerp has assessed the effect of automated supply vessels on the ship-to-ship supply scenario [11]. Their report can be found in Annex I.

4.2.1 Results

The analysis was based on input from the consortium partners and the TNO simulations. The number of SOV's that are serviced by a supply vessel was treated as a variable and three cases are considered with 2, 4 and 6 SOV's. Multiple crew ethnicities were also evaluated, as this is quite common in offshore industries [11]. The results of the most expensive crew are shown in Figure 19 for all four wind farms in this study.
The University of Antwerp has assessed the effect of automated supply vessels on the ship-to-ship supply scenario [11]. The analysis was based on input from the consortium partners and the TNO simulations. The number of SOV's that are serviced by a supply vessel was treated as a variable, for which the values 2, 4 and 6 SOV's were used. Multiple crew ethnicities, with their respective cost implications, were also evaluated, as this is quite common in offshore industries [11]. The results of the most expensive crew are shown in Figure 19 for all four wind farms in this study.

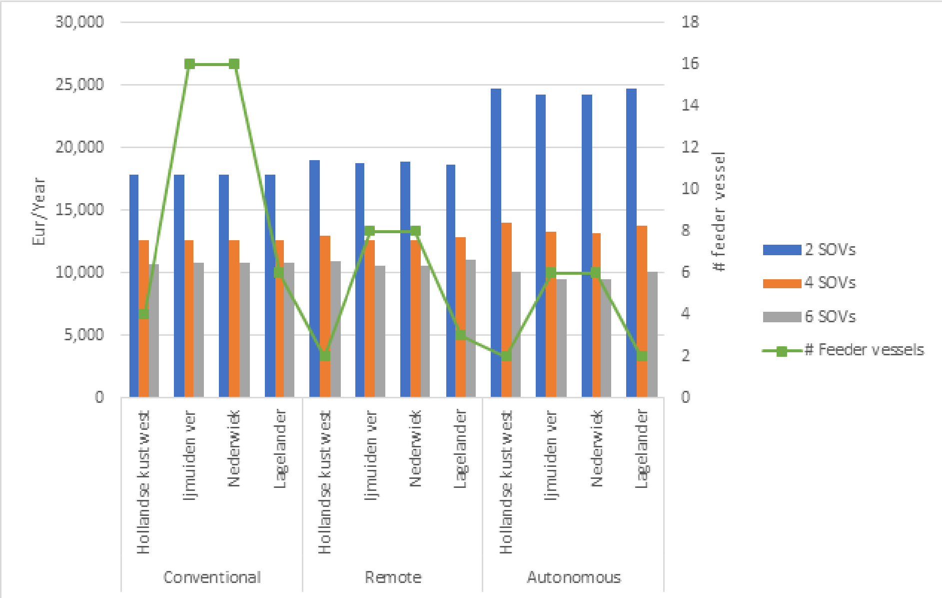

Figure 19: results of supply vessel automation analysis. [11]

It is seen that for servicing two (blue bars) or four (red bars) SOV's the overall costs of automated supply vessels (right hand side of the graph) are higher than those of conventional vessels (left hand side of the graph). Only for the situation where six SOV's are serviced, benefits become visible for using autonomous vessels.
Figure 20 shows the results of the evaluated automation scenarios relative to the conventional scenario.

The fully automated options show lower transport costs, which is why they become more favourable when a higher number of SOV's is serviced. Towards the further future (beyond 2030) when SOV's potentially cover more than 1.5 GW and autonomous vessels are more technically and economically mature, this option could see more adoption.

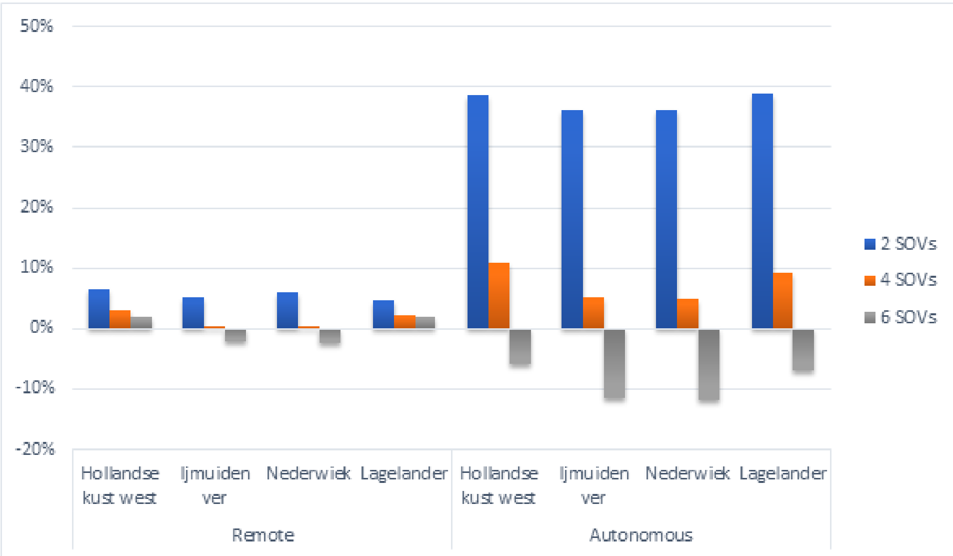

Figure 20: Cost comparison of the automation types versus the conventional supply vessels [11]

4.2.2 Conclusions

This analysis shows that the most economic option for servicing two SOV's is the conventional supply vessel. It should be noted that these results were derived from a particular set of input parameters. If certain assumptions are changed, the outcome of this analysis might become more favourable of automation.

