Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Fredrik Stennes Jacobsen

Effectiveness of Offshore Maintenance Bases in Norwegian Offshore Wind

Master's thesis in Marine Technology
Supervisor: Amir Rasekhi Nejad
June 2023

NTNU
Norwegian University of
Science and Technology

Fredrik Stennes Jacobsen

Effectiveness of Offshore Maintenance Bases in Norwegian Offshore Wind

Master's thesis in Marine Technology
Supervisor: Amir Rasekhi Nejad
June 2023

Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

NTNU
Norwegian University of
Science and Technology

Faculty of Engineering
Department of Marine Technology

MASTER THESIS IN MARINE SYSTEMS DESIGN

2023

Stud. techn. Fredrik Stennes Jacobsen

Effectiveness of Offshore Maintenance Bases in Norwegian Offshore Wind

Work description

Background

The Norwegian government has an ambition of releasing areas for offshore wind production with a combined capacity of 40 GW within 2040. The bathymetry of the Norwegian Continental Shelf allows a widespread development of floating wind production. Floating offshore wind is an expensive task, with the only large-scale floating wind park today, Hywind Scotland, having a projected levelised cost of electricity (LCOE) three times greater than an ordinary fixed offshore wind park. The motivation for this thesis work comes from the governmental ambition for offshore wind development and a personal interest in the development of sustainable ocean industries. Another personal motivation is to obtain knowledge within offshore wind production to continue to build upon competence gathered through studies and previous work.

Aim of thesis

The aim of this thesis is to see how different offshore maintenance base options can influence the cost of operation and maintenance and thereby potentially reduce the levelised cost of energy of upcoming offshore wind farms in Norway. Operation and maintenance of offshore wind production contribute to around 30% of the total costs over the lifespan of offshore wind projects. The thesis will analyse the usage of offshore maintenance bases compared to a traditional approach with service operation vessels. Initially, the thesis aimed to investigate methods to reduce operation and maintenance costs in floating offshore wind. Due to the areas addressed as suitable for the development of bottom-fixed offshore wind turbines in Norway being situated far from the shoreline, bottom-fixed wind farms will be included in the investigation. This thesis will therefore investigate the effectiveness of implementing offshore maintenance bases into bottom-fixed and floating Norwegian offshore wind through simulation of hypothetical offshore wind farms in the proposed areas for development.

Scope of work

1. Carry out a review of operation and maintenance of offshore wind through literature, building upon work done as part of project work carried out in Fall 2022
2. Carry out a review of offshore maintenance bases
3. Present methodology for investigation, including theory
4. Perform a code-to-code comparison between NOWIcob and COMPASS
5. Propose cases of hypothetical Norwegian offshore wind farms to carry out the analysis
6. Create a simulation of the proposed cases using the NOWIcob tool
7. Discuss the results from the simulation
8. Write the MSc thesis report

Start Date: 16.01.2023

Due Date: 19.06.2023

Supervisor: Amir Rasekhi Nejad

Trondheim 16th June 2023

Professor Amir Rasekhi Nejad

Abstract

The Norwegian government has ambitions for large-scale development of offshore wind. To achieve this goal, it is necessary to reduce costs. It is expected that costs associated with offshore wind will be reduced considerably in the coming decades, but this requires innovation. Offshore maintenance bases (OMB) can be an opportunity to lower the operating costs associated with offshore wind, which account for around a third of the total levelised cost of energy (LCOE) of offshore wind. The purpose of this master's thesis is to investigate whether offshore maintenance bases can reduce the costs associated with maintenance and operation (O&M) in Norwegian offshore wind.

Selecting effective strategies for maintenance is important to reduce the duration of the downtime of the wind farm, and it becomes increasingly important with wind farms that come further from the coast and consequently further from the O&M port. The O&M of offshore wind farms consists of many different processes that can be individually improved to reduce the LCOE. Vessel optimisation is important because of the many different vessels required for maintenance tasks. The vessels for maintenance include vessels capable of transporting and transferring personnel, performing heavy lifting, towing to shore and mooring and cable operations.

For offshore maintenance bases, the transfer of workers is carried out with smaller crew transfer vessels (CTV) typically used for shallow-water offshore wind farms. The transfer of the workers is carried out by forward propulsion into the wind turbine and providing access to a ladder to the turbine. Usually, this is carried out by larger service vessels (SOVs) with motion-compensated gangways. Consequently, the operational wave limit for a CTV is less than for a SOV.

Norway is in a unique situation, due to the geographical proximity to offshore oil and gas installations that can be used as OMBs. This was therefore included in the investigation, in addition to the investigation of OMBs with shared foundations with offshore substations. The investigation consisted of a case study with a quantitative approach to the problem, examining both floating and bottom-fixed wind farms on the Norwegian continental shelf. Since there are currently no large-scale wind farms on the Norwegian continental shelf, four hypothetical wind farms were constructed for this thesis in the areas proposed for development of offshore wind by the Norwegian Directorate of Water Resources and Energy. The areas consisted of Sørlige Nordsjø II, Sørvest B, Utsira Nord and Nordvest B. The investigation consisted of simulating the four offshore wind farms for their entire life cycle with different vessel selections. The simulation program utilised in the research was the powerful NOWICob tool developed by SINTEF.

The results of the case study concluded that OMBs have great potential for Norwegian offshore wind. Although the results vary with the local conditions, the OMB simulations generated promising results compared to the results using conventional methods of maintenance. Although the results of this quantitative survey should be interpreted with caution, the implementation of OMBs should be further investigated in the development and establishment of new Norwegian offshore wind farms.

Sammendrag

Den norske regjeringen har ambisjoner for en storstilt utvikling av havvind. For å nå målet er det nødvendig å redusere kostnader, spesielt for flytende havvind. Det er forventet at kostnader tilknyttet havvind vil reduseres betraktelig de neste tiårene, men det krever blant annet innovasjon. Offshore vedlikeholdsbaser (OMB) kan være en mulighet for å senke driftskostnadene tilknyttet havvind, som står for i underkant av en tredjedel av de totale livsløpskostnadene (LCOE) av havvind. Formålet med denne masteroppgaven er å undersøke om offshore vedlikeholdsbaser kan redusere kostnadene tilknyttet vedlikehold og drift i norsk havvind.

Valg av effektive strategier for vedlikehold er viktig for å redusere varigheten av nedetiden av vindparken, og det blir stadig viktigere siden vindparker plasseres lenger fra kysten og dermed lenger fra vedlikeholdsbasen på land. Vedlikehold og drift av havvindparker består av mange forskjellige prosesser som individuelt kan forbedres for å redusere LCOEen. Fartøyoptimalisering er viktig på grunn av de mange forskjellige fartøyene som kreves for vedlikeholdsoppgavene. Fartøyene for vedlikehold inkluderer fartøyer som er i stand til å transportere og overføre personell, utføre tunge løft, sleping til land og fortøyning- og kabeloperasjoner.

For offshore vedlikeholdsbaser utføres overføringen av arbeidere med mindre transportfartøy (CTV), som idag ofte brukes for vindparker lokalisert nærmere kysten. Overføringen av arbeiderne utføres gjennom å kjøre inntil vindturbinen og gi tilgang til en stige opp til turbinen. Vanligvis utføres dette av større servicefartøy (SOV) som har landganger som kan kompensere for bølgebevegelsene. Den operasjonelle bølgegrensen for en CTV er derfor mindre enn for en SOV.

Norge er i en unik situasjon på grunn av den geografiske nærheten til offshore olje- og gassinstallasjoner som kan brukes som OMBer. Dette ble derfor inkludert i undersøkelsen, i tillegg til undersøkelsen av OMBer med delt fundament med offshore trafostasjoner. Undersøkelsen tar for seg en kvantitativ tilnærming til problemstillingen, og undersøker både flytende og bunnfaste vindparker på norsk sokkel. Siden det i dag ikke eksisterer storskala vindparker på norsk sokkel, ble det i denne studien konstruert fire hypotetiske vindparker i områdene foreslått for utbygging av Norges vassdrags- og energidirektorat. Områdene som ble undersøkt bestod av Sørlige Nordsjø II, Sørvest B, Utsira Nord og Nordvest B, som alle har forskjellige karakteristikker. Undersøkelsen bestod av å simulere de fire havvindparkene for hele livsløpet med forskjellige valg av fartøy. Simuleringsprogrammet brukt i undersøkelsen var SINTEF sitt svært kraftfulle NOWIcob-verktøy.

Resultatene av undersøkelsen konkluderte med at OMBer har et stort potensial for norsk havvind. Selv om resultatene varierer med de lokale forholdene, genererte simulasjonene for OMBene svært gode resultater i forhold til resultatene med bruk av konvensjonelle metoder for vedlikehold. Selv om resultatene av denne kvantitative undersøkelsen må tolkes forsiktig, burde implementering av OMBer undersøkes videre i utviklingen og etableringen av nye norske havvindparker.

Preface

This thesis fulfills the requirements for the course TMR4930, and serves as the final piece that qualifies the author for the degree of Master of Science in Marine Technology, specialising in Marine System Design at the Norwegian University of Science and Technology (NTNU). The work presented began with the problem definition and project work in August 2022, while the thesis work was carried out from January 2023 until it was accomplished in June 2023. The work was conducted independently and was supervised by Professor Amir Rasekhi Nejad.

This thesis will cover an investigation of the effectiveness of offshore maintenance bases for Norwegian offshore wind and how its implementation affects the costs of operation and maintenance. The objective of this thesis is to investigate methods to lower costs within offshore wind, and potentially initiate further investigations of offshore maintenance bases. The thesis consists of two parts. The first part covers a literature review of maintenance around offshore wind and offshore maintenance bases and is based on project work carried out in the Autumn of 2022. The second part includes a case study of the implementation of offshore maintenance bases and an analysis of its performance in hypothetical Norwegian offshore wind farms.

Upon the completion of the thesis work, the process was highly interesting and educational even though the simulations proved to be time-consuming with a runtime totalling over 355 hours for the final round of simulations. The process of writing offered valuable insights into the operations of offshore wind farms and in the field of marine operations. The thesis also provided practical experience with ocean system simulation, which was a field of engineering that lacked personal experience throughout the studies.

Trondheim, 16th June 2023

Fredrik Stennes Jacobsen

Acknowledgement

The work of this thesis is carried out of a personal interest in the development of offshore wind. It is carried out without any involvement from external corporations, making the research free from any competing interests. The work of this thesis has been challenging and educational, and it had not been possible without the help I have received throughout the process.

First, I would like to show my appreciation to my supervisor, Amir Rasekhi Nejad, for his guidance throughout the project work and the master's thesis. His expertise within offshore wind has given me valuable insights and has influenced the research to be able to contribute to cost reduction efforts in the offshore wind industry. The feedback received from the supervisor has been much appreciated and it has been a pleasure to work with him. I would also like to thank Iver Bakken Sperstad and SINTEF for granting me access to the NOWIcob tool, which was necessary to achieve the objective of this thesis. Moreover, I would like to thank Birgitte Furevik from the Norwegian Meteorological Institute for providing me with data from the NORA3 weather reanalysis. Lastly, I would like to thank my family and girlfriend for their support through various challenges throughout the last two semesters and in my time studying in general.

Contents

List of Figures

List of Tables

List of Abbreviations

AHTS Anchor Handling Tug Supply vessel

CAPEX Capital expenditure

CLV Cable laying vessel

CTV Crew Transfer Vessel

DES Discrete event simulation

FMEA Failure Modes and Effects Analysis

GBP British Pound

HAWT Horizontal axis wind turbine

HVAC High voltage alternating current

HVDC High voltage direct current

KPI Key performance indicator

kW Kilowatt

LCOE Levelised Cost of Energy

MW Megawatt

MWh Megawatt hour

NPV Net present value

NVE Norwegian Water Resources and Energy Directorate

O&G Oil and gas

O&M Operation and Maintenance

OMB Offshore Maintenance Base

OPEX Operational expenditure

OWT Offshore Wind Turbine

RBI Risk-Based Inspection

RCM Reliability-Centered Maintenance

RNA Rotor-Nacelle assembly

RNG Random number generation

SOV Service Operation Vessel

SSCV Semi-submersible crane vessel

SWATH Small waterplane area twin hull

T2S Tow to shore

TTF Time to failure

VLSFO Very low sulphur oil

W2W Walk to work

1 | Introduction

1.1 Background

In the summer of 2022, the Norwegian government announced an ambition of releasing large areas for the production of offshore wind energy. The aim consisted of releasing production areas with a combined capacity of 30 GW that would be operational by 2040 (Royal Norwegian Ministry of Trade and Industry, 2022a). The government's ambition is contributing to global efforts to reduce emissions and decrease dependence on fossil fuels and aligns itself with the Sustainable Development Goals developed by the United Nations shown in Figure 1.1. The initiative of developing offshore wind energy will present a wide range of technical and economic challenges and opportunities for the Norwegian industry.

Figure 1.1: Sustainable Development Goals of the United Nations (United Nations, 2023)

The vast Norwegian Continental Shelf, composed of parts of the North Sea, the Norwegian Sea, and the Barents Sea, holds great potential for the development of large-scale offshore wind production. However, the continental shelf also presents significant challenges because of its bathymetry consisting of substantial water depths. To combat these challenges, complex floating wind production technologies need to be considered for most of the Norwegian Continental Shelf. Currently, there are a limited number of floating wind farms in operation, including the newly commissioned Hywind Tampen in Norway that powers the oil and gas installations Gullfaks and Snorre (Equinor, 2023). Today, most of the worldwide offshore wind production consists of conventional bottom-fixed wind turbines. Due to its complexity and immaturity, floating wind production is currently financially demanding, lacking state-of-the-art methods to execute parts of its associated operations.

The costs surrounding wind energy are typically measured in its levelised cost of energy (LCOE), which indicates the cost of generating electricity over the project's lifetime. This makes the LCOE a reliable key performance indicator (KPI) for comparison with other offshore wind projects. Equation 1.1 shows how the LCOE is typically calculated for offshore wind projects (BVG Associates, 2023), and consists of several components summarised at yearly intervals. Capital expenditures ($CAPEX_t$) and operational expenditures ($OPEX_t$) are accounted for each year t and discounted with the discount rate r. Likewise, the net energy generation for each year E_t is discounted. T indicates the lifetime of the offshore wind farm, while t_{pre} accounts for years associated with development, procurement and installation prior to the commissioning of the wind farm. The years of decommissioning are accounted for in t_{post}, accounting for costs associated with decommissioning.

$$\mathrm{LCOE} = \frac{\displaystyle\sum_{t=-t_{pre}}^{T+t_{post}} \frac{\mathrm{CAPEX}_t + \mathrm{OPEX}_t}{(1+r)^t}}{\displaystyle\sum_{t=1}^{T} \frac{\mathrm{E}_t}{(1+r)^t}} \tag{1.1}$$

The first operational floating wind farm in the world, Hywind Scotland, was commissioned in 2017. The pilot wind farm has a projected LCOE of more than 200 €/MWh according to Bull and Bringsværd (2020). In comparison, an ordinary bottom-fixed wind farm has an LCOE of around 100 €/MWh (Wood Mackenzie, 2019). The high costs are a main concern for the development of floating offshore wind. It is expected that the costs and the LCOE of floating wind production will reduce to a rate similar to bottom-fixed, as seen in Figure 1.2. This is due to larger turbine and farm sizes in addition to optimisation, technology and standardised production and operations. According to the works of Jansen et al. (2020), the LCOE of bottom-fixed wind farms have already decreased significantly by 28-49% from 2014 to 2019. The change in LCOE of both fixed-bottom and floating wind farms could in 2050 exceed 40-50% relative to the 2019 baseline value for fixed-bottom wind farms according to Wiser et al. (2021), as seen in Figure 1.2. With the LCOE of offshore wind decreasing and the demand for energy rapidly increasing, the outlook for both bottom-fixed and floating wind production is promising. This is especially important in Europe, where the need for new green energy sources to reduce the dependence on gas is vital to reach climate targets.

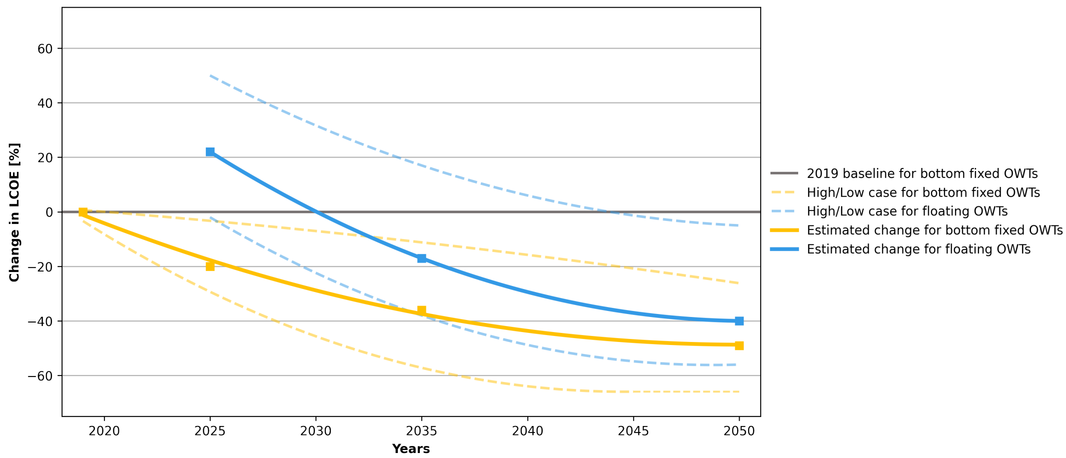
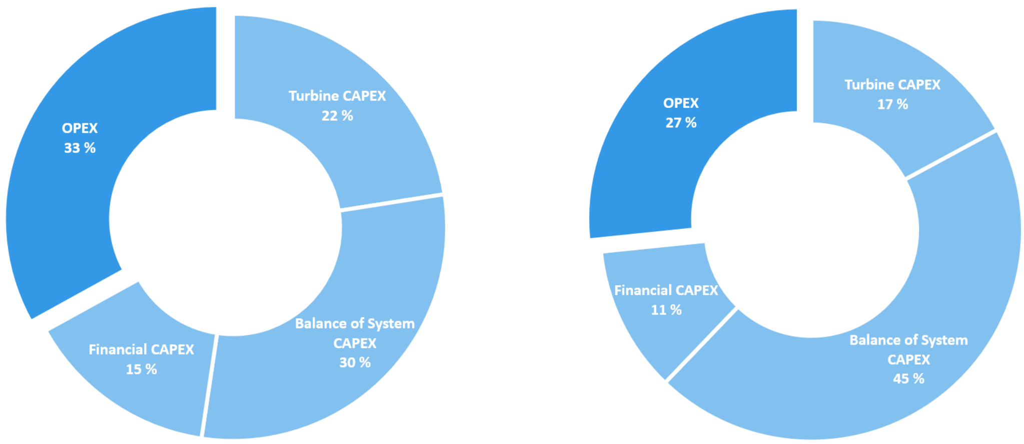


Figure 1.2: Change in LCOE based on estimates found in Wiser et al. (2021)

In order to reduce the overall costs associated with offshore wind production, new technology and methods are needed to be implemented and tested. Although new methods and approaches could reduce some cost components, it is important to investigate the full impact of the LCOE. For instance, the implementation of an offshore maintenance base (OMB) could reduce maintenance costs associated with OPEX, but its implementation would also affect the CAPEX and generated electricity. An investigation of the overall impact on the LCOE is therefore needed in order to see its effectiveness. In Figure 1.3, the current distribution between CAPEX and OPEX is seen for both bottom-fixed and floating wind farms. The balance of system is accounting for all the costs associated with the installation and commissioning of offshore wind farms except for the topside turbine itself.



(a) Bottom-fixed OWTs *(b) Floating OWTs*

Figure 1.3: Cost distribution of the LCOE of offshore wind(Stehly & Duffy, 2022)

1.2 Aim of thesis

The definition of the master's thesis started with an ambition for finding ways to lower costs of operation and maintenance (O&M) in floating offshore wind. The operation and maintenance presents many opportunities to lower costs as it is contributing significantly to the total costs of offshore wind. As depicted in Figure 1.3, around 30% of the LCOE of an offshore wind farm is contributed by O&M (Stehly et al., 2020). This thesis was inspired by the research article "*Analysing the effectiveness of different offshore maintenance base options for floating wind farms*" written by Avanessova et al. (2022). The article investigates the effectiveness of different offshore maintenance base options by conducting a case study for a hypothetical floating offshore wind farm in the Scotwind NE8 area. It compares using an OMB with crew transfer vessels (CTVs) against a traditional approach using service operation vessels (SOV). The study investigates the usage of OMBs in British waters, but how would an OMB perform in Norwegian waters and under Norwegian regulations? Could the numerous oil and gas (O&G) platforms in the Norwegian Continental Shelf be repurposed to support such an operation?