While remote controlled vessels show an increase in costs between 4% and 8% when compared with conventional vessels, there might be reasons to accept this increase. During one of the workshops with the consortium it was stated that it is difficult to find sufficient personnel to staff these vessels. Remote controlled ships could reduce or change the roles of personnel, increasing the chance to find personnel. Another advantage of less or no personnel on board that was mentioned is safety, since people are further removed from potentially dangerous situations.

During writing of this report, it is not feasible to sail fully autonomously on Dutch territorial waters, due to missing legislation. Remote controlled vessels have been used in small numbers, but only on an experimental scale. Changing legislation could increase the interest of potential developers and future adapters of this technology.

4.3 The effects of drones

The applications of drones have been investigated in combination with the ship-to-ship supply. The next subsections show the results of the three different fields that were identified for the application of drones: on-demand spare parts, offshore handling of oil/gas platforms and external inspection of wind farm subsystems. All three options are compared with the ship-to-ship supply scenario. In the end all drone options are combined to show the potential benefits of the complete drone scope.

4.3.1 On-demand spare parts

In Figure 21 and Table 13 the on-demand vessel is replaced by a USV. A reduction is seen in the vessel costs and an increase is seen in wind farm availability. The reduction in vessel costs is caused solely by the reduced cost of the USV, in comparison with the conventional on-demand vessel. The increase in wind farm availability is due to the larger weather workability of the USV. It is important to note that no research was done into smaller non-automated on-demand vessels. A smaller vessel could give a reduction as well.

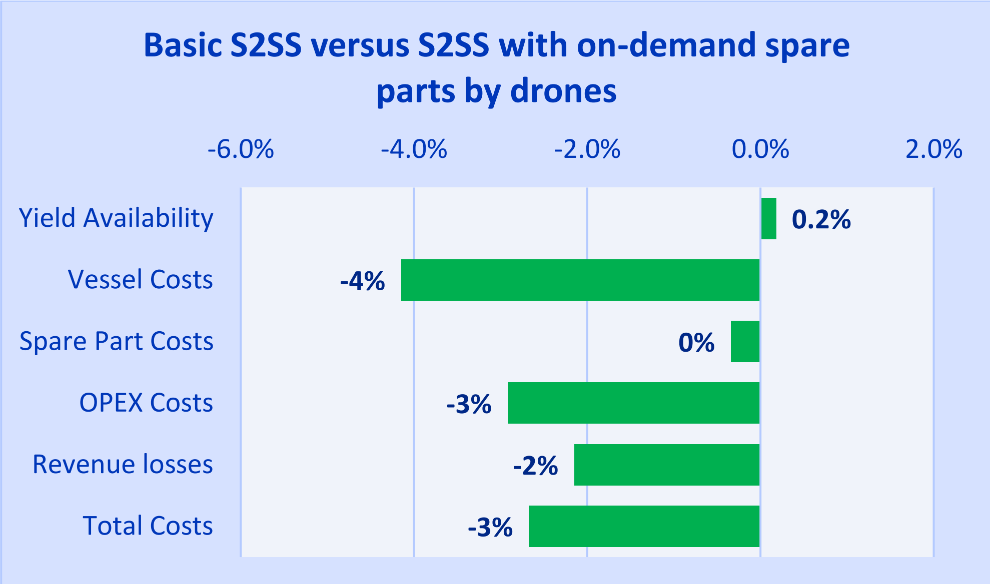

Figure 21 Comparison of the basic ship-to-ship supply scenario with the replacement of the on-demand spare part stream with drones.

	Unit	S2SS	S2SS + On-demand Drones	Δ [%]	Δ [M€/year]
Yield Availability	[%]	92.4	92.4	0.2%	
Vessel Costs	[M€/year]	522	506	-4%	-22
Spare Part Costs	[M€/year]	36	36	0%	0
OPEX Costs	[M€/year]	729	714	-3%	-21
Revenue losses	[M€/year]	337	338	-2%	-7
Total Costs	[M€/year]	1066	1052	-3%	-29

Table 13 Comparison of the basic ship-to-ship supply scenario with the replacement of the on-demand spare part stream with drones.

4.3.2 Offshore handling of oil/gas platforms

The offshore handling of the oil/gas platforms by SOV's or their daughter craft is replaced by drones. The offshore handling is assumed to be divided equally between an aerial drone and a USV. Both drones are assumed to be stationed at the SOV. The results are shown in Table 14. The results are net negative, close to zero. The vessel costs are stable due to the USV being more expensive than a daughter craft and the aerial drone being less expensive. An increase in availability was expected, due to the SOV daughter craft not performing this action. As it is a short action it can be weaved nicely in with other work orders. Due to this no change in availability is seen. If more offshore platforms are serviced, this phenomenon could be noticed but was not done in this study. This replacement on its own is not deemed economical.

	Unit	S2SS	Offshore Handling Drone	Δ [%]	Δ [M€/year]
Yield Availability	[%]	92.4	92.4	0.0%	
Vessel Costs	[M€/year]	528	527	0%	1
Technician Costs	[M€/year]	522	523	0%	1
Spare Part Costs	[M€/year]	36	36	0%	0
OPEX Costs	[M€/year]	95	95	1%	1
Revenue losses	[M€/year]	729	731	0%	2
Total Costs	[M€/year]	337	337	0%	0

Table 14 Comparison of the basic ship-to-ship supply scenario with the replacement of the offshore handling action by drones.

Even though on macro scale no immediate benefit is seen it could be a benefit if achieved on day-to-day scale as it could release pressure of the planning.