The OMBs main advantage is reduced transfer time of crew, reducing the duration of weather windows required for maintenance tasks. Most of the planned areas for development of bottom-fixed wind farms in Norwegian waters are situated over 140 km from the coastline (Norwegian Water Resources and Energy Directorate (NVE), 2023). According to the works of Hu and Yung (2020), solutions including accommodation should be utilised when operating at wind farms over 70 km from the O&M port. Hence, it was decided to include the proposed areas for development of bottom-fixed offshore wind farms in this study in addition to the areas suitable for floating wind farm development. A full map of the proposed areas can be seen in Appendix A.

The aim of the master's thesis is therefore to study the effectiveness of OMBs through a cost-benefit analysis in order to see if OMBs have any potential to reduce the costs of offshore wind production compared to conventional strategies. The work will consist of reviewing O&M of offshore wind production and OMBs through literature, and then conducting a case study for hypothetical wind farms within the proposed offshore wind areas within the Norwegian economic zone seen in Appendix A. The case study will include different scenarios regarding the location of the maintenance base and different vessel selections.

1.3 Limitations

Several considerations need to be taken into account in order to analyse the performance and effectiveness of OMBs in Norwegian waters. This thesis cannot include all aspects of the offshore wind farm, which leads to some limitations in the research. The thesis does not conduct vessel optimisation for the case study. The vessel optimisation would have been beneficial in terms of optimal performance, however carrying it out could have been a thesis in itself. Additionally, a complete review of the LCOE will not be considered as it would not be of significant importance for analysing the effectiveness of the OMBs.

Furthermore, the thesis does not consider any innovative technologies to enhance performance. This includes experimental technology for offshore wind turbine design, as this thesis will only consider standard three-bladed horizontal axis wind turbines (HAWTs). It also includes technologies such as underwater substations and lift systems installed locally on the turbine.

2 | Operation and maintenance of offshore wind farms

Reducing costs of maintenance operations are crucial for the competitiveness and financial sustainability of both bottom-fixed and especially floating wind farms. The costs of maintenance and revenue losses due to lack of maintenance are the greatest cost components of operation and maintenance, and they are important factors to influence the LCOE of a wind farm (Ren et al., 2021). Effective strategies are important for the LCOE to mitigate downtime duration, and this becomes increasingly important with wind farms situated further from the shoreline and consequently further from the O&M base. This is because transfer time for maintenance works increase. It will be increasingly important for the Norwegian offshore wind as the planned offshore wind production areas are situated far from the shoreline, further than current operating offshore wind farms globally.

Figure 2.1 shows how cost components of O&M compromise the total OPEX of an offshore wind farm. Maintenance planning and optimisation is an important factor in the development of offshore wind farms as it ensures optimal performance and extends the lifespan of offshore wind turbines. Selection of efficient maintenance strategies will in the long-term, reduce overall downtime caused by ageing equipment (Stehly & Duffy, 2022). However, several challenges need to be addressed and resolved. Firstly, the unfavourable nature of offshore weather conditions influences the accessibility of maintenance vessels, especially for the North Sea. Secondly, dynamic motions in bottom-fixed OWTs and especially floating OWTs caused by the weather conditions present some significant challenges to the maintenance operations. Moreover, offshore wind farms located far from the shoreline and ports pose greater logistical challenges which in turn increases the duration of OWT downtime, thereby driving up maintenance costs.

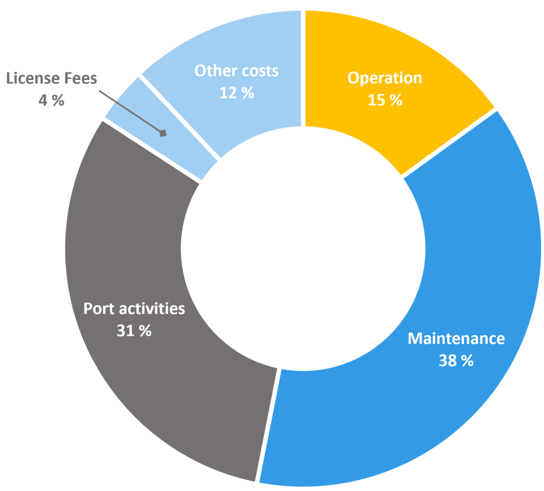


Figure 2.1: Cost breakdown of OPEX of offshore wind production (BVG Associates, 2010)

2.1 Maintenance strategies

The state-of-the-art review of O&M of offshore wind production by Ren et al. (2021) highlights that maintenance frequency is a trade-off between risks. On the one hand, frequent visits with a maintenance team of an OWT are important to mitigate failures and ensure optimal performance. However, a high frequency of maintenance visits could prove to be both costly and inefficient. Therefore, the trade-off and ultimate objective in the selection of maintenance strategies is to maximise the availability of the offshore wind farm while minimising O&M costs associated with vessels and day rates, fuel consumption, spare parts and the cost of technicians. In addition, the maintenance strategy should extend the lifespan of components which improves the overall operational life of the OWTs.

The works of Shafiee (2015) categorise maintenance strategies into two different main types, namely the failure-based reactive maintenance strategy and proactive maintenance strategy. In general, the reactive maintenance strategy functions as performing maintenance after a failure has occurred. The proactive maintenance strategy is about carrying out maintenance prior to the breakout of failures. Proactive maintenance can be divided into several sub-classifications of the proactive maintenance strategy, consisting of both time-based and sensor-based options. The different strategies are depicted in Figure 2.2, and are described in detail in section 2.1.1 to 2.1.3.

Risk-Based Inspection (RBI) and Reliability-Centered Maintenance (RCM) are examples of other types of maintenance strategies, where the core of the two strategies are risk identification and mitigation (Sanford, 2015). RBI is a maintenance strategy where the main goal is to identify and categorise risks and to control deterioration to the OWT components (Rangel Ramírez & Sørensen, 2012). For instance, Nejad et al. (2014) proposes a vulnerability map of gearbox components through reliability-based maintenance. The vulnerability map aims to identify components with low reliability for maintenance teams, which can be useful in the planning of scheduled maintenance activities. RCM is similar to RBI, where the main focus is to identify the most critical system functions and to mitigate failures in these functions thereby reducing costs.

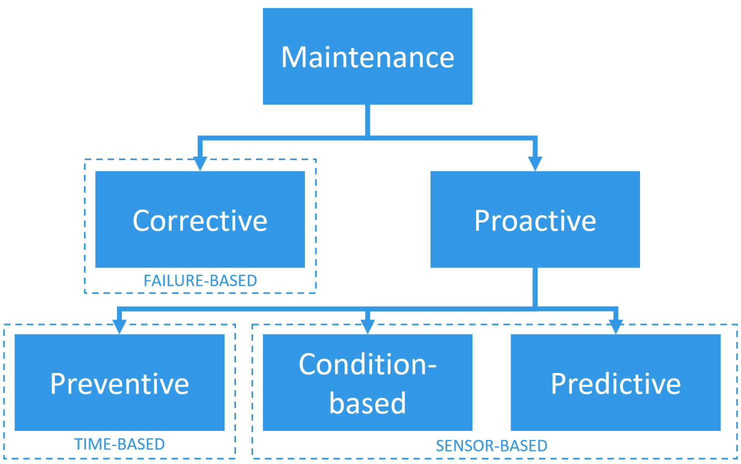


Figure 2.2: Classification of different maintenance strategies

2.1.1 Reactive maintenance

Reactive maintenance, often referred to as corrective maintenance or "run-to-failure", is a strategy based on performing maintenance after a failure has occurred. For large-scale wind farms, this strategy can prove to be troublesome due to high failure rates and low system reliability (Karyotakis & Bucknall, 2010). The harsh conditions of the ocean environment create several issues that could cause a greater number of failures. An increased number of failures would lead to increased downtime of the OWT. In addition, wind farms are located further and further away from the shoreline and O&M bases. This creates greater transfer times for the maintenance personnel which consequently increases the weather window needed for the maintenance. Due to the occurrence of failures being highly stochastic by nature, relying solely on this strategy will have significant negative effects on costs, revenue and availability that could potentially make the offshore wind farm close to futile.

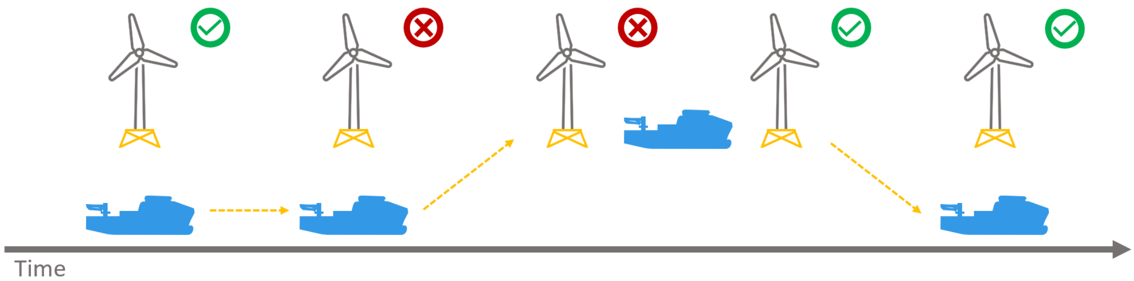


Figure 2.3: Illustration of reactive maintenance

The simplified visualisation in Figure 2.3 illustrates how reactive maintenance operates in practice at an OWT. The illustration depicts the issue of increased downtime with the system out of operation for the duration of the transit and maintenance activity assuming that the failure leads to a stop in operation of the OWT. The effectiveness of reactive maintenance being the only selected maintenance strategy for a system is highly dependent on the simplicity and reliability of the system in question, such as a car or similar. However, relying solely on reactive maintenance for offshore wind farms and OWTs, which are highly complex systems, could result in substantial costs due to the extensive downtime caused by reactive maintenance. As a result, a more comprehensive and proactive maintenance strategy is required in addition to reactive maintenance to ensure the optimal performance of offshore wind farms and OWTs.

2.1.2 Preventive maintenance

Preventive maintenance is a strategy performed to prevent and mitigate the risk of failure of components. Time-based preventive maintenance is usually executed at scheduled and fixed intervals (Utne, 2020). Preventive maintenance at fixed intervals is often assumed to be the chosen strategy when the aim is to maximise system availability. This is due to the expectation of components having a relatively long lifespan executing planned maintenance before the components deteriorate (Utne, 2020 and Moubray, 1997). Time-based preventive maintenance can take place either by scheduling after the reliability of components and costs, or by the effect of power generation on the deterioration of the OWT. Scheduling after costs and reliability of components suggest that if a failure occurs between two scheduled maintenance intervals, the OWT will be out of operation until the next scheduled maintenance activity. It is crucial to plan the scheduled maintenance activities and optimise the schedule to obtain the best results.

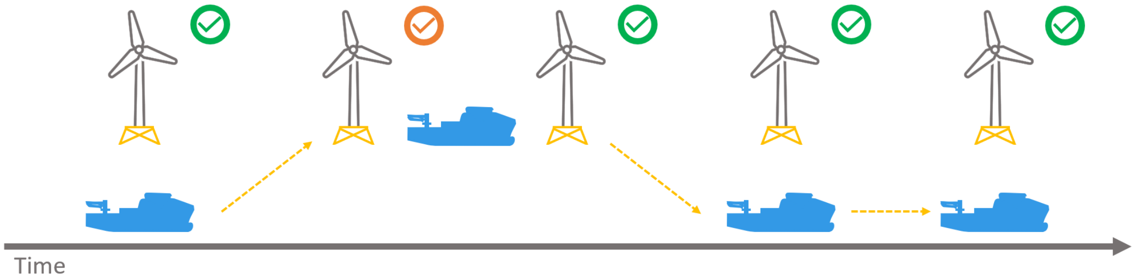


Figure 2.4: Illustration of preventive maintenance

Preventive maintenance has various benefits as a maintenance strategy for offshore wind production. Firstly, it helps in mitigating the chance of a failure occurring which can lead to costly downtime as seen in Figure 2.4. By identifying and addressing potential problems of components before they occur, the maintenance strategy reduces the likelihood of unexpected failures and unscheduled maintenance tasks.

Additionally, it enables the optimisation of vessel usage by maintenance scheduling and reduces waiting times for spare parts and chartering of vessels. Furthermore, scheduling maintenance allows for the identification of time windows to carry out the maintenance which decreases the dependency on unpredictable weather conditions which could disrupt the maintenance activities. The aim of preventive maintenance is to optimise maintenance schedules to ensure high system availability and operational efficiency, which in turn minimises the costs related to the maintenance of the system.

2.1.3 Sensor-based maintenance

Due to the harsh ocean conditions, OWTs could experience deterioration more frequently than similar systems onshore. A condition-based maintenance strategy is based on observing the current states of components through sensors and evaluating the results. Condition-based maintenance is therefore helpful to schedule maintenance of OWTs based on results in the analysis, where the sensors provide real-time conditions of the OWTs for maintenance teams. A study of an offshore wind farm with a capacity of 400 MW, found that a weekly scheduled condition-based maintenance strategy outperformed a combination of preventive and reactive maintenance due to lower maintenance costs and increased availability of the OWT (Walgern et al., 2017).

The predictive maintenance strategy is also sensor-based, similar to condition-based maintenance. The strategy relies on advanced statistical methods through measurement data to estimate whenever a failure occurs, and the aim is to predict whenever maintenance should be executed. Digital twins are one method of implementing a predictive maintenance strategy and are highly popular among several engineering disciplines. Digital twins create a virtual twin of the system where the remaining life of components could be computed and predicted, and studies such as the work of Sivalingam et al. (2018) present methods for its implementation in offshore wind farms.

A predictive approach would be beneficial in terms of maximising reliability and minimising downtime of the OWT. However, such extensive measurement equipment could be costly and difficult to implement in practice. This is a problem both for predictive and condition-based maintenance where an increased number of sensors makes the system more complex and costly. In addition, the implementation of sensors introduces new problems such as sensor failures, misreporting and security of data (Ren et al., 2021).

2.1.4 Opportunistic maintenance

As described earlier, maintenance planning is a critical aspect of OWTs due to the associated costs, potential downtime and accessibility. The two main strategies of reactive and proactive maintenance do have strengths and weaknesses, but relying solely on one strategy would be disadvantageous for complex offshore installations like an OWT or an offshore wind farm. A combination of different maintenance strategies would therefore prove to be needed to ensure optimal performance, mitigate downtime and failures, and ultimately lower the costs associated with maintenance.

In this context, an opportunistic maintenance strategy emerges as a hybrid approach utilising the strengths of both reactive and proactive maintenance approaches. The term opportunistic maintenance is somewhat vague, and its implementation varies depending on the system in question and operational conditions (Thomas et al., 2008). Essentially, it involves maintenance planning with a combination of different maintenance approaches to minimise costs and maximise performance. Several studies have shown the effectiveness of opportunistic maintenance in offshore wind.

One such study is the optimisation framework presented in the research article by Besnard et al. (2009). The study showed that the selection of an opportunistic strategy over a more traditional preventive maintenance approach could decrease the costs of maintenance by up to 43%. The study consisted of investigating a hypothetical offshore wind farm consisting of five 3 MW turbines and found that the hybrid opportunistic approach of both reactive and preventive maintenance could lead to reduced downtime of the turbines and an overall decrease in maintenance costs. Other studies like the paper by Zhang et al. (2017), demonstrate the benefits of using an opportunistic maintenance approach, in which the overall operational performance of offshore wind farms is improved.

2.2 Maintenance tasks

In order to gain a better understanding of the maintenance tasks needed for the operation of an OWT and an offshore wind farm, it is important to investigate the different components that make up the entire system. Therefore, a complete breakdown of the system is executed to understand potential types of failures and their required maintenance tasks. The two main root causes of failures are corrosion and mechanical overload according to a Failure Mode and Effects Analysis (FMEA) performed by Arabian-Hoseynabadi et al. (2010). FMEA can be a powerful method to identify failures and their effects on the system and study the reliability of power generation systems.

2.2.1 Breakdown of components

Figure 2.5 depicts a simplified breakdown of an offshore wind farm. It consists of a floating OWT (1) and a bottom-fixed OWT (2) together with mooring lines and anchors (3), array cables (4), a substation (5) and an export cable (6). The floating and bottom-fixed turbines are differentiated by their type of substructure.

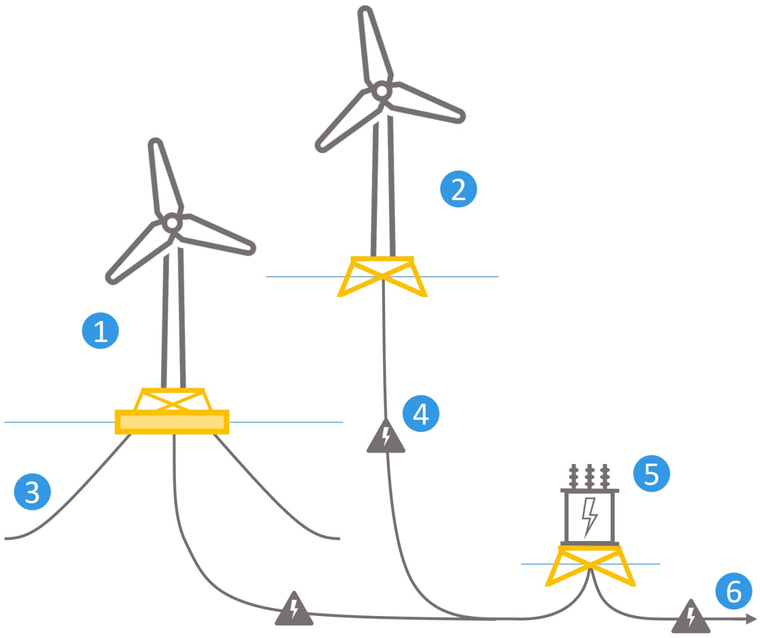


Figure 2.5: Simplified overview of an offshore wind farm

An OWT is the result of a two-stage design composed of the Rotor-Nacelle Assembly (RNA) including the tower and the substructure (Nejad & Torsvik, 2021). In the design phase, the two design stages typically have different suppliers even though the components are attached. The maintenance of OWTs tends to lean toward a similar approach with different suppliers of the maintenance. For this thesis, the substructure component is referred to as an external component of the OWT. The turbine itself and its subassemblies are referred to as internal components.

The floating substructure is subjected to greater dynamic motions than bottom-fixed substructures, increasing the complexity of the maintenance task operations. In addition to the substructures of the OWTs, other components like array cables and export cables, mooring systems and substations are referred to as external components for this thesis. It is important to consider these so-called external components as their failures contribute significantly to the OPEX of the offshore wind farm.

The turbine itself is similar between the bottom-fixed and floating OWTs. It is important to understand what a turbine is consisting of and to understand the required types of maintenance tasks. In general, standardised method of defining failures does not exist for the wind energy industry. This makes it difficult to predict unscheduled maintenance tasks for OWTs. In Figure 2.6, a breakdown of OWT components is depicted using subassemblies used by Luengo and Kolios (2015) and Carroll et al. (2015) for failure mode identification.

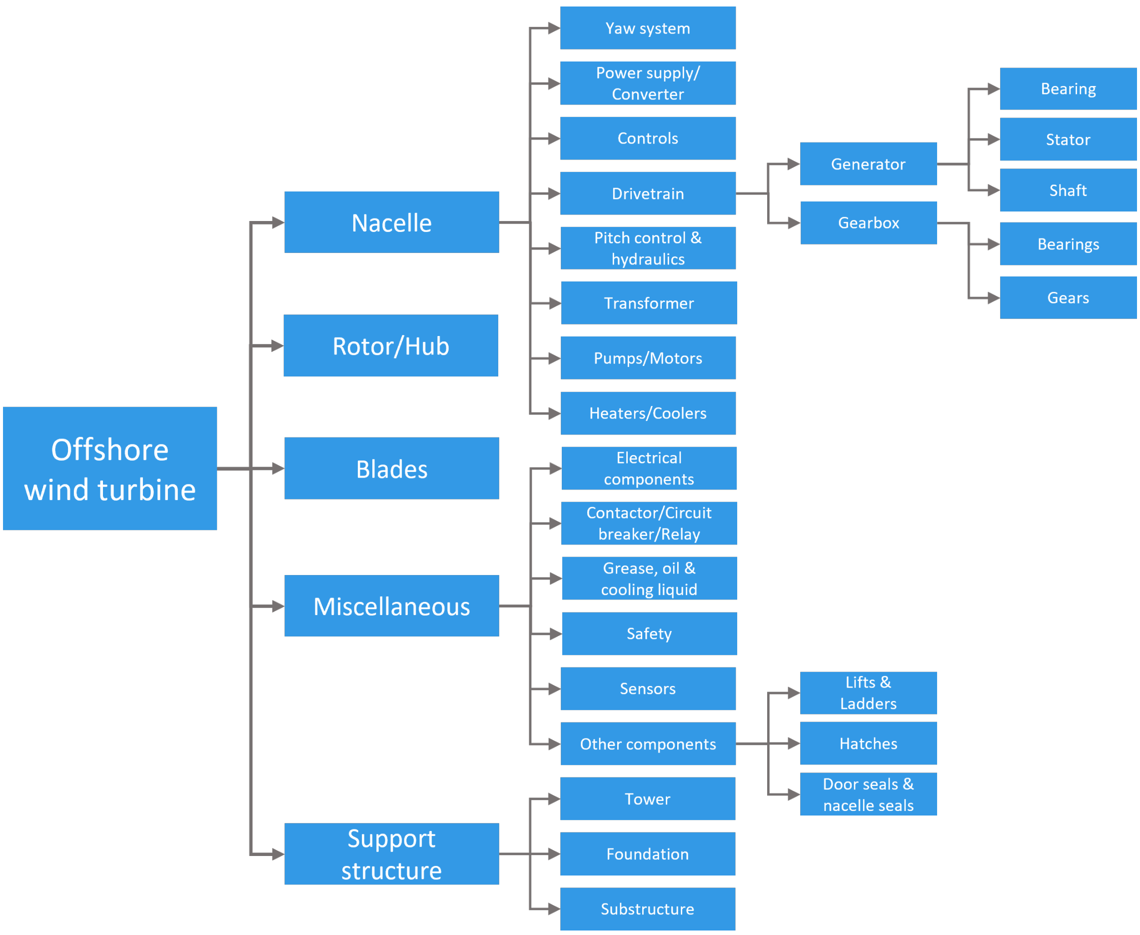


Figure 2.6: Breakdown of OWT's internal components

2.2.2 Failure modes of internal components

According to the article by Luengo and Kolios (2015), the failure modes of OWTs can generally be caused by two sources. It could be due to long-term operation and ageing, or short-term overload and sudden breakdown. Failure mode identification is vital during the planning stage and through the early operation of wind farms. The identification usually begins with a breakdown of the OWT into main components and subsystems in a hierarchical order, such as the breakdown in Figure 2.6. In addition, it is important to take the interaction between the different components and subassemblies into consideration.

The most common failure of the rotor, or the hub, of the OWT, is aerodynamic asymmetry and yaw misalignment (Caselitz et al., 1997a and 1997b). Examples of other failures in the rotor include mass imbalance, fatigue and corrosion, and non-uniform air gaps in the bearings. Rotor imbalance and aerodynamic asymmetry are mainly caused by defects in manufacturing, collections of dirt, ice and moisture, or damage to the blades (Lu et al., 2009). The integrity of the interaction between the rotor and the blades is therefore important for the operation of OWTs. OWTs can experience efficiency loss whenever the roughness of the blade surfaces increases. It is therefore important to mitigate surface wear of the blades. Additionally, blades are at risk of lightning strikes due to the blades being the highest point of the OWT (Cotton et al., 2001). It is difficult to monitor, and measures to mitigate damage are important.

The nacelle and the drivetrain of the turbine function like the heart of the wind turbine. It holds many of the important and most fragile components of the wind turbine, and manufacturers have tried to hermetically seal off the nacelle to mitigate the harsh conditions the ocean environment creates (Carroll et al., 2015). A simplified schematic of the drivetrain is shown in Figure 2.7 One of the most fragile components is the gearbox, which is also one of the components experiencing the most failures, where gear tooth damage and bearing failure are among the most usual failures (McNiff, 2007). In addition, the article by Luengo and Kolios (2015), mentions shaft-gearbox decoupling as a catastrophic failure. Other failures in the gearbox are considered with a lower criticality as they are detected early through condition monitoring. Similar to the gearbox, the generator experiences high failure rates. According to Popa et al. (2003), failures in bearings and the stator are the most common, accounting for about 78% of the failures.

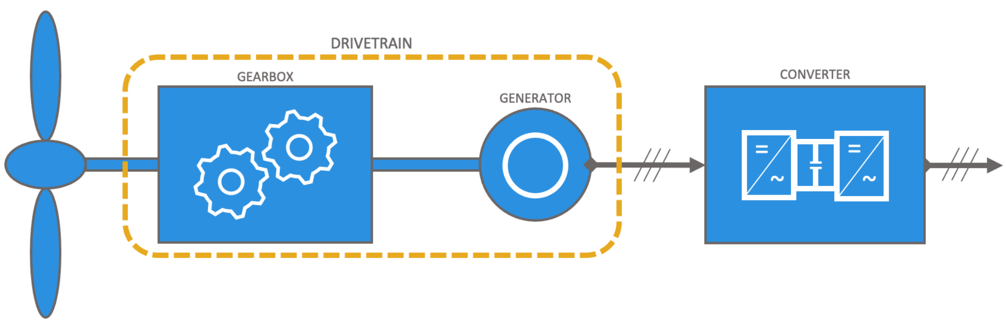


Figure 2.7: Schematic of a drivetrain with a gearbox interpreted from Nejad et al. (2022)

In addition to the drivetrain, several other components are situated in the nacelle. Pitch control is important for the OWT as pitching failure affects the energy capture, operational load mitigation, wind turbine stalling and aerodynamic braking (Hansen, 2007). Aerodynamic braking is important for stopping the OWT in strong winds and is often managed by a hydraulic or electric motor. 13% of total wind turbine failures are due to electronic controls (Lu et al., 2009), and failures such as semiconductor defects, overheating and measurement errors will therefore need to have increased attention.

In general, one could expect that floating OWTs experience higher failure rates as a consequence of experiencing greater dynamic motions due to the waves acting on the substructure. However, a study by H. Li and Guedes Soares (2022) investigated the failure rates and reliability of floating OWTs where the Bayesian network model presented in the study predicted lower failure rates than earlier studies for bottom-fixed, such as the works of Carroll et al. (2015). These findings could be explained by their model having higher precision than earlier analyses. However, the works of Nejad and Torsvik (2021) complements these findings with their research showing that the load effects on the floating substructure are outweighed by the wind loads of the OWT. This indicates that the difference in internal failure rates between floating and bottom-fixed OWTs are negligible. The difference in failure rates between the floating and bottom-fixed OWTs is found in their substructure, where floaters experience higher failure rates due to their higher complexity, e.g. the mooring systems of the floaters.

2.2.3 Maintenance of internal components

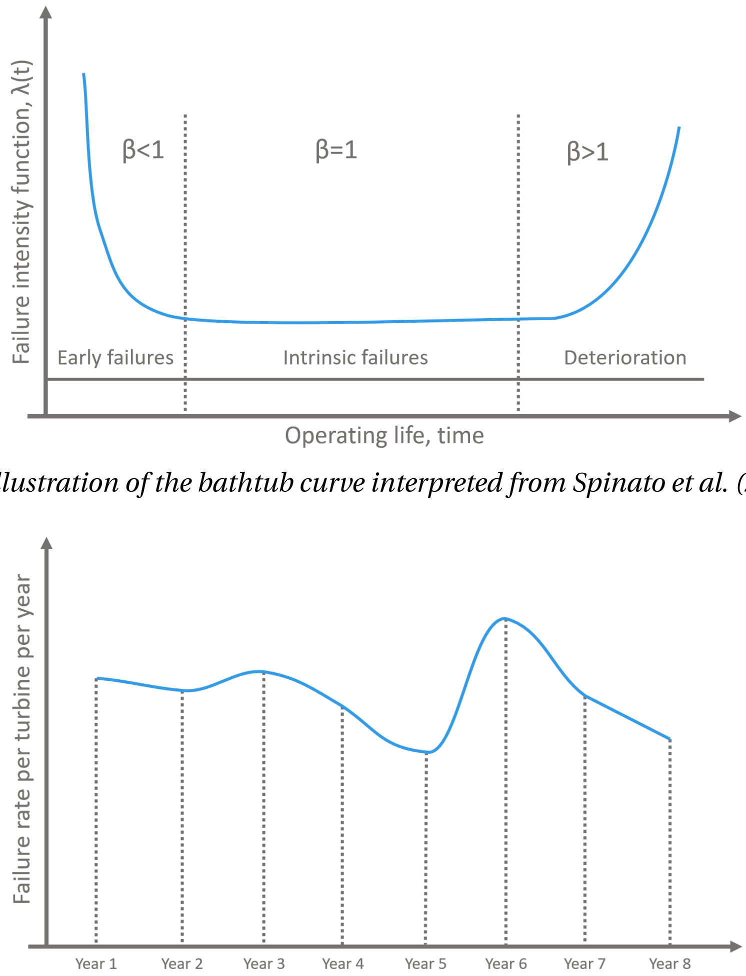
The different failures require different types of corrective maintenance. The extent of the task is determined by logistics, technicians and equipment required for the correction of the failure. The different failures and their corresponding tasks can be categorised into different maintenance categories according to their extent. The works of Carroll et al. (2015) utilise the Reliawind failure cost categories categorised as minor and major repairs, and major replacements (Reliawind, 2007).

The works of Carroll et al. (2015) differentiate the tasks based on the total material cost of each task. Minor repairs are considered for tasks with a cost less than €1 000, major repairs are for costs between €1 000 and €10 000, and major replacements are for costs above €10 000. The costs are exclusively related to the material cost of each task and they are not related to which type of vessel or labour involved. The study concludes that the failure rates presented are useful for cost modelling for O&M with different sailing distances from the O&M port. This will be important for the case study in this thesis due to the various sailing distances to ports for the proposed areas for the development of offshore wind in Norway.

Appendix B shows the calculated failure rates and their corresponding material costs, task duration and required personnel, interpreted from the study of Carroll et al. (2015). The study analyse a population of 350 OWTs over a 5-year period with an individual nominal power of between 2 and 4 MW. Equation 2.1 is used in the study to determine the different failure rates. λ describes the failure rate per turbine per year, I describes the number of intervals for which data is collected, K describes the number of sub-assemblies, $n_{i,k}$ describes the number of failures, N_i describes the number of turbines and T_i describes the total time period in hours.

$$\lambda = \frac{\sum_{i=1}^{I} \sum_{k=1}^{K} \frac{n_{i,k}}{N_i}}{\sum_{i=1}^{I} \frac{T_i}{8760}} \tag{2.1}$$

The failure rates of the components can vary over their lifetime. Several papers such as the works of Spinato et al. (2009) and Zhao et al. (2007) assumes that this variation resembles a bathtub curve which is a representation partitioned by three different phases of the operating life. An illustration of the bathtub curve is shown in Figure 2.8a. However, results from the study of Carroll et al. (2015) show that most of the components do not follow the bathtub pattern as seen in Figure 2.8b. The findings of the study showed that only a few of the components of a turbine follows the bathtub curve.



(a) Illustration of the bathtub curve interpreted from Spinato et al. (2009)

(b) Actual failure distribution interpreted from data from Carroll et al. (2015)

Figure 2.8: Illustrations of failure distributions

Whenever an error or a shutdown of an OWT has occurred, a manual reset or manual restart, is needed in order to restart the OWT. The manual restart does not include any active repairing action. This usually happens quite frequently compared to other failures, however typical values are not described in detail in current literature. Dinwoodie et al. (2015) utilise a typical frequency of 7.5 manual resets per turbine per year.

On the other hand, the works of Anderson et al. (2021) include non-remote manual restarts in the minor repairs category. The study obtains a total failure rate of 5.73 per turbine per year for minor repairs which is lower than the failure rate in the works of Carroll et al. (2015) which excludes the manual restarts. In addition to corrective maintenance tasks, scheduled preventive maintenance tasks are important to perform in order to reduce the chance of failures occurring. Regular service is therefore important for the integrity of the OWT and usually occurs in annual or similar intervals.

2.2.4 Maintenance of external components

Similar to the tower of the turbine, the foundation and substructure of OWTs cannot simply be replaced as the other components in section 2.2.2. The failure of these components may lead to the failure and collapse of the entire OWT, making it a highly critical component of the OWT. It is therefore important to have increased attention to the potential failure modes of the foundation through inspection and monitoring. Common failures in the foundation and substructure are corrosion, cracks and fatigue (Márquez-Domínguez and Sørensen, 2012 and Sørensen, 2015).

Foundations of OWTs don't have any kind of warranty in contrast to the wind turbine itself. However, the risks can be mitigated through certification, and failure detection largely consists of visual inspections and survey work (GL Gaarrad Hassan, 2013). Maintenance of the foundation and substructures should include marine growth removal and regular inspections to ensure failure detection. Additionally, the foundation is vulnerable to collision with service vessels. Even though the probability of collision is relatively low, and it is vital to implement measures to mitigate the risk to avoid collision. The mitigation of failures of foundations can be reduced through thorough maintenance planning, as discussed in the research article by Dai et al. (2013).

Figure 2.9 shows an illustration of different substructures for both bottom-fixed and floating OWTs, displaying a monopile (A) and a jacket (B) for the bottom-fixed OWTs, and a floating spar (C) and a semi-submersible (D) for floating OWTs. Other types of substructures exist as well such as tripods, barges and tension-leg platforms. For the floating substructures, maintenance of the mooring system is particularly important due to the large dynamic motions from the wave loads of the ocean environment. The floating substructures require a more complex design than their bottom-fixed counterpart, and therefore introduce new types of failures compared to the bottom-fixed substructures. Extensive monitoring of the mooring lines is needed to collect data to decrease the chance of failure. Maintenance of the mooring system includes monitoring and regular inspections of the mooring lines and their attached anchors.

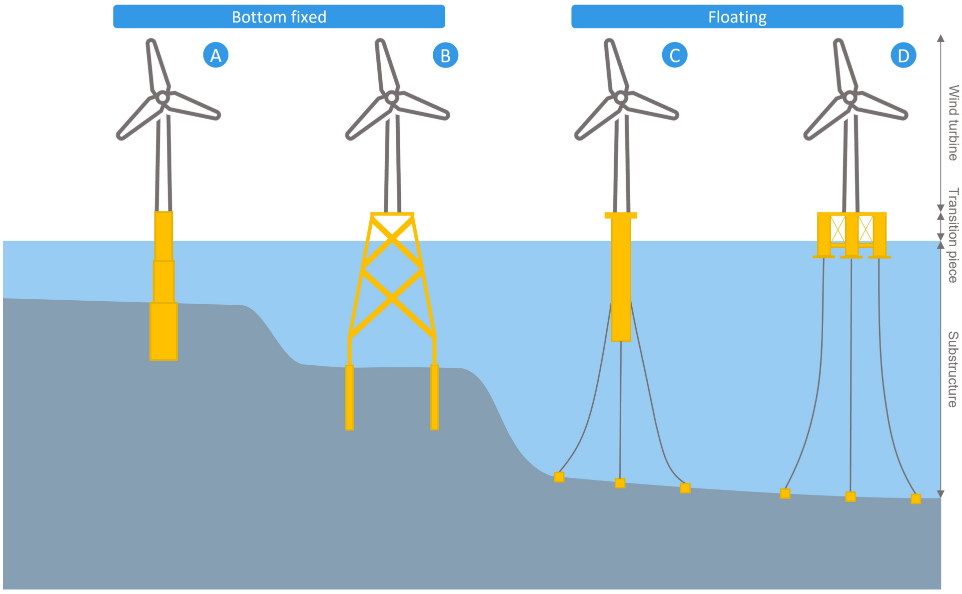


Figure 2.9: Illustration of substructures of OWTs

Cables in offshore wind include export cables and inter-array cables between the OWTs and substations. Subsea cables will need to withstand large movements and sediment flows, especially when considering floating OWTs. Subsea cables typically come with a 5-year warranty from the producers, but this covers only defects from manufacturing and not external factors (GL Gaarrad Hassan, 2013). The cables will therefore need extensive monitoring and surveying to ensure safe operation. The maintenance work of cables is typically carried out by a combined repair-and-layer ship. The vessels have to be relatively manoeuvrable since maintenance will involve two ends of the cable in contrast to only one end in cable laying work (Babicz, 2015).

For substations, the usage of technicians is needed to execute maintenance activities. The transfer and transit of maintenance personnel can be executed by airlift or transfer vessels, depending on the substation. The size of the substation construction is the deciding factor for the construction of helipads. Modern substations have a compact design with gas-insulated breakers insulated with SF6 gas (sulphur hexafluoride) (Aziz Biabani & Mohsin Ahmed, 2016). SF6 gas is a highly potent greenhouse gas (Dervos & Vassiliou, 2000), and major failures in the substations could cause environmental consequences. Details of different types of maintenance work needed on an extra high voltage substation are described in Aziz Biabani and Mohsin Ahmed (2016) for further reading.

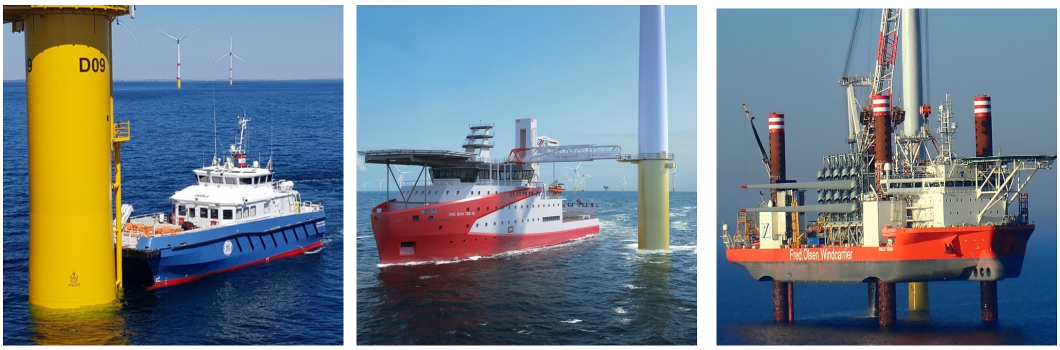
Some wind farms need to convert high-voltage alternating current (HVAC) generated in the turbines into high-voltage direct current (HVDC). This is due to minimise the loss of energy in the export cable, although this comes at a high cost. HVAC has a higher loss of energy per meter than HVDC (Williams, 2011). This means that offshore converter stations likely will be considered for wind farms located far from the shoreline, and it is highly relevant for the planned offshore wind areas in Norway which is situated far from the shoreline.

2.3 Logistics of O&M

The maintenance of OWTs is a demanding and costly operation. It could be between five to ten times more costly than similar work onshore. According to van Bussel and Zaaijer (2001), the maintenance of OWTs includes complex operations such as regular heavy lifts where the day rate for equipment is ten times greater than their onshore counterpart, assuming that each respective market has increased equally. The different operations required for O&M create a mixture of different equipment and vessel requirements. For that reason, the logistics of the O&M need to be investigated and addressed. The logistics of offshore wind can be categorised by strategic, tactical and operational decisions, which indicate long-term, medium-term and short-term decisions respectively. According to Shafiee (2015), strategic decisions have the greatest impact on the O&M and the most influence on the profitability of the wind farm.