4.3.3 External inspection of wind farm subsystems

Currently inspections of wind farm subsystems like rotor blades, towers or foundations are performed by technicians, based on SOV's or their daughter craft. By executing these activities with a USV (with an aerial drone), this frees up the SOV and daughter craft for other activities. This results in better plannability of maintenance actions and decreases the risk of delays due to unavailability of the SOV. In Figure 22 and Table 15 the results are shown in comparison to the basic S2SS scenario. Since the USV and the drone are more expensive than a conventional daughter craft, a slight increase in vessel cost is accumulated. A reduction in technician cost is shown since less technicians are used during maintenance. The largest benefit comes from the increase in wind farm availability. This results in a net benefit for the whole scenario. Important to note is that this scenario will require the presence of a USV, which likely has to be harboured somewhere with the SOV. Alternatively, they could sail to the wind farms upon request.

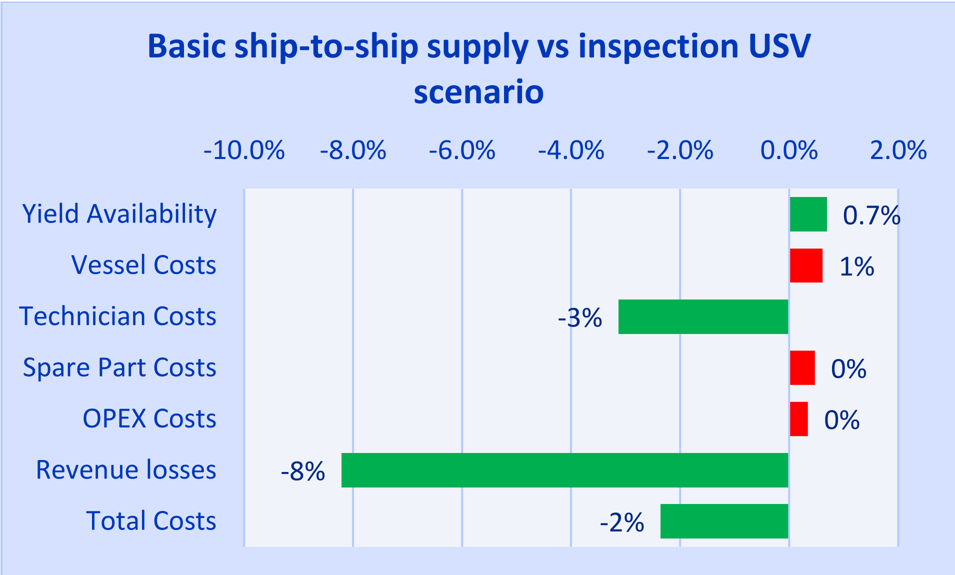

Figure 22 Comparison of the basic ship-to-ship supply scenario with the replacement of the inspection phase of outer components with drones.

	Unit	Basic S2SS	S2SS and Inspection Drone	Δ [%]	Δ [M€/year]
Yield Availability	[%]	92.4	93.0	0.7%	
Vessel Costs	[M€/year]	522	525	1%	3
Technician Costs	[M€/year]	36	35	-3%	-1
Spare Part Costs	[M€/year]	95	95	0%	0
OPEX Costs	[M€/year]	729	732	0%	3
Revenue losses	[M€/year]	337	310	-8%	-28
Total Costs	[M€/year]	1066	1041	-2%	-25

Table 15: Comparison of the basic ship-to-ship supply scenario with the replacement of the inspection phase of outer components with drones.

4.3.4 All drone applications

The combination of all drone applications is used in this scenario. The inspection USV is now used for both offshore handling and inspection. The on-demand USV is still modelled as a separate vessel. The results are shown in Figure 23 and Table 16.The combination results in a higher wind farm availability and a reduction in total project costs. The higher availability is mostly due to the external inspection action. Majority of the reduced costs are contributed by the change of the on-demand spare parts stream and a small contribution from the reduction of the cost of offshore handling. The total benefits are similar to the sum of the individual benefits. All options could therefore be implemented separately or combined. To strengthen these results, future studies should be performed around the application of drones in O&M activities.

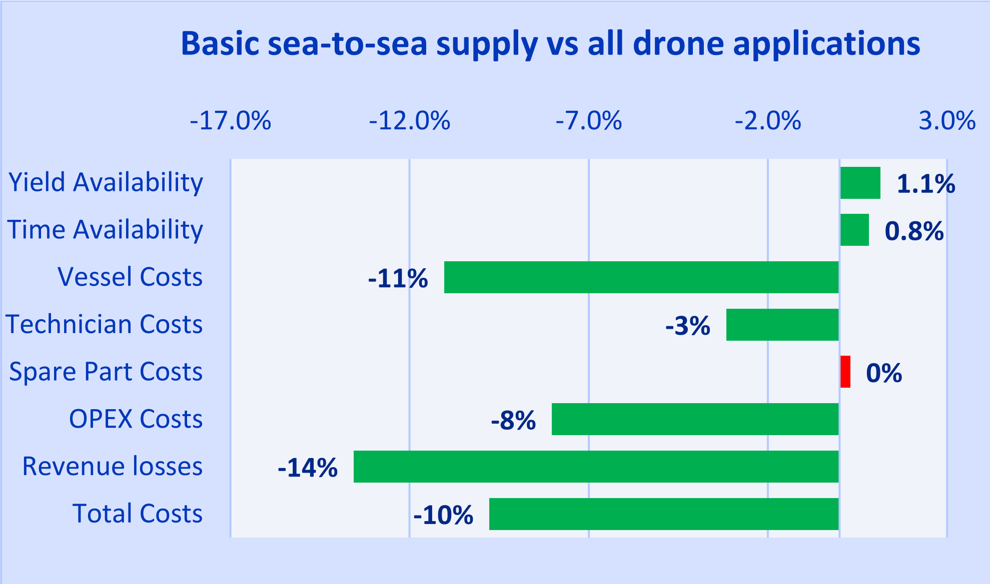

Figure 23: Comparison of the basic ship-to-ship supply scenario with the combination of all drone applications.