There are several methods to optimise the performance of offshore wind farms to lower costs. Vessel optimisation is one such method, due to the number of vessels and maintenance trips over the lifespan of an offshore wind farm. There are several factors to consider whenever optimising for vessels. For instance, service speed and size of the vessel or fuel consumption and emissions. The fleet composition required to fulfil every maintenance task is difficult to optimise, and an effective optimisation approach is therefore important when planning the O&M. The article of Dai et al. (2015) proposes a mathematical model for a vehicle routing problem with pickup and delivery for small offshore wind farms with up to 8 wind turbines. It applies the concept of maintenance grouping where different maintenance tasks are scheduled within the same period. The works of Stålhane et al. (2019) present a two-stage stochastic programming model of the fleet mix problem. The first stage is identifying what vessels to charter, and the second stage is how to utilise the chartered vessels to support the maintenance tasks.

As mentioned, the maintenance of OWTs requires different types of vessels to carry out the work. A selection of typical vessels involved in O&M of OWT is shown in Figure 2.10. According to Ren et al. (2021), maintenance of offshore wind turbines can be divided into three operations for onsite maintenance of OWTs; **i)** transit of equipment and personnel, **ii)** transfer of equipment and personnel, and **iii)** heavy lifts.



(a) Louis Dreyfus Armateurs, 2022 *(b) Royal IHC, 2023* *(c) Fred. Olsen Windcarrier, 2023*

Figure 2.10: Typical vessels for O&M: (a) CTV, (b) SOV and (c) Jack-up vessel

2.3.1 Transit of personnel and equipment

The personnel and equipment will have to be transported from the O&M base to the wind farm. A suitable and optimal fleet of vessels will be needed to perform this task, to minimise overall costs. The type of vessel depends on what type of transit the vessel will carry. Currently, smaller bottom-fixed wind farms in shallow near-shore waters are operated by smaller crew transfer vessels. Offshore wind farms situated further from the shoreline, typically use service operation vessels (SOVs) for the transit between the O&M base and the wind farm. A helicopter is also a viable option for the transit of personnel, but the typical size of the foundations of current bottom-fixed wind turbines cannot sustain a helipad.

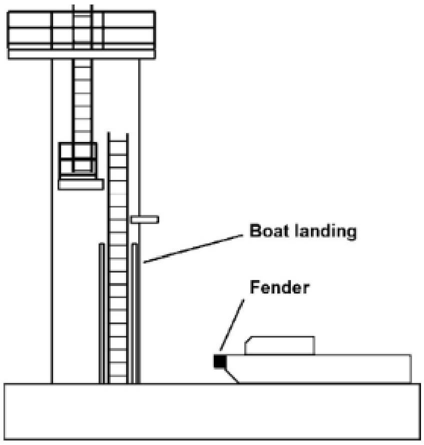
Weather conditions also need to be accounted for, as the vessel selection is severely dependent on what type of weather conditions the location of the wind farm experiences (Halvorsen-Weare et al., 2013). The weather is uncertain by nature and difficult to predict, and sufficient studies of the weather conditions should be conducted in order to select a fleet of transit vessels.

2.3.2 Transfer of personnel and equipment

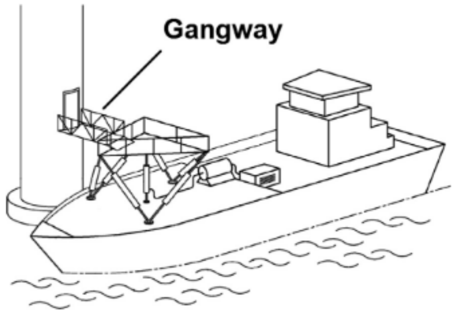
Safe docking of OWTs is essential for the security of the personnel and to avoid damages from a collision with the OWT. This is done through the usage of simple fenders or active motion-compensated systems such as a gangway often seen on larger vessels referred to as Walk-to-work vessels (W2W), seen in Figure 2.11. The simple fenders consist of a rubbery material situated between the vessel and the OTW, where forward propulsion keeps the bow of the CTV in contact with the OWT letting personnel board the OWT through a ladder. This method could be challenging due to the large vertical motions caused by wave motions.

One solution to this problem could be to implement a Boarding Control System presented in the study of Auestad et al. (2015), which reduces the vertical accelerations through an active air-cushion pressure control. Motion-compensated systems like gangways can be implemented if the vessel has sufficient deck space and weight capacity, although this is more costly than the simple fender option. This typically consists of a tower with a hydraulic gangway pointing out compensating for six degrees of freedom.

Ampelmann is a company that provides dynamic W2W solutions developed since 2002 from a research thesis at Delft University (Ampelmann, 2023). The transfer between vessel and OTW becomes increasingly more complicated when considering floating OTWs, as it will include two dynamic systems. Dynamic positioning systems will therefore be important to make sure of a safe transfer of personnel and equipment.



(a) Vessel with fender in bow



(b) Vessel with motion-compensated gangway

Figure 2.11: Docking options for transfer vessels (Guanche et al., 2016)

2.3.3 Heavy lifts

Some of the maintenance work of OWT components require lifting operations. This includes lifts of heavy components like gearboxes and blades, which are some of the most vulnerable components of the OWT due to complex operation and work intensity (M. Li et al., 2019). Lift operation carried out at sea is heavily dependent on suitable weather conditions like wave heights and wind speeds to ensure a safe lift operation, in contrast to similar operations at onshore wind turbines. Heavy lifting operations could be carried out by vessels such as different crane vessels and jack-up vessels, however these vessel types tend to have relatively high day rates being significantly higher than their onshore counterparts (Ren et al., 2021).

Floating wind turbines have a major challenge regarding heavy lifts, as the aforementioned vessels have a depth limit of 60 meters (Ahn et al., 2017). Whenever heavy parts, such as nacelles or blades, need to be replaced or worked upon, the current feasible option is to bring the turbine to shore in a tow to shore operation (T2S) and carry out the work in shallow waters with crane vessels or onshore cranes (McMorland et al., 2022). In addition, OWTs are becoming increasingly larger and lifting operations of heavy components therefore become more complex. An integrated lifting system could therefore be a solution to this problem both for bottom-fixed and floating OWTs, where a crane system is an integrated part of the OWT such as solutions that the Norwegian company Windspider provides (Windspider, 2022).

Additionally, alternative options for heavy lifts with floating OWTs are also available such as semi-submersible crane vessels (SSCV). Heerema's Sleipnir vessel is an example of a SSCV, being the world's largest SSCV (Heerema Marine Contractors, 2022) seen in Figure 2.12, which could be considered in order to prevent costly T2S operations. A heavy lift vessel has a very critical stability design to meet strict stability criteria, and several accidents for heavy lift vessels have occurred like the Mighty Servant

3 accident (Dankowski & Dilger, 2013). The article by Aborgela et al. (2022) explores the possibility of utilising SSCV in offshore wind. However, it is a difficult task considering the stability issues, especially regarding the increasing turbine sizes with 15 MW turbines having a hub height of around 150 meters (Gaertner et al., 2020).

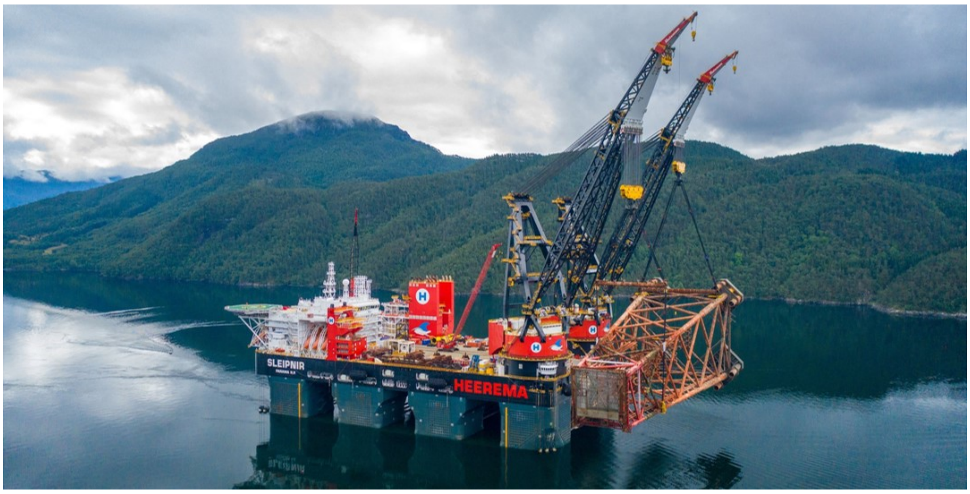


Figure 2.12: Image of the SSCV Sleipner (Heerema Marine Contractors, 2022)

2.3.4 Other vessel operations

The three onsite maintenance operations described earlier are not the only types of operations within the O&M of OWTs. Subsea components like mooring lines, anchors and substructures in general need regular inspections. Visual inspection is one of the most useful methods of inspecting underwater components (Na & Kundu, 2002), and it is used regularly within the industry. Typically, underwater visual inspections are performed by a remotely operated underwater vehicle (ROV). The images acquired from the ROV can provide detailed insight into the condition of the components through image processing algorithms (Rizzo, 2014). Other underwater inspection methods include magnetic particle inspection, ultrasonic testing and radiography (Na and Kundu, 2002 and Schull, 2002).

These inspection techniques, including visual inspections, all require expensive equipment and need to be operated from a capable vessel. A ROV requires a crane to be lifted into the water, either on the side of the vessel or through a moonpool. A vessel similar to a SOV or another specialised vessel should be suitable for such a task. Additionally, drones can successfully be utilised in blade inspections. According to Kabbabe Poleo et al. (2021), replacing inspection using rope access of wind turbine blades with drone-based inspection could decrease blade inspection costs by 70%.

Maintenance of OWTs includes tasks regarding underwater cables and underwater mooring systems as well. These are complex operations requiring special vessels like anchor handling tug supply vessels (AHTS) or cable laying vessels (CLV). For instance, the moorings of an offshore structure need to be inspected regularly (Ma et al., 2019) and one method of performing the inspection is to raise the moorings by a AHTS. Additionally, AHTS is important for T2S operations to hook and unhook the OWT from the mooring system (James & Ros, 2015). Underwater cables, including array cables and export cables, will need regular inspections and surveys. The cables will eventually require repair as well, and a suitable vessel like a CLV is needed for these to inspect, repair and jointing cables (Dresser & Tetra Tech, Inc., 2021).

2.3.5 Vessel selection

As described earlier, the vessel mix for maintenance operations for offshore wind can include a great number of different vessel types. In order to reduce costs, some of the specialised vessels should be individually chartered for maintenance tasks due to their sparse usage. Other vessels which operate more regularly in the maintenance of the offshore wind farm should be included as an investment in the project. Optimisation of the vessel fleet is important for any offshore wind project, and an approach presented in the works of Stålhane et al. (2019) could prove to be effective in order to save vessel costs related to maintenance which again affects the O&M costs and the LCOE.

An important aspect of vessel selection is addressing the operational limits of the different vessels. It is important to identify environmental conditions at the location of projects like wave heights and wind speed to select the types of vessel designs. Different designs have different operational limits. In order to account for uncertainties in the weather forecasts, alpha factors are introduced for the operational limits of the vessels (Guachamin et al., 2016). It is important to balance the alpha factor, by considering the uncertainty properly and mitigating the risk of problems during operation (Wilcken, 2012). However, this is more important for short-term operational planning.

Additionally, especially regarding the potential usage of OMBs, there is an option of using airlift through helicopters for the transportation of equipment and personnel. This is due to the size of the platform provides the possibility of a helipad and helicopter access. This will be important for the functionality of the OMB in order to effectively resupply it. For some floaters of floating wind turbines, like the semi-submersible seen in Figure 2.9 and barges, access to a helipad can be possible to transfer personnel and equipment due to the size of the floater (Chitteth Ramachandran et al., 2022).

Table 2.1 shows a suggestion for vessel selections for the maintenance tasks proposed in the works of Carroll et al. (2015). Some assumptions have been made regarding the major replacement operation of some components like the pitch system, electrical components and yaw system. Due to their cost, size and complexity, they are regarded as less extensive and require less cranage than the other components. The figure provides different options for the major replacement operation. The T2S include vessels like tugboats for towing and AHTS for hooking and unhooking to the mooring system.

Table 2.1: Suggestion for vessel selection for each type of OWT failures found in Appendix B

Component	Minor Repair	Major Repair	Major Replacement	
			bottom-fixed	Floating
Pitch/ Hydraulics	CTV, SOV or Daughter vessel	SOV	SOV	
Generator			Jack-up	T2S or SSCV
Gearbox				
Blades				
Electrical components			SOV	
Contactor/ Circuit breaker/ Relay				
Hub			Jack-up	T2S or SSCV
Yaw system			SOV	
Power supply/ Converter				
Transformer			Jack-up	T2S or SSCV
Controls			SOV	
Grease/Oil/ Cooling Liq.			-	
Safety			-	
Sensors			-	
Pumps/Motors			-	
Heaters/Coolers			-	
Tower/ Foundation			-	
Service items			-	
Other components			SOV	

3 | Offshore maintenance bases

The concept of an offshore maintenance base (OMB) and how it functions is important, and this chapter will therefore present a review of OMBs. The idea behind an OMB is to partially remove the need for long transit requiring costly vessels like SOVs and replace the transit with smaller vessels. In theory, this can improve the overall performance of an offshore wind farm if certain conditions are met, like transit times and weather conditions. The OMB must replace functionalities and utility functions of advanced vessels, in order to function as a reliable replacement for the vessels. This is challenging due to the harsh nature of the offshore environment. Addressing these issues and suggesting solutions is therefore important for the OMB and its subassemblies to be a reliable replacement for such advanced vessels.

Implementation of OMBs has several benefits for the O&M for offshore wind farms. As previously discussed, the implementation of OMBs will directly lead to reduced transfer time for technicians by replacing the time-consuming long transit between the onshore O&M port and the OWT with a relatively shorter transit between the OMB located within the offshore wind farm and the OWT. High weather availability is important for the CTV, as less dependency on suitable weather conditions is preferable as the weather is largely uncertain by nature. Furthermore, the implementation of OMBs can increase the efficiency of the offshore wind farm. The proximity to the wind farm makes the OMB's technicians able to respond quickly to any issues. This could further reduce the downtime of the individual OWTs and subsequently increase the generated income of the wind farm. Overall, OMBs could in theory provide a range of benefits including increased availability and performance, and reduced costs.

3.1 Concept of OMB

The concept of an offshore maintenance base is not a new concept and several variations of it have existed throughout the years. In 2008, the Danish company Ørsted A/S, formerly Dong Energy, introduced an accommodation platform for the Horns Rev II wind farm. The Danish offshore wind farm set 30 km away from shore, was installed with 91 wind turbines with a combined installed capacity of 209 MW. It was at the time the largest wind farm in the world and the furthest one away from shore (Ørsted A/S, 2022). A similar project was also implemented by the Swedish company Vattenfall at the Dantysk wind farm, located in the North Sea around 70 km off the shoreline (Vattenfall AB, 2022). These two projects in addition to several other projects around the world, included a single accommodation platform for personnel.

The Norwegian company Fred. Olsen Windcarrier, a major player in the offshore wind market, has also proposed an OMB concept. "Windbase" as it is called, is based upon different attachable modules for different needs and an illustration of the "Windbase" with three modules is shown in Figure 3.1. In 2016, the Norwegian software simulation company Shoreline conducted a study on behalf of Fred. Olsen to analyse the effects of implementing OMBs (Fred. Olsen Windcarrier, 2016b). This was a joint project between Shoreline and a major developer of offshore wind farms operating in the United Kingdom.

The study consisted of investigating three scenarios. The first scenario consisted of investigating the performance of a single service operation vessel (SOV) equipped with accommodation for technicians and a helipad. The second scenario consisted of the utilisation of two SOVs with walk-to-work (W2W) capabilities operating alongside Fred. Olsen Windbase-concept. The last scenario consisted of the Fred. Olsen Windbase utilises three crew transfer vessels (CTVs) for the transfer of technicians. The results from the study concluded with all scenarios producing relatively high availability. Notably, it was the third scenario containing the utilisation of CTVs which produced the most efficient performance with a remarkable 98% availability rate.

Figure 3.1: Illustration of the Windbase concept (Fred. Olsen Windcarrier, 2016a)

Typically, a large SOV is a complex vessel that can support maintenance through many functionalities, such as W2W-concept, a large deck space for storage, helipad, daughter crafts and accommodation for technicians. Motion-compensated gangways are important for the W2W functionality as discussed in section 2.3.2. As a result, the OMB and its subassemblies will be required to replace some or all of these capabilities. Most important would be for the OMB to include accommodation, helipad access and storage space. According to Avanessova et al. (2022), the selection of SOV with daughter crafts generally performs better in terms of availabilities and costs than an OMB with CTVs. The study suggests investigating the cost of additional structures to substations, to see if the OMB option may perform better in terms of total costs. It is important to view both CAPEX and OPEX when investigating the cost performance of OMB implementation.

3.2 Crew transfer vessels

The OMB will need to replace the transfer of personnel and equipment from the O&M base and the OWT. For the OMB concept, the aforementioned helicopter access can be important for the transfer between the onshore base and the offshore OMBs. Crew transfer vessels are necessary for the OMB, as they have the ability to transfer and transit technicians and equipment from the offshore O&M base to the OWTs. CTVs are considerably smaller than SOVs and they are limited to transferring technicians and equipment to the site of maintenance activity. A CTV is considered to be insufficient for any major repair and major replacement, as seen in Table 2.1.

Table 3.1: Typical characteristics of CTV vessels found in Stumpf and Hu (2018)

		Catamaran	**Trimaran**	**SWATH**	**TRI SWATH**
Length	[m]	20	18	20	27
$\text{Speed}_{\text{max}}$	[kn]	25	20	23	35
Passengers	[-]	12	12	12	12
Cargo	[tons]	10	1	2	4.5
$H_{s,\,\text{max}}$	[m]	2	2.5	2.5	3

The type of CTV will affect the operational limits. Currently, CTVs can operate in considerably smaller waves than large SOVs with motion-compensated gangways, depending on the type of hull. The report by Stumpf and Hu (2018) presents an overview of different hull options for CTVs, seen in Table 3.1. $H_{s,\,\text{max}}$ indicates the operational limit for the significant wave height. Typical values for operational wave limits for different types of CTVs range from 1.5 m to 3 meters. Traditional mono-hull CTVs are only capable of operating in sea states with a significant wave height of between 1.2 to 1.5 meters. Other hull designs such as different variants of catamarans, including small waterplane area twin hull (SWATH), and trimarans, including TRI SWATH, can achieve higher operational wave limits. Considering the harsh weather conditions in the North Sea, traditional mono-hull designs should not be considered for a CTV. Catamarans and SWATH designs, seen in Figure 3.2, provide more comfort for passengers and better behaviour in heavy seas (Thalemann & Bard, 2012) and should therefore be considered in this thesis.

Figure 3.2: Illustration of a CTV SWATH design (Alicat Workboats, 2017)

3.3 Major challenges

Several challenges present themselves for the implementation of OMBs with CTVs as transferring vessels. The harsh conditions of the North Sea make the operational limits of CTVs seen in Table 3.1, problematic. Figure 3.3 shows a weather analysis of the mean significant wave height data of the two offshore wind areas from 1998 until 2022. The data is gathered from Copernicus (2023), which is an open library consisting of several types of weather data in six-year intervals from 1959 until the present. The areas considered for this weather analysis are the current opened areas for wind production in Norway, by 2022, and include the bottom-fixed wind production area of Sørlige Nordsjø II and the floating wind production area of Utsira Nord.

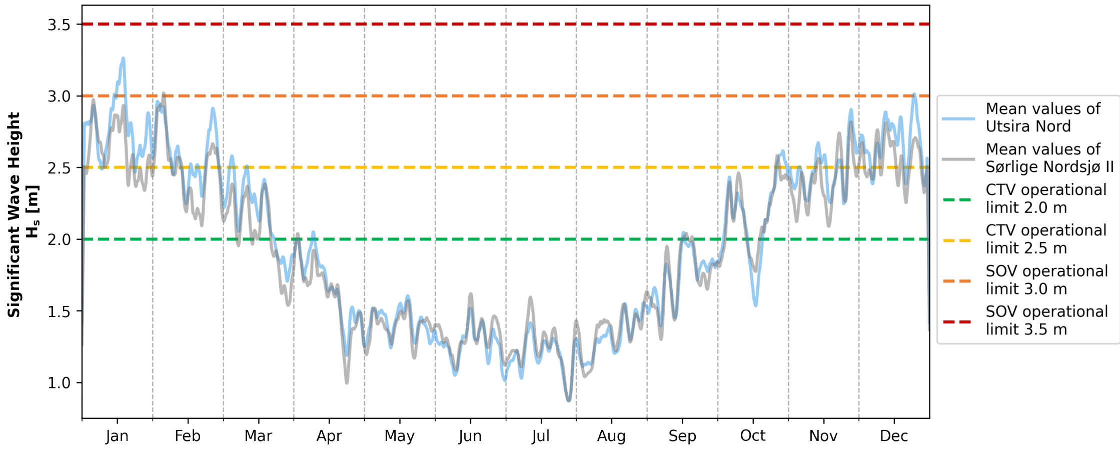


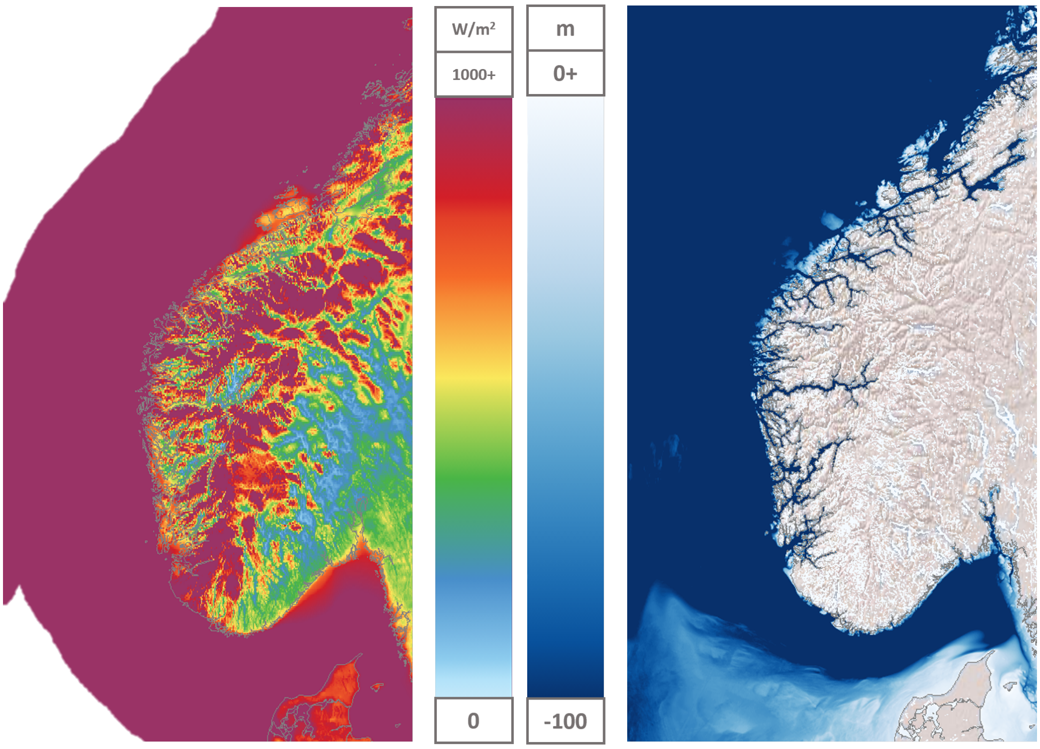
Figure 3.3: Mean wave heights (Appendix C) for Sørlige Nordsjø II and Utsira Nord compared to operational wave limits for vessels

The graph considers every hour of a normal year of 365 days. The data show that there is a significant increase in wave heights during the winter period of January, February, March, October, November and December. This will be problematic for CTVs with an operational wave limit of less than 2.0 meters. As Figure 3.3 shows, the CTVs with an operational limit of 2.0 meters will only be available for the transfer and transit of personnel for maintenance activities for about half of the year. Low weather availability is problematic when the aim is to lower costs and increase system availability.

Additionally, as highlighted by the study of Avanessova et al. (2022), it could be a possibility that the CTVs will be unable to deploy at the OMB. This is due to the great distance and harsh sea conditions between the wind farm and the shoreline. This will especially become a challenge for the wind farms located furthest away from the shoreline. It is assumed that this is not an issue in this thesis. Moreover, the shared foundation with either O&G installation or substations presents additional challenges. They will need to comply with standard regulations and safety measures, in order to continue to function with existing functions and as an OMB.

3.4 Feasibility of OMBs in Norwegian offshore wind

Currently, accommodation platforms for offshore wind are only situated in offshore wind farms with relatively shallow waters. Deepwater OMBs will encounter several challenges with their implementation, especially with a shared foundation. Norway is in a unique situation, due to the geographical proximity of offshore O&G installations. Furthermore, the weather conditions provide a great starting point with an overall wind power density exceeding 1000 W/m^2 in the North Sea and Norwegian Sea, as seen in Figure 3.4a. This could turn out to be a great opportunity for large-scale development of offshore wind, accelerated by competence from the O&G industry. For that reason, Norway could together with its bathymetry shown in Figure 3.4b, become a global leader in development of floating offshore wind.



(a) Map of wind power density *(b) Map of bathymetry*

Figure 3.4: Maps gathered from Global Wind Atlas (Technical University of Denmark (DTU), 2021)

3.4.1 Overview of the Norwegian market

Norwegian suppliers of offshore wind appear to be enthusiastic to participate in the upcoming Norwegian offshore wind production. Bringing a rich maritime history into account, strongly influenced by O&G in the last century, the Norwegian industry has great ambitions within offshore wind. The current Norwegian government has stated that Norway should have a 10% market share of the offshore wind industry by 2030

(Royal Norwegian Ministry of Trade and Industry, 2022b). Hywind Tampen is the only large-scale offshore wind farm in Norway today, with a total capacity of 88 MW. Additionally, the areas of Sørlige Nordsjø II and Utsira Nord are the only current areas open for the development of offshore wind. The two areas have an estimated potential of 4.5 GW in electricity generation capacity. A study estimated that the first step of the development of Sørlige Nordsjø II will, at earliest, commission into service in 2032 (Fauli et al., 2022).

The Norwegian industry collectively agrees that competence and experience from the O&G industry can be important for the development and innovation of offshore wind (Austrheim & Nesse, 2021). However, the competence is only transferable in some fields with turbine deliveries being such a non-transferable field. Several major developers and suppliers in the offshore wind industry have expressed interest in competing in the Norwegian market. Several of these corporations are based in Norway with experience in the O&G industry. Equinor is the leading actor among these companies and is a market leader globally within floating offshore wind. Equinor has also expressed an interest in using Norwegian suppliers for its projects, like when the Norwegian suppliers Aibel and Seaway7 were chosen for the development of a wind farm at the Doggerbank in the United Kingdom (Aslesen et al., 2022).

The Norwegian government also has an ambition of widespread collaboration between Norwegian actors, through the programmes "Entry Programme Offshore Wind" and "Team Norway". This is coinciding with the ambition of the Norwegian offshore wind industry to generate Norwegian jobs. A study conducted by Aslesen et al. (2022), expects somewhat between 11 700 and 52 000 jobs to be created in Norwegian offshore wind by 2050. This is about 25% of the total number of employees in the Norwegian O&G industry in 2019. Overall, the Norwegian government and industry demonstrate both being capable and interested in making Norway a global leader in the development of floating offshore wind.

3.4.2 Weather windows

As discussed in section 3.3, weather conditions will be a vital factor when implementing CTVs for the transfer of personnel in an OMB concept. This is due to the harsh weather conditions of the seas surrounding Norway. A study of the potential available weather windows for different operational limits was therefore conducted, to see if the usage of OMBs with CTVs as transferring vessels is a realistic opportunity. The weather data are gathered from the ERA5 database (Copernicus, 2023), and the study considers only wave heights. Wind speeds are important as well, climbing in the OWT is not allowed beyond wind speeds of 20 m/s (Ren et al., 2021). However, the wind speed limit was not considered as critical as the operational wave limits of the vessels for this feasibility study.

The number of weather windows is detected by finding the number of windows where the vessel's operational limit of wave heights is higher than the current average significant wave height in the area. The weather data used for this analysis is found in

Appendix C. The wind farms considered are the two areas currently open for development, namely Sørlige Nordsjø II and Utsira Nord. An important notation is that the data are based upon the mean value of 25 years of wave data shown in Appendix C, and the data are not randomly generated through a discrete weather simulation.

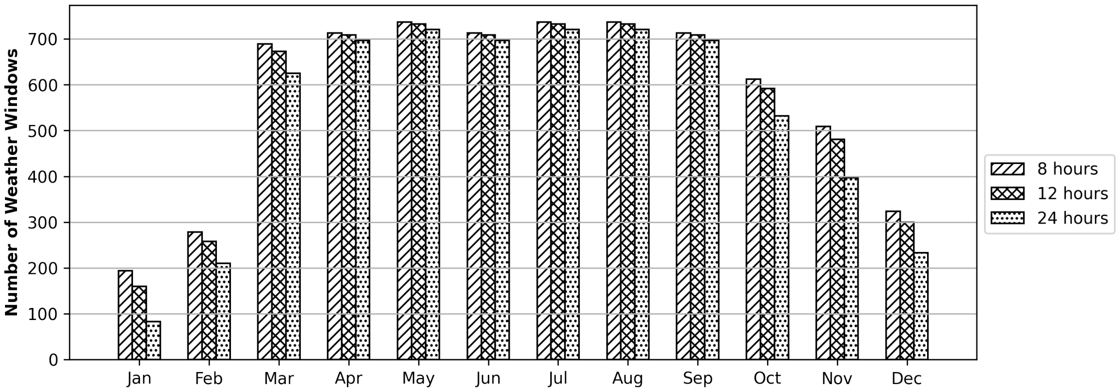


Figure 3.5: Weather windows for CTV in Sørlige Nordsjø II with $H_{s,\ max}$ = 2.5 m

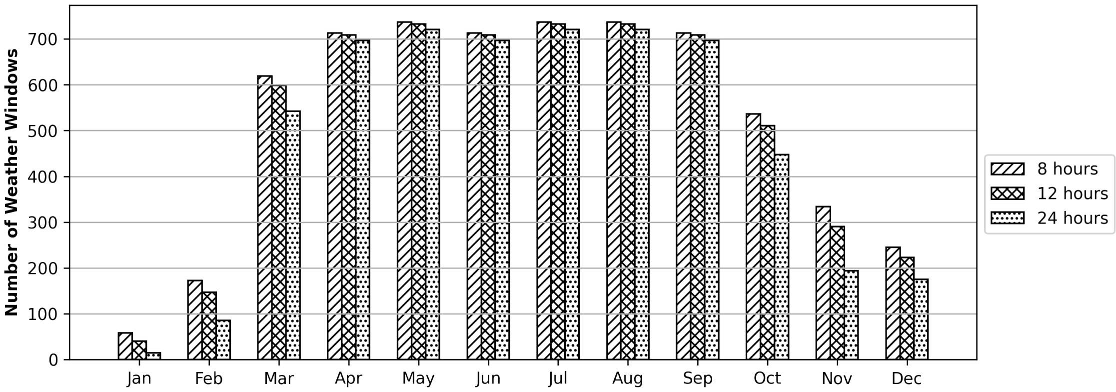


Figure 3.6: Weather windows for CTV in Utsira Nord with $H_{s,\ max}$ = 2.5 m

As seen in Figure 3.5 and 3.6, the CTV options have a limited amount of available weather windows in the winter months of January, February and December compared to the summer months. A CTV in Utsira Nord with an operational limit of 2.5 meters has severely limited weather availability in January, making it close to useless. This is expected after observations found in Figure 3.3. The North Sea experiences heavy winter storms (Behrens & Günther, 2009), and the following weather is creating weather conditions unsuitable for smaller vessels such as CTVs. If CTVs with an operational limit of 2.5 meters are considered, extensive planning for scheduled maintenance is needed to avoid the winter storms. This is especially important for the Utsira Nord area. However, the rest of the year has considerably calmer weather conditions. There is a great number of weather windows available for both wind farms, meaning that the CTV is a viable option.

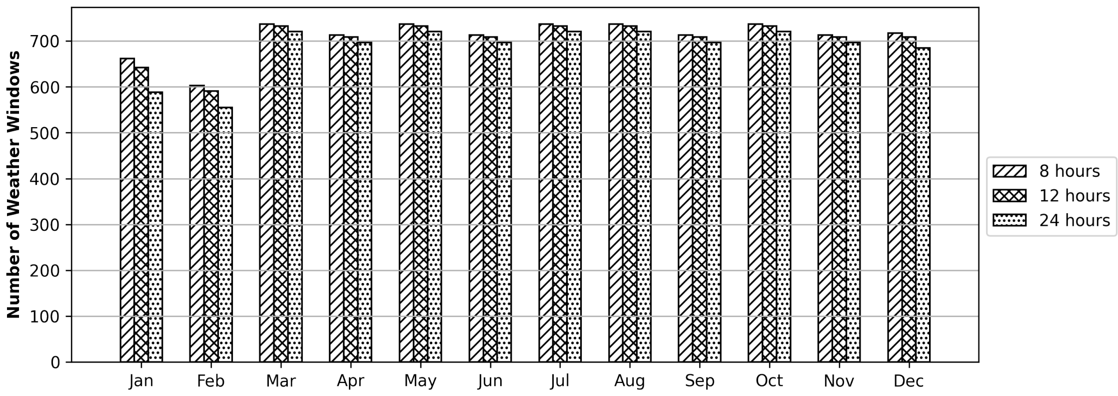


Figure 3.7: Weather windows for SOV in Sørlige Nordsjø II with $H_{s,\,max}$ = 3.0 m

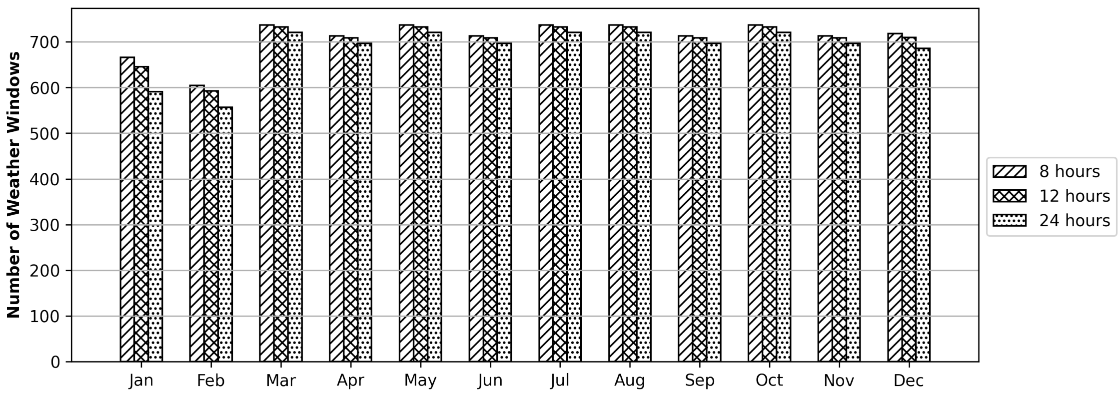


Figure 3.8: Weather windows for SOV in Utsira Nord with $H_{s,\,max}$ = 3.0 m

Overall, the SOVs have more available weather windows than the CTVs. However, they also experience the impact of winter storms similar to the CTVs. This is clearly shown in Figure 3.7 and 3.8, where January, February and December has fewer available weather windows than the rest of the year. In reality, the SOV should have fewer windows per month due to the transit between the port and the offshore wind farm. This was not considered for this weather analysis, in order to directly compare the SOV to the CTV with the number of weather windows for maintenance tasks. Overall, the weather analysis shows that CTVs with an operational limit of 2.5 meters, are a viable option for offshore wind farms situated in the North Sea.

It is important to mention that this analysis only considers significant wave heights and does not consider wind speeds which is important as well. The weather analysis does not consider the relation between the motions of the vessel and floating OWTs. This could complicate the transfer of technicians and equipment between a CTV and the OWT. Additionally, floating OWTs experience large motions in comparison to ordinary bottom-fixed OWTs, especially in pitch illustrated in Figure 3.9. This could make maintenance work dangerous for technicians.

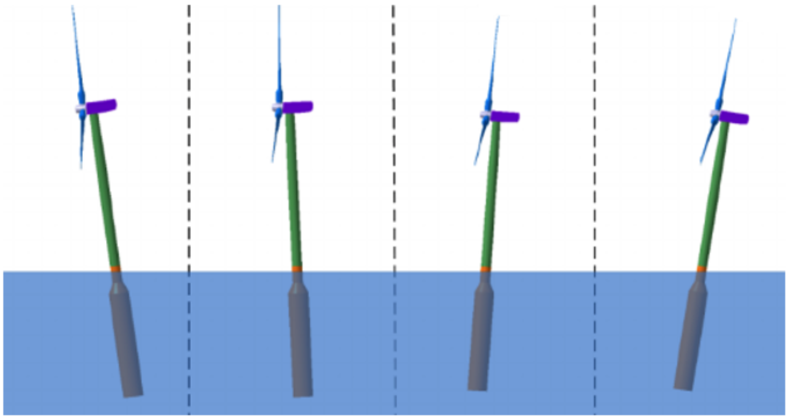


Figure 3.9: Pitching motion of a floating OWT (Tran & Kim, 2015)

3.4.3 Shared foundation with substation

The shared foundation of the OMB with substations faces several challenges, especially regarding the number of hazards personnel could be exposed to. Some of the hazards include exposure to electromagnetic fields created by electrical components, electrical shock, arc flashes and exposure to chemical substances like SF6 gas found in gas-insulated components (Piotrowski et al., 2016). This could complicate the accommodation part of the shared substation and OMB platform. Sufficient safety measures to mitigate these hazards are vital to achieve a functional and safe platform.

Bottom-fixed substations are currently a matured technology used widely throughout offshore wind farms in the world, with industrial such as DNV-ST-0145. The greatest challenge in connection with hazards for substations is electromagnetic fields created by electrical components. Typical safety distances to mitigate exposure are several meters, however it varies for each substation design. The safety distances must be considered in the design of a shared foundation between substations and an OMB.

The cost of additional structures can be difficult to determine without an extensive investigation of the system and how the different modules affect the foundation. However, a bottom-fixed offshore substation typically costs 125 000 GBP/MW to construct (BVG Associates, 2023), where 60 000 GBP/MW is associated with the structure of the substation. A 500 MW substation typically has a topside weight of 2000-3000, and by applying a weight ratio it is possible to obtain cost estimates of the shared OMB and substation. Using weight data of container-based accommodation modules gathered from OEG Offshore (2023), an OMB with the capacity of 36 technicians and general-purpose spaces such as a gallery and recreational rooms, could weigh up to 400 tonnes.

If the weight-to-cost ratio is utilised for the substation and the additional weight of the OMB, the foundation will cost around 35 million GBP. This is based upon a water depth of 30 meters which is half of the average water depth at the proposed areas for development of bottom-fixed wind farms in Norway. The works of Oh et al. (2018) present some estimations of the increased cost with increasing water depth, and a logarithmic regression of the estimates is implemented in Equation 3.1. The equation estimates the foundation costs by summarising the weight of the topside modules i and utilising a weight-to cost-ratio $k_{\text{weight ratio}}$. Lastly, the estimate is adjusted for the water depth d.

$$C_{\text{foundation}}(d) = k_{\text{weight ratio}} \left(\sum_{i=1}^{I} m_i \right) \left(1 + \frac{55.04 \ln(d) - 181.53}{100} \right) \tag{3.1}$$

The cost of the OMB can then be determined by cost coefficients for the different modules. A suggestion for the cost coefficients is shown in Table 3.2, interpreted from values gathered from System Based Ship Design (Levander, 2017).

Table 3.2: Cost to weight ratios of OMB modules

Module	**Cost coefficient [GBP/tonne]**
Accommodation	7 240
Storage spaces	5 000
Other (cranes, helipads)	2 000

On the other hand, floating substations experience large motions and constant vibrations from waves that create several challenges to high-voltage electrical equipment. In 2022, DNV initiated a joint industry project with 30 major industry stakeholders to solve issues regarding floating substations and update the DNV-ST-0145 standard (Dippel, 2022). A solution to these challenges could be implementing subsea substations which could decrease costs by 30% (Aker Solutions, 2022). However, this is not further investigated in this thesis.