	Unit	Basic S2SS	S2SS with all drone applications	Δ [%]	Δ [M€/year]
Yield Availability	[%]	92.4	93.5	1.1%	n.a.
Vessel Costs	[M€/year]	522	464	-11%	-58
Technician Costs	[M€/year]	36	35	-3%	-1
Spare Part Costs	[M€/year]	95	95	0%	0
OPEX Costs	[M€/year]	729	671	-8%	-58
Revenue losses	[M€/year]	337	292	-14%	-46
Total Costs	[M€/year]	1066	962	-10%	-104

Table 16 Comparison of the basic ship-to-ship supply scenario with the combination of all drone applications.

4.4 Conclusion

The development of drones is going at a very rapid pace, where the next generation of drones could already be applied within the next few years. When the capacity of airborne drones substantially increases, the balance between airborne drones and USV's could shift significantly. This might result in the application of airborne drones to be applied for transporting on-demand spare parts, where they are currently assumed to be transported solely by USV's. If this happens, the response times will be significantly reduced.

Similar as with autonomous vehicles, legislation can hamper the implementation of drones into the O&M activities. Proper advising governmental bodies about the opportunities, limits and risks of drones should go hand in hand with the technological development and the implementation in the industry.

5 2050 Outlook

In the year 2050, the Dutch government expects 70 GW of offshore wind power to be installed in Dutch waters, connecting to offshore wind farm zones in the United Kingdom, Germany and Denmark.

Because technology is expected to develop rapidly, this 2050 outlook comprises the sea-to-sea supply concept and all innovations that are found to be beneficial from the previous sections as fully applied technology in 2050.

Airborne drones (Section 2.4.2) Deploying airborne drones for inspections of wind turbine rotors, towers and foundations will be common practice. Airborne drones could either “live” inside the wind farm with a fixed docking station(s) for power and data transfer or be docked on the SOV2.0 It is also imaginable that airborne drones will be widely used for distribution of “on-demand” spare parts from onshore facilities.

Unmanned Surface Vessels (Section 2.4.2): with larger areas to be covered by SOV, the previous conclusion was that the business case is improved by using USV’s for delivering on-demand spare parts to the SOV, handling packages for oil/gas platforms and performing inspections. Similar to the airborne drones, the USV’s can either “live” inside the wind farm with a fixed docking station(s) for power and data transfer or be docked on the SOV2.0

As described in section 2.5 an extrapolation was done to obtain insight in the new concept’s potential by projecting it onto the expected situation in 2050. The existing state of the art was compared with a scenario containing ship-to-ship supply and all drone innovations. This represents the difference between keeping business as usual and simply enlarging the operations, with implementing new processes and technologies.

5.1 Results

The results of the 2050 outlook scenario are shown in Figure 24 and Table 17. In general, a positive result is shown with the yield availability increasing by 1% and the total project costs being reduced by almost 12%.
The Ship-to-ship supply concept mainly affects the yield availability, while the drone applications are mostly responsible for the cost reductions. The increase in spare parts costs can be explained by the fact that a higher wind farm availability results in more wear and tear of wind turbines, leading to more failures. This is a known effect of the UWiSE model as it is stochastic. The vessel costs are further reduced compared to the scenario where all drone applications were combined. This can be attributed to the larger average distance towards the wind farms.

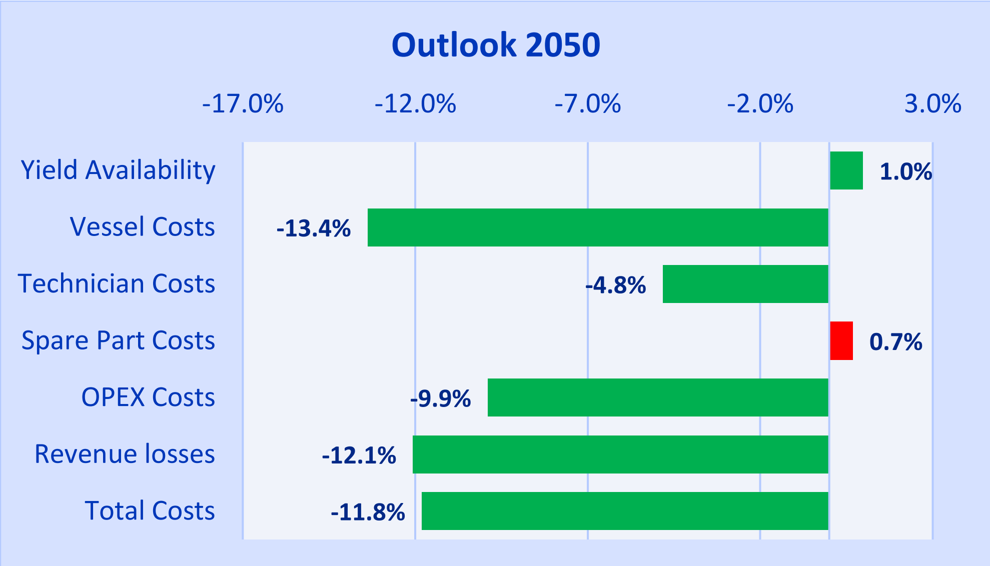

Figure 24 Results for outlook 2050

	Unit	Existing state of the art	S2SS + all innovations	Δ [%]	Δ [M€/year]
Yield Availability	[%]	92.5	93.4	1.0%	n.a.
Vessel Costs	[M€/year]	925	801	-13%	-124
Technician Costs	[M€/year]	60	57	-5%	-3
Spare Part Costs	[M€/year]	157	158	1%	1
OPEX Costs	[M€/year]	1,269	1,143	-10%	-126
Revenue losses	[M€/year]	556	489	-12%	-67
Total Costs	[M€/year]	1,824	1,632	-12%	-193

Table 17 Outlook for 2050 for the existing state of the art scenario and the combination of ship-to-ship supply plus all innovations for 30 GW and 40 oil/gas platforms .

5.2 Conclusions

This simulation is dependent on assumptions done in 2023 for the year 2050, so there is a high level of uncertainty in the results. The recent war in Ukraine has shown that the world can look vastly different within a year's time. It is however shown that there is potential to optimise towards the future by implementing new methods and technology.

One could argue that within the coming 20+ years autonomous sailing is likely to be applied to some extent. It could be interesting to expand the automation study by the University of Antwerp with more scenarios and varying inputs, to assess potential benefits in that field.

With the assumed methodologies that were used to determine the results of the 2050 outlook scenario, several changes to the design of SOV's should be done to make them fit for purpose

- SOV’s need to have equipment and facilities to safely transfer goods and personnel between itself, the supply vessel and the FCS’s.
- SOV’s should be equipped for permanent residence of one or more daughter craft.
- SOV’s could be equipped for the permanent residence of an USV and an airborne drone
- Marine crew quarters could be made more comfortable, due to the longer period away from the conveniences of onshore facilities.

Since the current generation of SOV’s could already stay out at sea for very long periods of time from a technical perspective, no statements are made about structural changes to the vessel, nor its corrosion resistance capabilities.

6 Required port functionalities

To be able to meet the demanding increase in offshore wind energy, the Port of Den Helder will use the results of this report to validate the intended Port Development Steps of *Maritiem Cluster Den Helder* [12] with the market demands. The roadmap that was set up for this change, consists of several major steps:

1. Removing the *Moormanbrug*, to give access to a larger part of *Het Nieuwe Diep*.
2. Improving and restructuring of the quay wall of *Het Nieuwe Diep* to function as a logistic hub.
3. Developing a logistical hub in Den Helder's inner harbour at *Kooyhaven*
4. Development of a logistical hub at *Harssens*, from which the supply vessels and crew transfer vessels will depart to service the SOV's in the wind farms.

These steps were set up based on the results of a previous study by TNO [2] that indicated the need of 4 to 6 hectares of space to be realised for these activities. This will result in an efficient port area and supply chain that are fit to service a significant part of the offshore wind farms in the Dutch territorial waters. To ensure this roadmap aligns with the (technological) developments of the future and is cost-effective, the results of the ship-to-ship supply concept can be used to validate the order of magnitude of the port size requirements. Secondary, the required seaport infrastructure is assessed based on the results of the assessment of automation and an exploration with the consortium partners and Royal Haskoning DHV.

6.1 Sea port size requirements

In Section 3.1.4 the resulting port calls are presented for the Existing state of the art scenario and the ship-to-ship supply scenario. The number of port calls were determined for SOV's, supply vessels, personnel transfer vessels and on-demand vessels. As mentioned, the TNO study from 2019 indicated that the Port of Den Helder could have a 30-50% share of the wind power market on the North Sea in both 2030 and 2050 [2]. The number of expected port calls were therefore determined both for the 2030 situation and for the 2050 situation.

For 2030, the 9 GW-share of wind farms would be serviced by twelve SOV's, for which the required port calls were derived from the model results. The following assumptions are used to derive the required quay length in the port:

1. Vessels are serviced 24 hours per day
2. The zones for goods and personnel transfer are separated
3. On demand vessels have their own location, to ensure a quick response time.
4. Quay length required per vessel type are estimated, based on ship lengths of example vessels
5. The FCS types are assumed to use the same berth

All results are shown in Table 18.

Vessel type	Annual port calls	Daily port calls	Service time [hrs]	Quay length required per berth [m]
Supply vessels	78	0.2	6	120
FCS (small)	234	0.6	2	60
FCS (Large)	78	0.2	2	60
On-demand vessels	414	1.1	2	120

Table 18: vessel types and their berth requirements for the situation in 2030

For the expected situation of 2050, same assumptions apply that were shown for 2030. The only change is that the on-demand vessels are now replaced by USV's, following the reasoning from Chapter **Error! Reference source not found.**. The results are shown in Table 19.

Vessel type	Annual port calls	Daily port calls	Service time [hrs]	Quay length required per berth [m]
Supply vessels	260	0.7	6	120
FCS (small)	780	2.1	2	60
FCS (Large)	260	0.7	2	60
On-demand vessels	1,380	3.8	2	60

Table 19: vessel types and their berth requirements for the situation in 2050

Vessels servicing different wind farms could all have separate berths, although that results in inefficient use of quay space. With collaboration between wind farm owners and proper logistic planning it could be possible to make use of the same quay space. Since it is not known up to what extent this will be possible, this report does not provide absolute numbers for the quay length that is required. However, no evidence was found in this study that the proposed setup specified in the report [12] of the *Maritiem Cluster Den Helder* needs to be adjusted.

The floor space requirements as indicated by TNO in 2019 are still deemed valid. The presented ship-to-ship supply is intended to increase efficiency in the entire logistical chain for O&M activities in offshore wind, which would theoretically reduce the floor space required. It is expected that this reduction will be compensated by the increased ambitions of the Dutch government in terms of installed wind power in 2030, and the potential onshore activities around electrolysis, tidal energy and sea weed harvesting.