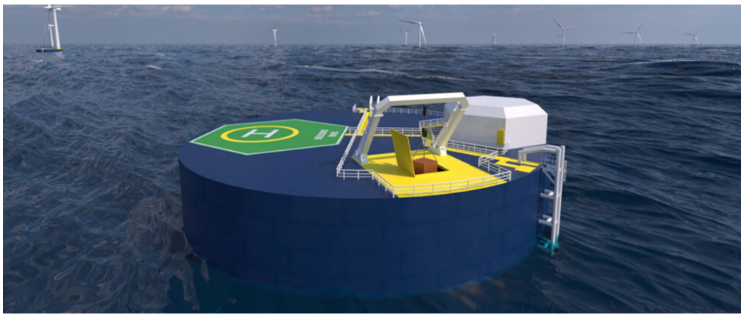


Figure 3.10: Illustration of Sevan SSP floating substation (Sevan SSP, 2023)

Sevan SSP introduced a floating substation concept into their SCUP floater design seen in Figure 3.10, which includes a substation integrated into the hull, a helipad and storage facilities with two access points for W2W-vessels (Sevan SSP, 2023). A similar concept could be considered for the shared foundation of substations and OMBs for floating wind farms, yet the additional cost of the OMB is difficult to estimate. Generally, weight equals cost in the design of semi-submersible platforms (Patricksson, 2012). The works of Myhr et al. (2014) investigated the cost of different floaters of

OWTs. The SCUP design was not included in the investigation, however, the investigation estimated that Windfloat's tri-floater design was estimated to cost around 7.5 million GBP with a generic 5 MW turbine weighing around 600 tonnes. If a similar weight-to-cost ratio approach is used as in Equation 3.1, it is possible to obtain cost estimates of the floating shared substation and OMB.

The calculation of the floating foundation is shown in Equation 3.2. The calculation does not account for the considerably lower centre of gravity of substations compared to OWTs, which will affect the design and cost of the floater. The costs include estimates for mooring and anchoring costs, assuming 9 mooring lines and anchors together with the mooring cost estimates of Myhr et al. (2014) adjusted for 29% inflation from 2014 (Bank of England, 2023) and converted to GBP with a rate of 0.87 (Xe, 2023).

$$C_{\text{foundation}}(d) = k_{\text{weight ratio}} \left(\sum_{i=1}^{I} m_i \right) + 2131d + 1323540 \tag{3.2}$$

3.4.4 Shared foundation with oil and gas installations

Norwegian offshore wind could also repurpose O&G platforms to have a shared OMB and O&G platform. Currently, there are 844 active O&G installations under Norwegian legislation (Norwegian Petroleum Directorate, 2023). The installations can be seen as yellow markers in Figure 3.11, or further investigated in Appendix D. Some of the installations are subsea installations which are not possible to repurpose as OMBs. The proximity of O&G installations can make them a less costly option for the implementation of OMBs in Norwegian offshore wind farms.

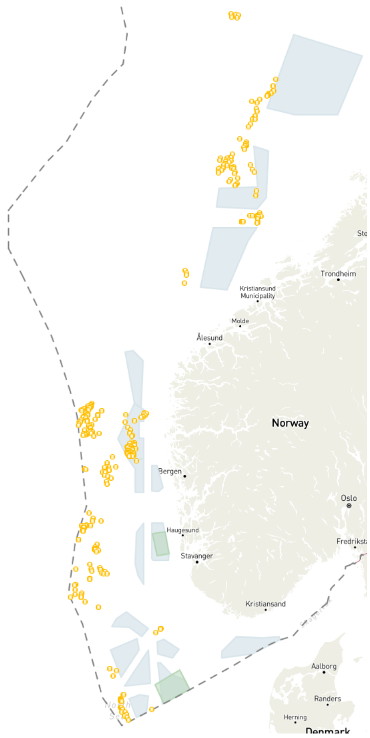


Figure 3.11: Map of O&G installations and proposed offshore wind farm areas

Different platforms have different purposes, and not all platforms will be suitable for repurposing as OMBs. Likewise to the variety of foundations of OWTs, O&G platforms have different types of substructures depending on the water depth and the ocean floor. Different types of O&G platforms can be seen in Figure 3.12. Additionally, each installation has several different functions, which can include drilling, varieties of injection, distribution, loading, production and accommodation. The superstructure often consists of different modules, and this modularity makes the shared OMB and O&G installation a feasible option by switching modules. Floating production, storage and offloading (FPSO) vessels are also widely used on the Norwegian shelf, however, these are considered not possible to be repurposed as an OMB due to the size constraints of a ship.

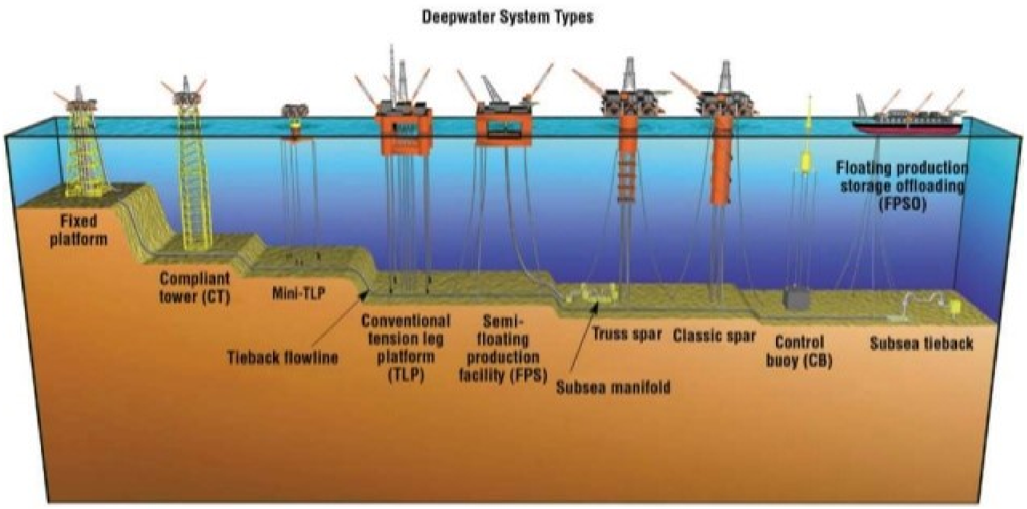


Figure 3.12: Typical O&G platform types gathered from National Ocean Industries Association (2023)

The main addition that is needed to repurpose an O&G platform into an OMB, is accommodation and storage spaces. The platform must be capable of implementing these spaces. Another challenge that complicates the operation, is the height difference between the sea level and deck height of the platform. The height difference will complicate the transfer between the platform and a CTV. This transfer is important to address before investigating the usage of an O&G platform, in order to maintain a safe transfer of technicians and equipment between the platform and CTV. As previously discussed in section 3.4.3, the substructure is the most cost-critical component of an OMB. This cost is eliminated in a potentially shared foundation with an O&G platform since the platform already exists. Consequently, the cost will only consist of the addition of the OMB spaces into the superstructure and the cost of taking the O&G platform out of production.

4 | Methodology

This chapter will present the methodology of the case study conducted in the thesis. The objective of this thesis was to investigate the effectiveness of OMBs in comparison to conventional methods of performing O&M with the utilisation of SOVs. It consisted of a cost-benefit analysis of the implementation of the two methods of O&M, which is a useful method of assessing the desirability of projects by examining the projects with a long-term perspective together with a broad inclusion of all relevant costs and factors influencing the benefit of the project (Prest & Turvey, 1966).

4.1 Step by step approach

In order to evaluate the effectiveness of OMBs in Norwegian offshore wind, it was important to consider both qualitative and quantitative approaches to gain a holistic understanding of how an OMB would perform at Norwegian offshore wind farms. Therefore, a bottom-up approach to the problem, which in this context was about starting at the desired output and assessing the steps needed to obtain the output. The desired output was to find the costs related to O&M for OMBs and conventional O&M with SOVs in bottom-fixed and floating wind farms and compare the overall impact of the LCOE. In order to achieve this output, it was important to understand how the O&M of offshore wind farms functions. This has already been covered in Chapter 2. Furthermore, it was important to understand how an OMB is designed and how it functions. This has been covered in Chapter 3, where deductive reasoning was used by applying existing concepts and theories of OMBs.

The next step was to test the performance of OMBs against conventional methods for Norwegian wind farms. For this thesis, a quantitative case study containing several wind farms was conducted to account for different conditions at the Norwegian Shelf. An issue with Norwegian offshore wind was that the only operative offshore wind farm was Hywind Tampen with a relatively small capacity of 88 MW. Hypothetical large-scale offshore wind farms were therefore constructed based on the proposed areas for development developed by NVE. The case development included investigating parameters such as the size of the wind farm, the type of substructure and the O&M port. A detailed map of the selected areas can be seen in Appendix D.

A simulation of the different wind farms was conducted to analyse the performance for the entire lifespan of the offshore wind farm. The simulation is further described in section 4.2. Since the simulation contained the entire lifespan of the offshore wind farm, it was important to calculate the Net Present Values (NPV) during the simulation. The formula for NPV is shown in Equation 4.1, where NCF_t is the net cash flow at moment t and r is the discount rate. The time t indicates the moments when the discount rate is applied, which typically is set to yearly intervals.

$$\text{NPV} = \frac{NCF_t}{(1-r)^t} \tag{4.1}$$

The simulation required different types of input data in order to run. The input data consisted of wind farm characteristics, vessel selections, failure data and weather data. The weather data selected for the case study consisted of the ERA5 (Copernicus, 2023) and the NORA3 reanalysis (The Norwegian Meteorological Institute, 2023), and is further described in section 4.3. Failure data was required to simulate whenever failures occur and consequently whenever unplanned maintenance was needed. The case study utilised the failure rates of Carroll et al. (2015), shown in Appendix B. It is important to note that the failure data produced from this work was based upon bottom-fixed OWTs with a capacity of 2 to 4 MW. The vessel selection was required due to the different maintenance tasks requiring different vessels. The vessels selected for unscheduled maintenance are the suggestions shown in Table 2.1. For the scheduled maintenance, the least costly available and suitable vessels were selected for each case. Turbine specifications were also needed, where the IEA Wind 15-MW Turbine (Gaertner et al., 2020) was selected with its power curve shown in Appendix E.

After assessing all of the required inputs, the simulation was ready to run and produce output. The simulation process was a time-consuming iterative process due to the several adjustments needed to achieve a realistic output. It was therefore important to have a qualitative process in assessing the input data. The output of the simulation would not have given the total OPEX, as the OPEX contains several other components than what was simulated. An OPEX estimate was therefore calculated through Equation 4.2, where k_{other} accounted for the additional costs surrounding OPEX. The yearly accumulated $C_{O\&M,\,\text{simulation}}$ was NPVed and summarised for the entire lifespan Y. $P_{turbine}$ and $n_{turbines}$ denote the turbine capacity and the number of turbines.

$$OPEX_{\text{estimate}} = k_{other} \frac{\sum^{Y} C_{O\&M,\,\text{simulation}}}{n_{turbines} P_{turbine} Y} \tag{4.2}$$

The last step consisted of comparing the different wind farms in the case study. This was conducted by comparing the OPEX component of the LCOE shown in Equation 4.3, where $E_{p,TOT}$ was the total generated electricity during the wind farm lifespan. C_{OMB} accounted for the additional cost for an OMB with its calculation shown in Appendix F. The calculation utilised Equation 3.1 and 3.2. The weight-to-cost ratio for bottom-fixed was set to 14 286 GBP per tonne topside, based upon the estimates of BVG Associates (2023) and a substation weight of 2 100 tonnes. The ratio for the floating option was set to 37 738 GBP per tonne and was based upon the Windfloat floater estimate by Myhr et al. (2014) and the relative cost increase of covers and ballast in the article of Chen et al. (2023). The weight of the topside OMB modules was determined by weighting, where the accommodation module was set to 50% of the total weight. The storage spaces and other components were set to 35% and 15% respectively. The cost coefficients were based upon the suggestion shown in Table 3.2. It was assumed that the shared substation would not increase the initial installation costs. The additional cost of repurposing O&G platforms was solely based on the cost of the OMB modules, and costs related to the repurposing itself and its impact on the O&G platform were not included.

$$LCOE_{OPEX} = \frac{C_{OMB} + OPEX_{\text{estimate}}}{E_{p,TOT}} \tag{4.3}$$

4.2 Simulation

A simulation is an imitation of a real-world process (Slette, 2022), and it should account for uncertainty and stochastic natural processes such as weather and time of failures. The simulation should utilise discrete system states that change at events to simulate these stochastic processes, through a simulation technique called discrete event simulation (DES). DES is different from continuous simulation which changes at times, illustrated in Figure 4.1. To account for the stochasticity, DES use pseudo-random numbers in order to generate different random scenarios. The result of one DES scenario will not be a sufficient representation of the simulated system. Several iterations should therefore be performed with a different sequence of pseudo-random numbers. Monte Carlo techniques can be used for scenario generation, which models the system as a series of probability density functions and repeatedly samples these functions to generate multiple sets. Lastly, the Monte Carlo method computes the statistics of interests from the generated sets of data (R. L. Harrison, 2010).

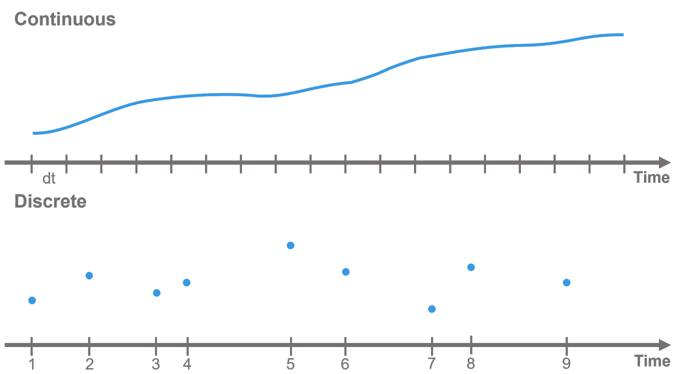


Figure 4.1: Difference between continuous and discrete events (Helal, 2008)

The complexity of the various operations in O&M of offshore wind farms can make it difficult to construct realistic simulation software to embrace the entire system. Commercial tools were therefore considered for this thesis. The input data required to run the simulation were dependent on the type of simulation tool. Hence, it was important to establish the data before simulating to attempt to reduce the number of adjustments and iterations.

There are several simulation tools established for the simulation of O&M of offshore wind farms, like SINTEF's NOWIcob tool (Hofmann et al., 2017), ORE Catapult's COMPASS tool (Gray, 2021) and DNV's O2M-tool (Montoya, 2022). Common for these simulation tools is that they are used for internal projects, making access to them restricted. ORE Catapult's COMPASS tool is a Python-based O&M simulation tool obtaining reliable estimates of OPEX of offshore wind farms (Gray, 2021) and it was also the tool used in the study of Avanessova et al. (2022). The time-domain mode of the simulation tool checks whether maintenance is required for each time step. It then checks for suitable weather conditions and the availability of personnel and vessels. Monte Carlo simulations of potential failure modes are conducted to account for unplanned maintenance. Lastly, the tool then summarises all the time steps in order to obtain a cost estimate. DNV's O2M tool has been developed since 2005 and considers the maintenance of all aspects of the wind farm including OWTs, substations and cables. The tool utilises years of historic data to estimate failure rates and repair times of failures. The tool can consider different maintenance strategies to present the best option overall (Montoya, 2022).

The NOWIcob tool from SINTEF is an analysis tool created with MATLAB for the simulation and optimisation of offshore wind farms developed since 2011, which targets researchers and commercial wind farm developers and operators. The tool can serve as a useful tool for decision-making in offshore wind farms, such as the potential implementation of OMBs. The NOWIcob tool is the simulation software selected to conduct the simulation for this thesis due to its availability and suitability for the problem of the case study.

4.2.1 NOWIcob

The NOWIcob model uses a discrete-event Monte Carlo simulation technique where the maintenance of an offshore wind farm is simulated over several years at an hourly resolution. The simulation accounts for uncertain variables such as weather, failure rates and electricity price scenarios. The input data consist of historical weather data, general data on the wind farm, maintenance and failure data, and vessel data. The results of each Monte Carlo iteration are saved, and the final results are delivered by histograms. The results include KPIs such as availability, an O&M cost split and the profitability of the wind farm. A simplified flow scheme of the NOWIcob tool is seen in Figure 4.2. The following description of the NOWIcob tool is based directly upon the technical documentation by Hofmann et al. (2017).

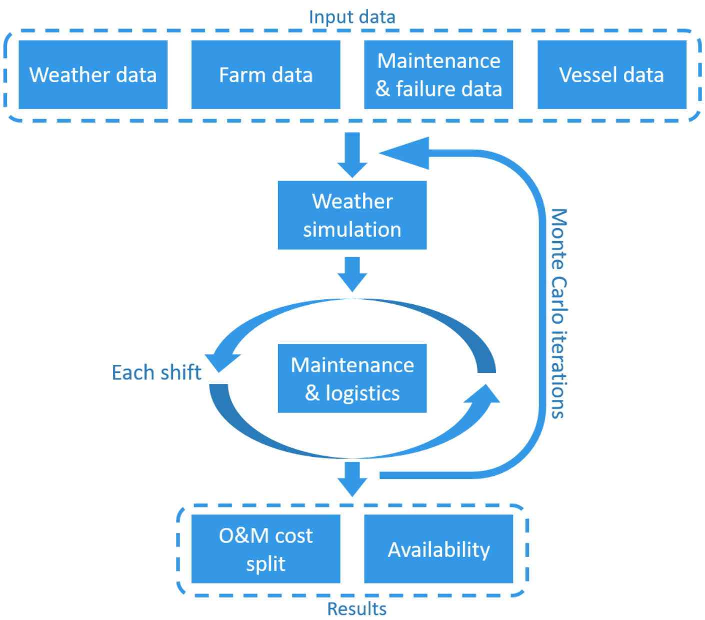


Figure 4.2: Simplified flow scheme of NOWIcob tool (Hofmann et al., 2017)

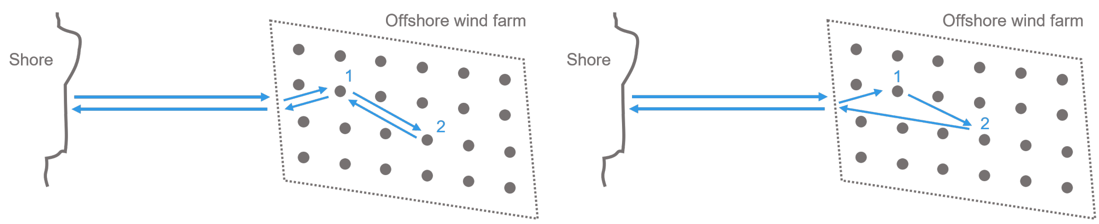
The weather time series and times of failures are treated as stochastic variables in the NOWIcob software. The method of random number generation (RNG) is the Mersenne Twister RNG integrated into MATLAB, which produces the required pseudo-random numbers. The RNG is set to the default seed 0 at the start of each simulation, ensuring that the same random number sequence and consequently the results are the same each time the same case is simulated. At the start of every Monte Carlo iteration, a weather simulation is conducted based on historical weather data. The weather simulation is carried out by applying a Markov chain process, which can generate weather time series with the same statistical properties as the input historic weather time series (Hagen et al., 2013). The weather simulation is important for estimating the generated wind power electricity and for the weather availability of the vessels.

In NOWIcob, the time to failure (TTF) is derived from a homogeneous Poisson process with annual failure rates as input. It means that, on average, a given number of failures will occur throughout a year even though the TTF remains uncertain. The TTF is calculated with Equation 4.4 and RNG. The variable u is gathered from a uniform distribution between 0 and 1.

$$\mathrm{TTF} = -\frac{1}{\lambda}\ln u \tag{4.4}$$

As discussed in section 2.2.3, some components of the OWT experience changes in their failure rates throughout the lifespan of the component. The NOWIcob tool has the ability to alter the failure rates of specific components after a given number of years, i.e. to a bathtub curve. In addition to corrective maintenance, NOWIcob implements predetermined preventive maintenance by specifying fixed intervals of maintenance. It is possible to change the start date of the maintenance tasks to adjust for seasonal availability due to weather. Moreover, NOWIcob can account for condition-based maintenance by determining the probability of potential failures and pre-warning time. However, this was not implemented in the case study of this thesis due to the availability of data for the utilised failure categories.