The anticipated intensification of the port area use will increase the need of the combined use of the seaport and the logistic hub at *Kooyhaven*. Connecting these two locations with reliable logistics will enable the most efficient use of the scarce seaport area.

6.2 The effect of automation on the required port infrastructure

University of Antwerp assessed the impact of automated infrastructure on the costs of the port by comparing the economic performance of autonomous vessels with that of conventional vessels for in-port logistics. The remote-controlled vessel option, that was used as an intermediate level of automation in Section 2.4.1, is not considered a feasible option for inland shipping and is therefore not presented in this section. They are mostly suitable for open waters with less traffic and fewer collision risks [11].

6.2.1 In-port logistics analysis

The in-port logistics model as developed by the University of Antwerp determines the costs of three transport modalities to transport cargo from the inner harbour in *Kooyhaven* to the sea port. The three transport modalities

1. Conventional inland vessels
2. Autonomous inland vessels
3. Road transport

The costs comprise of the shore control centre costs, voyage costs, operating costs and capital costs [11]. For the first two modalities, four ship classes were evaluated, ranging from small to larger vessels. In addition, two sailing regimes were used for the two vessel modalities, representing the operational windows. Under regime A, vessels sail for 14 hours per day, 5 days per week. Regime B allows vessels to sail 24/7.

It was found that Regime A would lead to a more economically appealing situation. Based on this, the results of the three different transport modalities are shown in Figure 25.

It was concluded that due to the relatively low cargo flow and the short distance that is covered, the smallest conventional vessel is the most economic option [11].

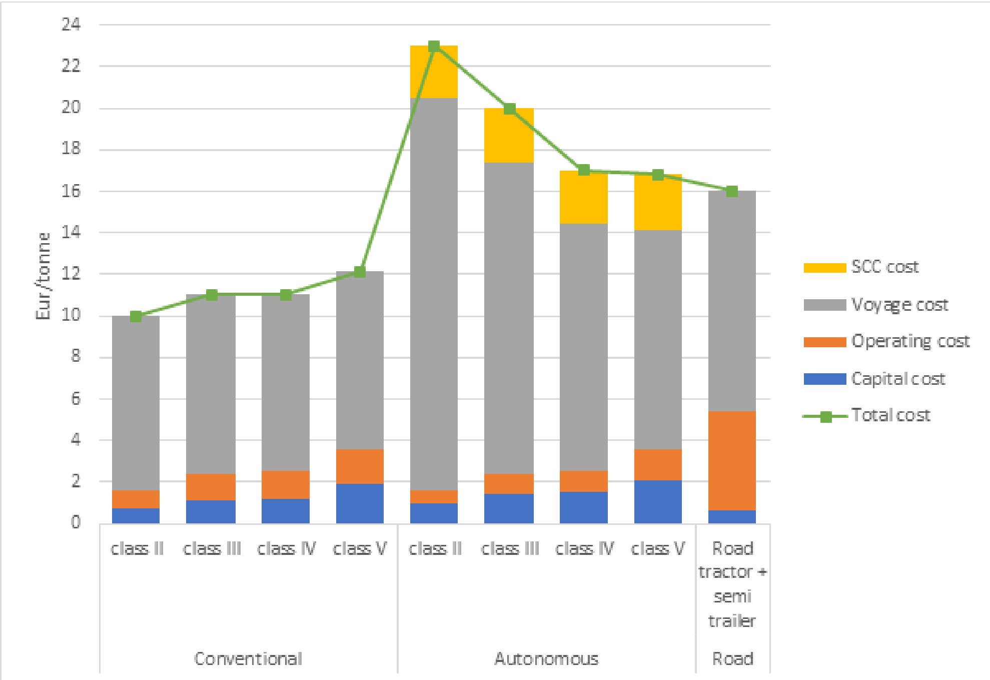

Figure 25: Results of in-port logistics analysis [11]

6.2.2 Terminal investment analysis

In addition to the analysis of the in-port logistics, a terminal investment analysis was done for both the conventional and the automated scenario. the required terminal rate is determined in Euro/tonne, resulting in a Net Present Value (NPV) of the different options. This represents the costs of owning and operating a terminal [11]. The full model setup can be found in Annex I.

Based on a cargo throughput of 202,000 tonnes per year and a set of input parameters specified by the consortium, the costs were evaluated for four terminal types; conventional and autonomous both for a truck terminal and for a vessel terminal. The results are shown in Figure 26.

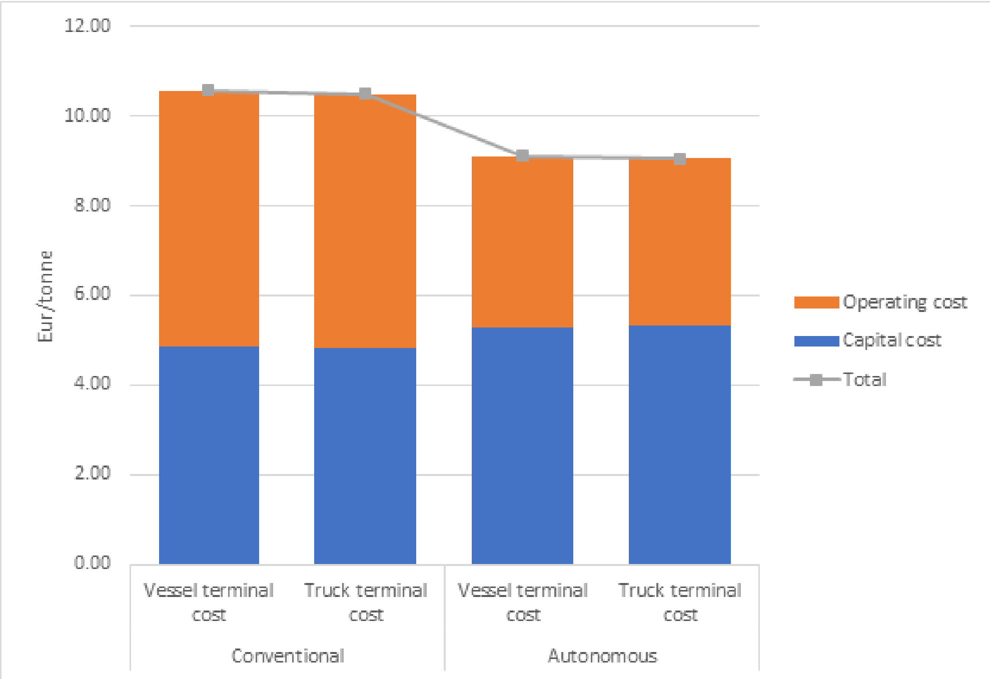

Figure 26: Results of terminal investment analysis [11]

It is found that there is no significant difference between a vessel terminal and a truck terminal in both levels of autonomy. The autonomous terminal does show lower total costs than the conventional terminal.

6.2.3 Conclusions

The combination of a small cargo flow and short inland sailing distance results in an unfavourable business case for automating the inland vessels. Since this analysis is performed on specific input parameters, a wider study could be performed to investigate under which circumstances the use of autonomous vessels would be recommendable. Increasing the cargo flow is the first area that could be considered, which might be achievable by combining the cargo flows for the offshore wind farms with other cargo flows towards the sea port.

6.3 Exploration into port infrastructure requirements and options

Port of Den Helder has requested Royal Haskoning DHV to make an initial exploration study into future trends and developments in port infrastructure and technologies, as a result of the findings of this study. The results of this explorational study were discussed during a workshop with many of the consortium partners. Below the discussed topics are described, followed by the recommendation or areas of attention for their use in the Port of Den Helder (also applicable for other Dutch O&M ports) in light of O&M activities for offshore wind.

6.3.1 Shore power

Future trends often include electrification, which is also identified as a crucial step in the adaptation of renewable energy in The Netherlands [10]. To enable future-proof port logistics, widely available shore power is identified as important facility for the upgrade of the Port of Den Helder.

6.3.2 Automated handling

Handling of cargo has already successfully been automated in large container terminals, like on the *Tweede Maasvlakte*. Both cranes and transport equipment have been relieved of human intervention to cut down on human resource costs and to reduce human errors.

- For the smaller cargo volumes that are expected in this project, this will not likely be beneficial for the costs, as it requires a high investment.
- Quays where these types of operations are done need to be blocked off for personnel and will require fixed setups.
- This option is not considered as a (large) time-saver yet.
- Key parameters for deciding on automated handling are the total cargo volume and the cargo size variety.
- Automated handling could become a relevant feature if the O&M supply chain allows standardisation of its cargo flows in the future, for example by using standard spare part sets.

6.3.3 Energy island

Artificial islands as a concept for energy storage and conversion is on the agenda in several European countries. With adjustments, these islands could also be suitable for acting as storage and distribution hub for O&M activities. (12]

- The costs of building an energy island are incredibly large, making it very expensive land. It will be far more expensive to reserve space on an artificial island than in an existing port for O&M activities. This is therefore not considered as an economically feasible option. [13]
- If an energy island is made in the future, it will still require logistic streams from the mainland, possibly from the port of Den Helder. If the onshore logistics are already routed via Den Helder, it would make sense to investigate the required infrastructure adjustments for energy island servicing.

6.3.4 Remote pilotage

Conventionally, pilots are sailed to incoming vessels to help navigate vessels in the port areas. By relocating this function to shore and have the pilots perform their guidance via remote control, they save time and therefore increase their efficiency and safety.

- For vessels up to 85m there is a dispensation in place with approved Pilot Exemption Certificates (PEC): the captain or first mate is exempt from compulsory pilotage if proved by the authorities.
- Due to possible new pilotage legislation, remote piloting could be beneficial, if Den Helder can no longer make use of the dispensation as stated above.

6.3.5 Roll-on-roll-off (Ro-Ro)

The Roll-on-roll-off principle uses ramp structures on the quay and fixed berths for vessels to allow rolling cargo to move directly onto the vessels. An example of a Ro-Ro solution is the ferry service between Den Helder and the island of Texel.

- Roll-on-roll-off has its advantages, but it requires large investments and has its limits as well (e.g. you would likely need to jack up a vessel in port before loading heavy cargo)
- On its own, a Ro-Ro solution makes a challenging business case, but in case an existing ramp is present, or one is required for other purposes, it can provide an additional logistic option of loading cargo. In case of the Port of Den Helder, this might be combined with the indicated emergency ramp for the Den Helder-Texel ferry, or with activities in Oil & Gas logistics.
- This solution is considered as a nice-to-have solution, due to the high costs. If this option is considered, an assessment is required to determine the applicability with respect to the expected cargo types for offshore wind.

6.3.6 Automated mooring

Automated mooring systems can take over the function of conventional mooring methods (bollards and ropes), saving time in the mooring process. Due to their elimination of the human intervention, they can increase operational efficiency and improve safety of the mooring operation.

- Automated mooring can be done with magnetic or vacuum clamps. They can save time in the operations, but they are expensive.
- What this solution lacks is flexibility, as ships will need to dock at specific locations for these solutions to work.
- Automated mooring is not suited for higher sea states, so conventional bollards will still be required on the quays.
- A big question for the applicability of automated mooring systems is if there is sufficient quay space to fit them in.