In addition, the NOWIcob tool has the ability to schedule several maintenance tasks in one shift. If a task is not finished within one shift, it can allocate the task over several shifts. Access vessels, such as CTVs and SOVs, can serve tasks at different locations in parallel as seen in Figure 4.3a, by delivering technicians at one location before picking them up at a later stage. Other vessels are modelled with sequential maintenance, as illustrated in Figure 4.3b. The NOWIcob tool can also set up specific maintenance tasks requiring jack-up operations like some of the major replacement tasks.



(a) Parallel tasks *(b) Non-parallel tasks*

Figure 4.3: Illustration of internal travels for different tasks (Hofmann et al., 2017)

Lastly, when all of the required input is set up, the NOWIcob tool can begin to simulate and produce KPIs of the offshore wind farm. The total produced electricity of the wind farm, E_{real}, is found with Equation 4.5 for all time steps t. The definition of each variable in the equation is described in the list below.

$$E_{\text{real}} = A_{\text{trans}}(1 - L_{\text{wake}})(1 - L_{\text{el}}) \sum_{t=1}^{T} \sum_{n=1}^{N} (E_{\text{theory},n,t} A_{\text{turbine},n,t}) \tag{4.5}$$

$E_{\text{theory},j,t}$	–	Theoretical electricity production if OWT n has 100 % availability at time step t
$A_{\text{turbine},j,t}$	–	Availability of OWT n at time step t
A_{trans}	–	TA of main components that transport or transform electricity
L_{wake}	–	Loss of production due to wake effects
L_{el}	–	Loss of production due to electrical infrastructure
T	–	Number of time-steps for the whole simulation with hourly time-steps, indicated by t
N	–	Number of OWTs in wind farm, indicated by n

The time-based availability (TA) and the energy-based availability (EA) are calculated through Equation 4.6 and 4.7 respectively. T_{lifetime} indicates the lifetime of the turbine in years and T_{downtime} is the downtime of the OWT due to failures and maintenance tasks.

$$TA = \frac{T_{\text{lifetime}} - T_{\text{downtime}}}{T_{\text{lifetime}}} \tag{4.6}$$

In Equation 4.7 the E_{real} indicates the produced electricity accounting for the downtime of the turbine in addition to losses caused by wake effects and electrical equipment.

$$EA = \frac{E_{\text{real}}}{E_{\text{theory}}(1 - L_{\text{wake}})(1 - L_{\text{el}})} \tag{4.7}$$

The results of NOWIcob simulations include KPIs such as income, lost income due to downtime and O&M cost split. The annual income and the lost income due to downtime are summarised on a monthly basis and then discounted in order to determine their NPV. The O&M costs are summarised for each year, which include the cost of spare parts, fixed costs, fuel costs and charter costs for the vessels, technicians and costs related to the O&M base location.

The NOWIcob tool has also the ability to take investment costs into account to determine the LCOE of the wind farm. However, this was not considered in this thesis due to the focus on O&M costs. The cost estimations for the eventual investment costs would have introduced a large amount of uncertainty in the results. Moreover, the NOWIcob tool has an economic sensitivity add-on which can show the cost sensitivity for the input data. This proved to be useful in order to properly discuss the results of the simulations, and how different inputs would have changed the output.

4.3 Weather data

Metocean data were needed for the NOWIcob software to generate the weather simulations for each case. The NOWIcob software can read weather data consisting of time, wind speed and direction, and wave height, period and direction. The weather data must have an equally distributed time resolution, e.g. 3 hours. The program will automatically linearly interpolate the weather data to its desired resolution. However, the software only requires wind speeds and wave heights in order to run. This thesis only considered wind speeds and wave heights and their directions for the case study.

ERA5 (Copernicus, 2023) was selected as the primary weather data set for the simulation, covering the entire globe with historical data from 1940 to the present day. According to the documentation by ECMWF (2023), ERA5 is their fifth-generation atmospheric analysis built upon previous projects and is updated daily with a five-day latency. It was possible to obtain a vast amount of different weather variables for a user-specified area at an hourly resolution in their data library. The wave data and wind data which were considered in this study were gathered with a horizontal spatial resolution of 0.50° and 0.25° respectively (Copernicus, 2023), which equivalates to around 55 km and 28 km.

Since the ERA5 is provided in a user-specified area, the mean value of the data points in the area was selected to illustrate the historic weather conditions in the area. Extreme values are important as well, however, it would be more relevant in the operational planning stage of the maintenance. The difference in extreme and mean values in Utsira Nord and Sørlige Nordsjø II areas are shown in Figure 4.4. The figure, which is based upon data shown in Appendix C, shows that the extreme value of the significant wave height (H_s) of the areas was approximately 4 to 8% greater than the mean H_s. The graphs show that the two areas in question have opposite seasonal trends for the difference between extreme and mean values. Even though the difference between mean and extreme values seems insignificant, utilising the extreme values could have had a significant impact on vessel availability on a strategic level, as the simulation simulates the entire lifespan of the wind farm.

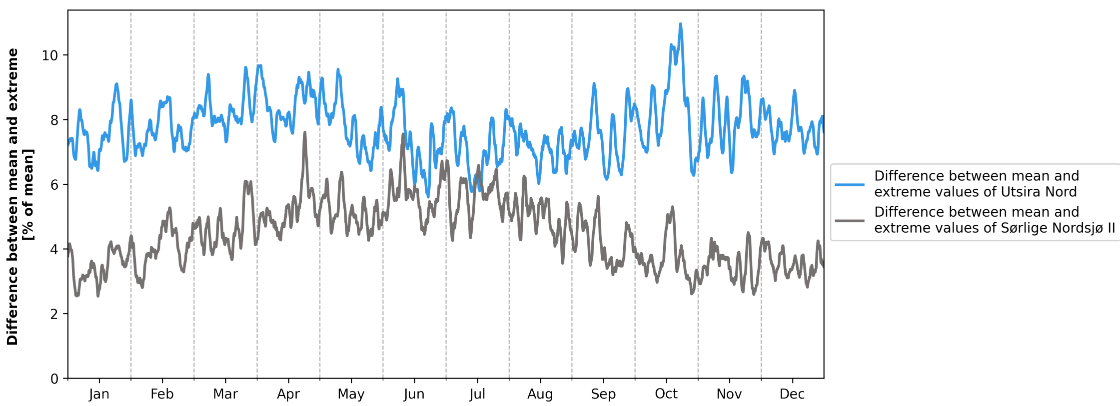


Figure 4.4: Difference between the mean and extreme H_s of Sørlige Nordsjø II and Utsira Nord

Additionally, the 3-km Norwegian Reanalysis NORA3 developed by The Norwegian Meteorological Institute (2023), was considered in the simulation in order to see the effects of different weather data in the simulation. The NORA3 atmospheric hindcast (Haakenstad et al., 2021) and the NORA3 wave hindcast (Breivik et al., 2022) provided models of past atmospheric and wave conditions of the North Sea, the Norwegian Sea and the Barents Sea. NORA3 provides a detailed reanalysis with a horizontal resolution of 3 km, making the spatial resolution significantly greater than ERA5. According to Haakenstad et al. (2021), NORA3 provides more realistic weather data in ocean environments than its predecessor NORA10 and ERA5.

4.3.1 Extrapolation of wind speed

In order to obtain the most precise calculations of the generated electricity, the measurements should be in the height of the rotor of the OWT. It was therefore important to adjust the height of the measured wind speed to the rotor height of the OWT, as the ERA5 data is only available at 10-meter and 100-meter heights. The vertical extrapolation of wind speeds was calculated through the empirical power law shown in Equation 4.8, due to its mathematical simplicity compared to other methods (Emeis & Turk, 2007). The NORA3 data was not extrapolated as it was provided at a 150-meter height.

$$u(z) = u(z_A)\left(\frac{z}{z_A}\right)^n \tag{4.8}$$

The empirical power law (4.8), also referred to as the Hellmann approach, considers a reference height z_A and a Hellmann exponent n. The Hellmann exponent is heavily dependent on the type of surface at the location. Approximation values for the Hellmann exponent for different coastal locations were found in the works of Kaltschmitt et al. (2007), where the values for open water surfaces are shown in Table 4.1.

Table 4.1: Hellmann exponent approximations for open water surfaces (Kaltschmitt et al., 2007)

Stability	***n***
Unstable	0.06
Neutral	0.10
Stable	0.27

A study performed at a series of nodes in the North Sea found that the normalised distributions of the Hellmann exponent peaked between 0.00 and 0.05 (Hasager et al., 2013). Considering the results from Hasager et al. (2013) and the approximations in Table 4.1, a Hellmann exponent of 0.05 was chosen for this case study. It is important to note that the Hellmann exponent and consequentially the empirical power law provide merely rough estimates of the actual wind speeds, and more detailed measurements should be performed to obtain a precise prediction of the wind speed and subsequently the accuracy of the electric power generation.

4.4 Data analysis

It can be difficult to determine the number of Monte Carlo iterations needed when conducting simulations. The separate iterations will produce varying results, which will independently vary from the true mean of the simulation. A higher number of Monte Carlo iterations will provide more accurate results, however, too many iterations would be time-consuming. A convergence study was therefore conducted for the simulations in order to see the required number of Monte Carlo iterations needed to achieve convergence of the simulations below a specified acceptance level. A 95% confidence interval was selected, calculated using Student's t-distribution which is a statistical distribution typically used for small sample sizes. The confidence interval was calculated by Equation 4.9, where μ is the mean value of the sample in question and SE is the standard error.

$$\mathrm{CI}_{95\%} = \mu \pm \mathrm{SE} \tag{4.9}$$

The standard error (SE) was calculated by Equation 4.10, where σ_n is the standard deviation of the sample and n is the sample size.

$$\mathrm{SE} = t_{95\%,n-1} \frac{\sigma_n}{\sqrt{n}} \tag{4.10}$$

The $t_{95\%}$ was calculated through the scipy library in Python with its calculation and the remaining error calculation being shown in Appendix G. The values were then plotted with a cubic interpolation to achieve readable graphs. This approach was identical to the convergence study conducted in Avanessova et al. (2022) and the minimum acceptable SE for each simulation in the case study was set to 2 %.

Verification and validation are important to check whether the simulation model produces realistic and plausible results or not. This can be achieved in multiple methods, such as benchmarking the results of the simulation model with other studies. In this case study, the results were compared to a range of other studies such as the study of Musial et al. (2020) and Dinwoodie et al. (2015). Additionally, a code-to-code comparison was conducted with NOWIcob in the case study carried out by Avanessova et al. (2022), which used the ORE Catapult COMPASS tool to investigate if there were any differences between the two simulation software. The code-to-code comparison was helpful to understand how the NOWIcob software functions and any potential limitations of the software.

The NOWIcob software has gone through a series of validation processes. This includes presenting the model to the commercial actors in the industry and ensuring that the software produces realistic results (Hofmann et al., 2017). The NOWIcob model has been compared to the O&M modelling tools of the developers ScottishPower and Iberdrola, which showed that the models agree on the sensitivities. However, the models do not agree on the absolute values of availabilities. The majority of the difference between the models was most likely due to differences in the modelling of the jack-up vessel charter strategy. The technical documentation Hofmann et al. (2017) describes its validation processes in detail for further reading.

4.5 Limitations

Even though NOWIcob is a holistic O&M modelling tool that produces realistic results, it has its limitations. For instance, the NOWIcob tool cannot interpret the relation between failure rates and scheduled services. In reality, this relation influences the TTF substantially. Moreover, the weather generation does not generate variations in the weather conditions within the offshore wind farm. However, this was not seen as a problem as the case study simulated the wind farms on a strategic level, and not on a tactical or operational level. The appendix in Hofmann et al. (2017) describes its limitations in detail for further reading.

Furthermore, NOWIcob is not created with the intention to simulate the O&M of floating wind farms, as there is not a straightforward method of modelling T2S operations implemented in NOWIcob. The jack-up modelling was therefore interpreted to model the T2S operations and SSCV operations in the case study. Another limitation of the case study in general, was that the input data is solely based on estimations and results found in available studies and literature. It would have been better to obtain data from actual wind farms and developers, and it was, therefore, important to have sufficient verification of the results.

5 | Code-to-code comparison

This chapter will cover the code-to-code comparison conducted with the case study in Avanessova et al. (2022), which investigated different offshore maintenance base options for a theoretical offshore wind farm in the Scotwind NE8 area using the COMPASS simulation tool. The code-to-code comparison was conducted by running simulations with the same input and comparing the outputs of the simulations. The code-to-code comparison in this thesis compared the results of the NOWIcob and Ore Catapult's COMPASS tool. The code-to-code comparison provided valuable insights into the performance of the NOWIcob software and how it functioned differently from other tools, which was useful for the simulation of the case study conducted in this thesis.

5.1 Input for Scotwind NE8

The hypothetical offshore wind farm in the Scotwind NE8 area was located in the east of Scotland. The case study of Avanessova et al. (2022) considered three different vessel scenarios:

- An OMB located within the wind farm, with three CTVs with an operational wave limit for transit and transfer at 1.75 m.
- An OMB located within the wind farm, with three CTVs with an operational wave limit for transit at 2.50 m and transfer limit at 1.75 m.
- A mother vessel with an operational wave limit for transit at 3.50, and a daughter craft with a transfer limit at 1.75 m

In the vessel scenario with the mother vessel, the transfer of personnel and equipment was performed by a daughter craft. The characteristics of the daughter craft were not specified, but similar traits as the CTVs were assumed. The mother vessel was based upon North Star SOVs, which consists of one vessel of the VARD 4 19 design and two vessels of the smaller VARD 4 12 design according to Vard Design concept designer Thomas Brathaug (Buljan, 2021). The vessel specifications for all the vessels are found in Appendix H, where CTV 1 and CTV 2 are the CTVs considered in the code-to-code comparison.

The Scotwind NE8 area had a maximum water depth of 100 meters, making floating OWTs the only viable option. The port of Peterhead was selected as the O&M port for the area, which was situated approximately 100 km from the Scotwind NE8 area. The case study configured the wind farm with 66 turbines with an individual capacity of 15 MW, which resulted in a combined capacity of 990 MW. The reference turbine and its affiliated power curve, shown in Appendix E, were assumed for the code-to-code comparison. The data of the wind farm are shown in Table 5.1.

Table 5.1: Wind farm data for Scotwind NE8 considered in Avanessova et al. (2022)

		NE8
Number of turbines	[-]	66
Turbine capacity	[MW]	15
Distance to the port	[km]	100
Maximum water depth	[m]	100

5.1.1 Weather data

The case study of Avanessova et al. (2022) considered two types of weather data, which were the ERA20C reanalysis and the previously discussed ERA5 reanalysis. Similar to ERA5, ERA20C is also a publicly available weather reanalysis. The two sets are different in their spatial and time resolutions, however, this was not an issue as this was solved by the NOWIcob software. Observations in the study discovered that the ERA5 database had a higher average wave height than the ERA20C data. Additionally, ERA5 had a greater number of yearly observations available than ERA20C. Because of the more conservative data and yearly observations, the weather data of ERA5 were the only weather data considered for this code-to-code comparison.

The weather data of ERA5 were gathered for the time period between 1990 and 2015 from a single coordinate (58.5, -1.0) within the Scotwind NE8 area. The weather data considered in the case study consisted solely of wave data, however, wind data were included for the code-to-code comparison because it was required for the NOWIcob software. The input wind data were set at a 150-meter height, as it is the hub height of the previously mentioned 15 MW wind turbine IEA reference turbine (Gaertner et al., 2020). The 150-meter height is an estimation for bottom-fixed turbines, which could prove to be different from the actual height of the transition piece of the foundation heights of floating OWTs. Since the ERA5 wind data were only available at a height of 100 meters, the data were extrapolated as previously explained.

5.1.2 Maintenance tasks

The article attempted to explain the different failure rates in great detail. For the unscheduled corrective maintenance, the article explained that there was a lack of data for failure rates and replacement costs for floating OWTs. The article explained that the study interpreted failure rates and replacement cost data from the O&G industry. The data used in the case study are shown in Table 5.2. However, the study failed to explain how the data were used in the simulation in greater detail. Additionally, any discussion or presentation of the input data was absent for the internal components of the OWT. Gray (2021) explains that the COMPASS tool has built-in rates for OWT components based on literature such as Carroll et al. (2015). This was the same study the data in Appendix B were based upon. However, the absence of details presented some challenges to the code-to-code comparison as the input data would not be identical.

Table 5.2: Failure rates and replacement costs of subsea components assumed in the case study of Avanessova et al. (2022)

Component	**Failure rate (failures per component per year)**	**Cost (GBP per component)**
Semi-submersible platform (structure damage)	0.018	-
Hybrid synthetic mooring	0.0017 [km^{-1}]	520 000
Anchor	0.00012	67 900
Array cable	0.003 [km^{-1}]	-
Dynamic cable	0.003	200 000

The case study assumed annual surveys to check the moorings, carried out by remotely operated vehicles (ROV). Moreover, a special survey was conducted every 5 years where the moorings were raised to the surface for inspection. It was assumed that half of the special surveys were conducted by a ROV while the other half was physically raised to the waterline. It was expected that the inspection of anchors was included in the mooring line surveys. The dynamic cables were to be surveyed with an ROV biennially. This meant a vessel capable of ROV operations was needed for these planned inspections. In addition, a marine growth removal operation was assumed every fifth year. Similar to the inspections, it was assumed that this was carried out by a ROV as well.

5.1.3 Assumptions

Similar to NOWIcob, the COMPASS software uses Monte Carlo simulations in order to obtain random TTFs. Therefore, several iterations were needed to obtain low errors and realistic outputs. The research article, therefore, conducted a convergence study in order to determine the required Monte Carlo iteration. Avanessova et al. (2022) used a 95 % confidence interval where a SE of 2% was considered acceptable. The case study observed that the different cases converged after 20 Monte Carlo iterations. This was the basis for NOWIcob simulations in this code-to-code comparison.

The two software had different input structures, and several assumptions were needed in order to run the NOWIcob software. As seen in Table 5.2, the input values for unscheduled maintenance were somewhat vague. Therefore, an investigation of the design of the FWT was needed. The article mentioned the usage of semi-submersible platforms and it was therefore assumed to be a tri-floater design popularised by the WindFloat-project in Portugal (Liu et al., 2016). A three-legged semi-submersible platform typically has three mooring lines and consequently three anchors, despite that a greater quantity is possible like the WindFloat project which has six mooring lines.

Furthermore, a semi-submersible platform has a great advantage in its towing ability according to Jiang (2021). Due to its maturity, the towing strategy was chosen for the heavy lift operations of the platforms. In its installation phase, the installation is typically assisted by an anchor handling vessel (AHTS) which assists with unhooking from the mooring system (James & Ros, 2015).

The works of Bessone et al. (2022) summarise assumptions for T2S operations of semi-submersible OWTs from several pieces of literature and were the basis for the assumptions made in this code-to-code comparison. The duration of active maintenance on the platform in port was difficult to predict. It was assumed a total of three weeks of active maintenance in addition to 55 hours of logistics. This duration did not account for the time needed for towing from the wind farm to the port, which was manually implemented based on the vessel speed and the distance to the O&M port. The cost was based on shipyard fabrication cost estimates for a floater of an 8 MW turbine, adjusted for size and inflation (Díaz et al., 2016).

For the maintenance operations of the mooring lines and the anchors, an AHTS was assumed to be utilised. The maximum water depth in the area of 100 m was assumed for all assumptions regarding water depth, due to the lack of more detailed water depth descriptions of the Scotwind NE8 area. The article stated that it assumed the mooring lines to be 6 times the water depth. The failure rate was adjusted to account for this.

The total length of the array cables was not stated in the article. The layout of the hypothetical wind farm in the article showed that the turbines were grouped in sets of 6 to 9 turbines with looping array cables in between them. In total, this equivalated to 75 array cables distributed among the 66 turbines in the wind farm. The average distance between the turbines of 2 km was assumed for each array cable, making the average array cable length for each turbine 2.27 km. The assumption for the repair cost of the array cables was based upon the specified value for the dynamic cables, adjusted for cable length.

The duration of all subsea operations was based upon an article published by PMI, which stated that a typical subsea cable repair could take between 3-5 days (PMI Underwater Cable Solutions, 2015). It was assumed that the operations surrounding the mooring lines and anchors were of similar complexity as the cable repairs. A cable laying vessel (CLV) was assumed appropriate for the maintenance tasks surrounding cables.