7 Conclusions and recommendations

7.1 Ship-to-ship supply of wind farm-bound SOV's

In this section the main research question of this study is answered: Is it possible to increase the yield and reduce the Operation & Maintenance costs of offshore wind farms by applying ship-to-ship supply of SOV's, following fixed schedules?

- Ship-to-ship supplying of wind farm-bound SOV's, following fixed schedules can significantly contribute to reducing the Levelized Cost of Energy with more than 2%. This conclusion remains intact with varying energy prices (but lower total project costs reduction in case of lower MWh pricing), increasing vessel day rates (increasing total project costs reduction at higher day rates), more than one SOV serviced (the more the better) and despite seasonality (higher total project costs reduction at higher wind speeds). When the basic ship-to-ship supply scenario is compared with the Existing state of the art scenario, the yield availability of the wind farm is increased by 0.6%. The total project costs for this scenario are reduced by 2.2%. The increased vessel costs that are implied by the ship-to-ship supply scenario are more than compensated by the large decrease of revenue losses

Sensitivity analyses have been performed to assess the robustness of the outcomes, showing that the ship-to-ship supply scenario remains beneficial, even when varying key parameters. The conclusions of these analyses are:

- Varying the electricity sales prices does not impact the yield availability of the wind farm but impacts the total project cost reduction negatively. The business case is still found in favour of the Ship-to-ship supply scenario.
- The vessel costs were varied with 20%, which had no effect on the wind farm availability, and only a minor influence on the reduced total project costs. The ship-to-ship supply scenario is found beneficial.
- It was found that ship-to-ship supply is still beneficial during the winter months, where the weather conditions are likely to increase the duration of O&M activities. It was even shown that due to the high wind speeds during that season, it is even more beneficial than during the summer months.
- It was shown that by servicing a higher number of SOV's will result in even larger cost savings by using the ship-to-ship supply scenario.

Finally, it was determined how well the new logistical concept holds up in the farther future by extrapolating the results to the expected situation for the Port of Den Helder in 2050.

- The ship-to-ship supply concept, combined with the application of drones is found to increase the availability of wind farms with 1%, while reducing the total project costs with 12%.

It can be concluded that the concepts that are presented in this study show promising results, both on the medium term (2030) and the long term (2050)

7.2 Capabilities of SOV 2.0

One of the secondary research questions is to determine what the next generation of SOV's should be capable of. Based on the presented methods, results and the outlook towards 2050, the potential new features of the next generation of SOV's have been deducted:

- SOV's need to have equipment and facilities to safely transfer goods and personnel between itself, the supply vessel and the FCS's.
- SOV's should be equipped for permanent residence of one or more daughter craft.
- SOV's could be equipped for the permanent residence of an USV and an airborne drone. This would also imply that the SOV is outfitted with a drone control room
- Marine crew quarters could be made more comfortable, due to the longer period away from the conveniences of onshore facilities.

It should be noted that no statements are made about the size of the future generation SOV's. Arguments were presented by consortium mentioned for both larger and smaller SOV's, hence no solid conclusion was reached.

7.3 Innovations

Conclusions about the possibilities for autonomous sailing of the supply vessels originates from the workshops with the consortium, and the study by the University of Antwerp.

- It is concluded on a qualitative level that platooning is not desirable for offshore activities, since it is more effective to travel in a straight line to a destination. Traveling in a circle to follow another vessel would only increase the costs.
- For the evaluated case study around the Port of Den Helder, automation of the supply vessels only becomes beneficial if supply vessels service at least six SOV's.
- Remote controlled vessels were not found to be beneficial within the bounds of the performed case study

The application of drones has a positive effect on the ship-to-ship supply concept. It can be concluded that:
Using drones to take care of on-demand spare part shipments, delivering packages to oil/gas platforms and inspection of external parts of wind turbines the wind farm yield availability increased with 1.1%, while the costs were reduced by 10%.

- The application of drones increases the yield availability of the wind farm for ship-to-ship supply with 1.1%, while the total project costs were reduced with 10%.
- The benefits are caused by the higher workability, resulting in significantly reduced downtime and thus decreased revenue losses, and lower vessel costs.

7.4 Port infrastructure requirements

The analysis on the in-port logistics by the University of Antwerp, the workshops with the consortium partners and the exploration by Royal Haskoning DHV provide the foundation of the following conclusions on the requirements to the port infrastructure:

- The results of this study endorse the earlier indicated 4 to 6 hectares of required floor space as found by TNO in 2019 [2]. The increased efficiency that is brought by the ship-to-ship concept is expected to compensate for the increased ambition for offshore wind power in the Dutch territorial waters and potential other sustainable activities surrounding them.
- Promising technologies that could be applied in the Port of Den Helder to effectively service offshore wind farms are remote pilot centres and automated mooring installations. Both options can be investigated in more detail to obtain better estimations on their profitability and their applicability.
- Conventional inland vessels are found to be the most economic method of transporting cargo within the port of Den Helder. They outperformed autonomous vessels and road transport.
- Automation of the terminal itself resulted in lower costs when compared to a conventionally operated terminal.

7.5 Recommendations

The results and conclusions from this report were derived by evaluating specific case studies. With varying parameters, the outcomes might change, even though the overall conclusion on the benefits of ship-to-ship supply is expected to remain valid. It is therefore recommended to further investigate the technology that will be required to materialise this logistic concept, like proper transfer methods and equipment.

Since it was found that servicing more SOV's per supply run is beneficial for the costs, and for the option to automate supply vessels, it is recommended to further investigate this aspect and to determine the optimal number of SOV's that one supply vessel can service. A basis for this sequential study could be a mathematical approach to the milk run principle.

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Appendix A
Report University of Anwerp

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