The assumptions are shown in Table 5.3, where $n_{comp.}$ shows the number of components per turbine, λ denotes the failure rate per year per turbine, r shows the duration of each maintenance task, n shows the number of technicians needed per maintenance task and C_{SP} show the cost of spare parts for each maintenance task. The number of technicians was based on similar operations seen in Appendix B.

Table 5.3: Updated failure rates and replacement costs of subsea components per turbine

Component	$n_{comp.}$ [−]	λ [−]	r [h]	n [−]	C_{SP} [10^3 GBP]	**Vessel selection**
Semi-submersible platform (structure damage)	1	0.01800	559	21	8 671	Tugboats and AHTS
Hybrid synthetic mooring	3	0.00102	96	10	520	AHTS
Anchor	3	0.00012	96	10	67.9	AHTS
Array cable	1	0.00681	96	10	873	CLV
Dynamic cable	1	0.00300	96	10	200	CLV

Even though export cables and substations were mentioned in Avanessova et al. (2022), it was not stated any maintenance operations surrounding the components. Therefore, the maintenance of substations and export cables was neglected for this code-to-code comparison even though they contribute significantly to the O&M costs. It was highly likely that the costs surrounding these components would be similar for the three vessel scenarios, and it was therefore not considered important to evaluate the performance of the OMB.

Since the internal failure rates of the OWT were not stated in the article, the failure rates presented by Carroll et al. (2015) were used, as shown in Appendix B. The vessels selected for the different failures were based on the selection described in Table 2.1. Moreover, the NOWIcob software required initial values for the wind farm such as discount rate, fuel and electricity price for vessels, fixed technician cost, shift data and losses in electricity production due to wake effects and electrical losses. The working hours per shift were set to 12 hours starting at 06:00. This was based on the default values in NOWIcob, and the remaining required input values are shown in Table 5.4.

Table 5.4: Default values for test-case in NOWIcob

Input		**Value**
Wake loss	[%]	9,0
Electrical losses	[%]	4,0
Lost production due to downtime of electrical infrastructure	[%]	1,0
Discount rate	[%]	5
Fuel price vessels	[GBP/l]	0,6
Constant electricity price	[GBP/kWh]	0,34

5.2 Control study

In addition to the maintenance tasks shown in Appendix B, a control study was conducted for the different vessel scenarios using failure values and maintenance tasks gathered from the case study conducted by Dinwoodie et al. (2015). The maintenance tasks and their affiliated failure rates are seen in Table 5.5. This was performed as a control case, in order to verify the results of the NOWIcob software and investigate if the complexity of maintenance tasks in NOWIcob would affect the outcome. The values of the major replacement were hard to determine due to the complexity of a T2S operation. The assumptions for T2S operations described earlier were therefore implemented in addition to the repair times shown in Table 5.5. Additionally, the control study considered the maintenance tasks described in Table 5.3.

Table 5.5: Input values for reference case interpreted from Dinwoodie et al. (2015)

	Repair time [h]	**Required technicians**	**Vessel type**	**Failure rate [-]**	**Repair cost [GBP]**
Manual reset	3	2	CTV/SOV	7.5	0
Minor repair	7.5	2	CTV/SOV	3.0	1 000
Medium repair	22	3	CTV/SOV	0.275	18 500
Major repair	26	4	SOV	0.04	73 500
Major replacement	52	5	T2S	0.08	334 500
Annual service	60	3	CTV/SOV	1	18 500

5.3 Results and discussion

Table 5.6 shows the simulation results compared to the results of Avanessova et al. (2022). It shows that the results of NOWIcob did not follow the same pattern as in the COMPASS study. The cost results were significantly higher for the second vessel scenario than the results of COMPASS. On the other hand, the time availability (TA) and energy availability (EA) followed a similar pattern for each scenario. Detailed results of all the vessel scenarios are shown in Appendix I.

Table 5.6: Results of OPEX, time availability (TA) and energy availability (EA) from all three simulated scenarios from NOWIcob and COMPASS

		OMB 1.75 m ERA5		OMB 2.5 m ERA5		SOV 3.5 m ERA5	
		This Thesis	Avanessova et al., 2022	This Thesis	Avanessova et al., 2022	This Thesis	Avanessova et al., 2022
OPEX	**[GBP/kW]**	43.90	46.21	65.16	46.67	55.24	49.01
OPEX error	**[%]**	4.00	1.43	2.72	1.76	2.81	0.96
TA	**[%]**	89.84	92.06	92.97	94.22	95.83	97.12
TA error	**[%]**	0.09	0.13	0.07	0.08	0.02	0.02
EA	**[%]**	89.04	89.64	92.53	92.77	95.68	97.18
EA error	**[%]**	0.11	0.12	0.07	0.09	0.03	0.04

The NOWIcob simulations achieved a significantly higher error than the results of COMPASS, with all of the vessel scenarios being above the acceptance level after 20 Monte Carlo iterations. Figure 5.1 shows how the error develops with the iterations of the vessel scenarios together with the control study scenarios.

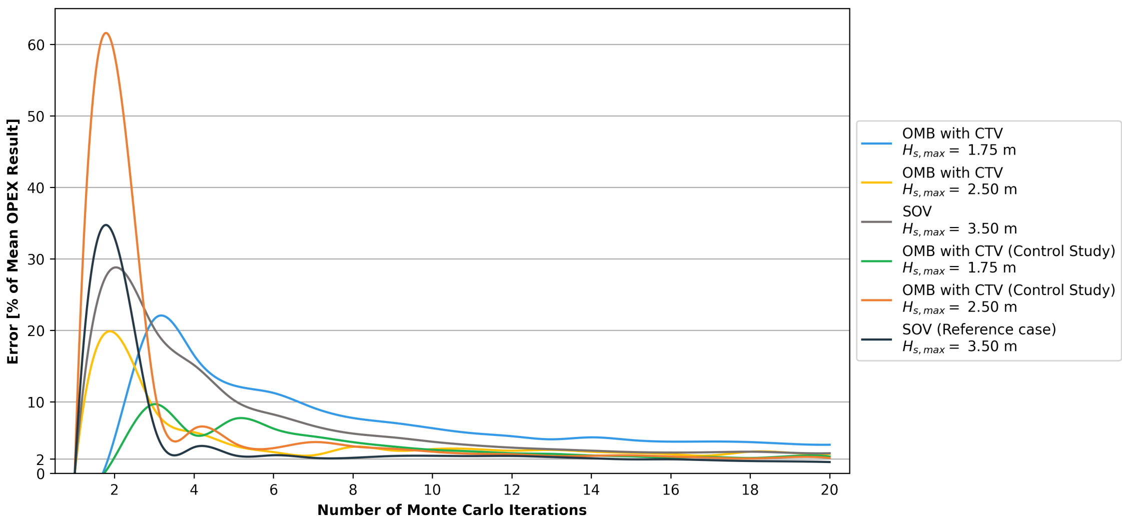


Figure 5.1: Graph of convergence after 20 iterations for Scotwind NE8

Even though all of the scenarios converged at around 10 Monte Carlo iterations, the errors of the vessel scenarios were higher than the acceptance level. The control study cases interpreted from the study of Dinwoodie et al. (2015) achieved similar error rates as the COMPASS study. This could indicate that the maintenance task modelling of the NOWIcob study is more complex and that the input of the study by Avanessova et al. (2022) is more similar to the modelling of Dinwoodie et al. (2015).

The O&M cost split was investigated to try to explain the trend difference shown in Table 5.6. As expected, Figure 5.2 shows that the results of this thesis and the results of the control study cases followed the same pattern in spare parts costs, fixed vessel costs and technician costs for each case. However, the chartering costs and consequently the fuel costs were significantly higher for the OMB with an operational wave limit of 2.5 m. There was a significant increase in the number of charter periods for this scenario even though the spare parts costs remained at approximately the same level. This indicates that the charter periods increased while the number of repairs remained.

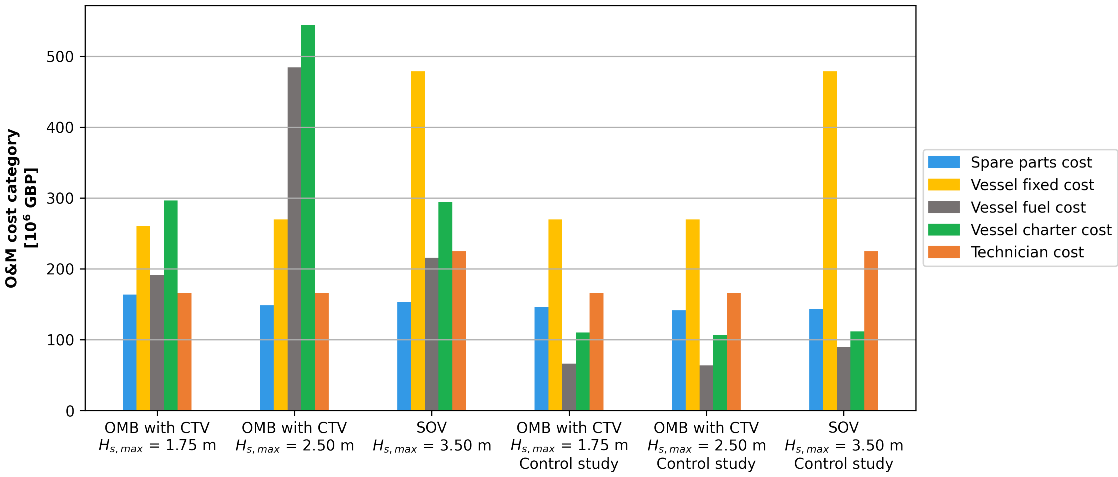


Figure 5.2: O&M cost split of the different cases

This is most likely explained by an error in the modelling of the T2S operations and the operations requiring AHTS and CLVs in NOWIcob. The T2S operations were interpreted into the jack-up modelling in NOWIcob, which might have unnecessarily increased the number of charter periods of the tugboats. The modelling of T2S operations and the operations requiring AHTS and CLVs were therefore reviewed for the case study. Additionally, the daughter craft of the mother vessel was not in use for the third vessel scenario, even though it was modelled correctly. This suggests that the weather conditions were not suitable for the daughter craft whenever the mother vessel was active.

Another explanation of the results and shifts in trends could be due to uncertainty in the input data. The input values were gathered from literature dating back almost a decade, and coupled with the exponential growth of the offshore wind industry created some uncertainty in the input. As the market changes with time, basing the cost estimates solely on inflation may have oversimplified the current situation.

6 | Case development

This chapter will present the different cases investigated in the case study. The cases consisted of four hypothetical offshore wind farms, simulated for three scenarios. The first scenario was an OMB with a shared foundation with a substation within the wind farm. The second scenario was the usage of SOVs resupplied in the O&M port. The third scenario consisted of repurposing a nearby O&G platform to an OMB. It was selected that two of the wind farms were bottom-fixed and the remaining two would consist of floating OWTs.

The previously mentioned wind farms of Sørlige Nordsjø II and Utsira Nord were investigated, bottom-fixed and floating respectively. The last two consisted of the Nordvest B area suitable for floating OWT development and the Sørvest B area suitable for bottom-fixed OWT development. The different areas are shown in Figure 6.1 together with the assumed O&M ports, in blue markers, and the closest O&G platforms, in yellow markers, deemed being able to be repurposed as OMBs. This map and all following maps were extracted from the map shown in Appendix D.

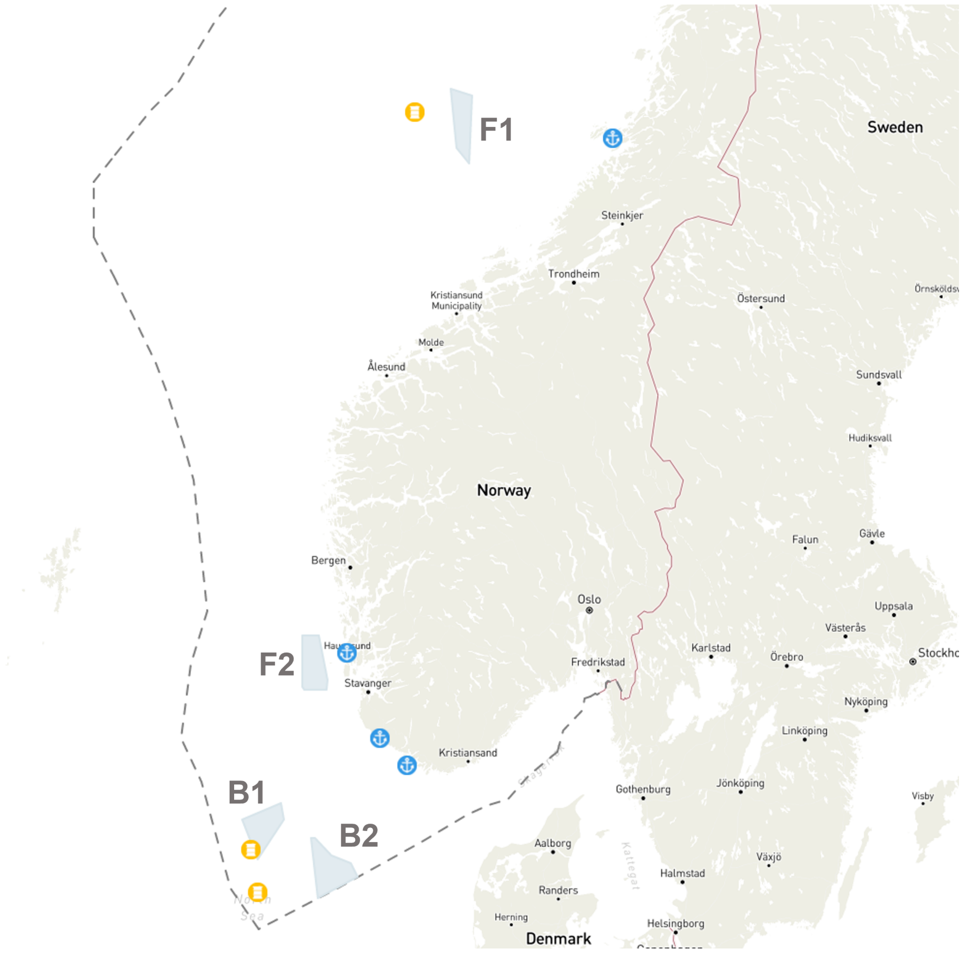


Figure 6.1: Map of hypothetical farms considered for simulation where F1 is Nordvest B, F2 is Utsira Nord, B1 is Sørvest B and B2 is Sørlige Nordsjø II

6.1 Description of wind farms

The data used for the different hypothetical wind farms are shown in Table 6.1. The O&M ports were selected from various ports suggested by Indrevær et al. (2021). The distances between the ports and centre of each of the areas were calculated using Searoute's calculator for voyages at sea (Searoutes.com, 2023). The average distance between each wind turbine was assumed to be 2 km, similar to the Scotwind NE8 case.

Table 6.1: Data for wind farms considered in case study

		Sørlige Nordsjø II	Sørvest B	Utsira Nord	Nordvest B
Total capacity	**[MW]**	1500	1500	750	750
Turbine capacity	**[MW]**	15	15	15	15
No of turbines	**[-]**	100	100	50	50
Depth$_{average}$	**[m]**	60	65	265	250
Distance to port	**[km]**	183	200	50	204
Distance to oil and gas installation	**[km]**	109	39	-	34

6.1.1 Sørlige Nordsjø II

The area of Sørlige Nordsjø II is one of the currently open areas for development of offshore wind production in Norway. It has newly been incorporated into the Sørvest F area, which was the boundary utilised in this case study. The area is suitable for development of bottom-fixed wind turbines with an average depth of around 60 meters. The area is planned to be developed in two steps, the first one consisting of the development of 1 500 MW in total capacity. It is expected that the single OWT capacity will be 15 MW, which results in a total of 100 OWTs in the first step. According to a study conducted by Sweco and Energi Norge, the wind farm is expected to commission and be fully operational by 2032 (Fauli et al., 2022). This case study only considered step 1 of the development. A map of Sørlige Nordsjø II is shown in Figure 6.2, displaying the location of Ekofisk L and the location of Farsund.

The O&M port selected for Sørlige Nordsjø II is the port of Farsund. Furthermore, Farsund can provide with areas for storage and fabrication in the currently defunct Lista Airport outside the city (Indrevær et al., 2021). In addition to the OMB in the wind farm, the case study will investigate repurposing an O&G platform as an OMB. The accommodation platform Ekofisk L in the Ekofisk field was selected, even though platforms such as the Trym platform is situated closer to the wind farm. This is due to the other nearby platforms being deemed not suitable to be repurposed as OMBs.

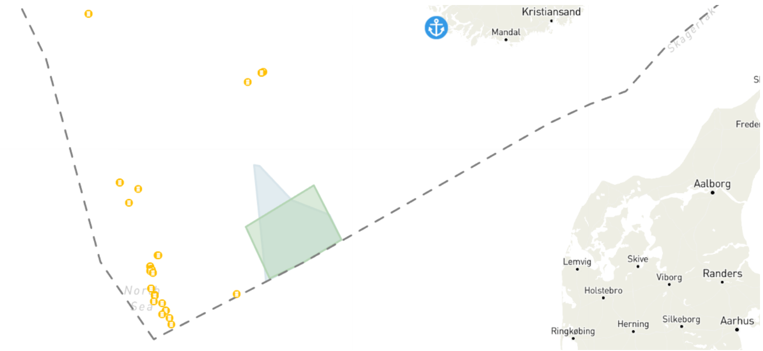


Figure 6.2: Map of Sørlige Nordsjø II (green) and Sørvest F (blue)

6.1.2 Sørvest B

The area of Sørvest B has the westernmost location of the areas proposed for development of offshore wind by Norwegian Water Resources and Energy Directorate (NVE) (2023). The area largely compromises the area formerly known as Sørlige Nordsjø I. Similar to Sørlige Nordsjø II, the area is suitable for development of bottom-fixed wind turbines with an average depth of around 65 meters. The two areas are situated upon the so-called Egersundbanken which provides the conditions for the development of deepwater bottom-fixed OWTs. It was assumed that the area will be of the same size as Sørlige Nordjsø II in terms of total capacity. The area is situated next to several O&G platforms, clearly seen in the map of Sørvest B in Figure 6.3. The closest platform is the Oda platform, situated 39 km away from the centre of Sørvest B. The Oda platform was deemed suitable to be repurposed as an OMB. The O&M port selected for Sørvest B is Egersund port, situated 202 km away from the centre of Sørvest B.

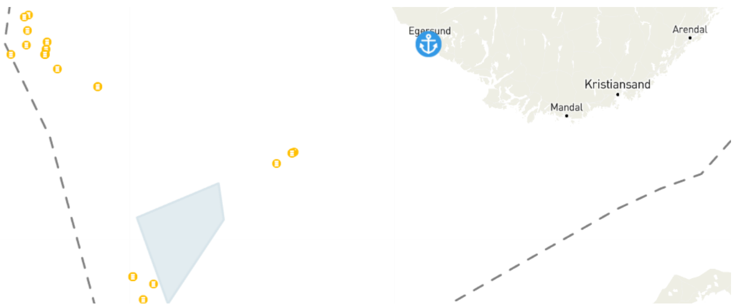


Figure 6.3: Map of Sørvest B

6.1.3 Utsira Nord

Utsira Nord is the only opened area for development of floating wind production, and is situated outside the island of Utsira. Similar to Sørlige Nordsjø II, the area has newly been incorporated as a part of the larger Vestavind F area with an average depth of 265 meters. The area has an expected total capacity of 1500 MW. In 2022, Energi Norge recommends partitioning the area into three parts with an individual capacity of 500 MW

(Energi Norge, 2022). However, the capacity considered in this case study was chosen to be 750 MW. It is expected that turbine capacity will grow, and it was assumed that the individual turbine capacity for floating wind farms was 15 MW, similar to the bottom-fixed expectations. For Utsira Nord, the port of Karmsund in Haugesund was chosen as O&M port. Utsira Nord will not be investigated for the third scenario regarding O&G platforms. This was due to the location of the nearest O&G installations being further away from the wind farm than the O&M port. This is clearly visible in the map of Utsira Nord shown in Figure 6.4.

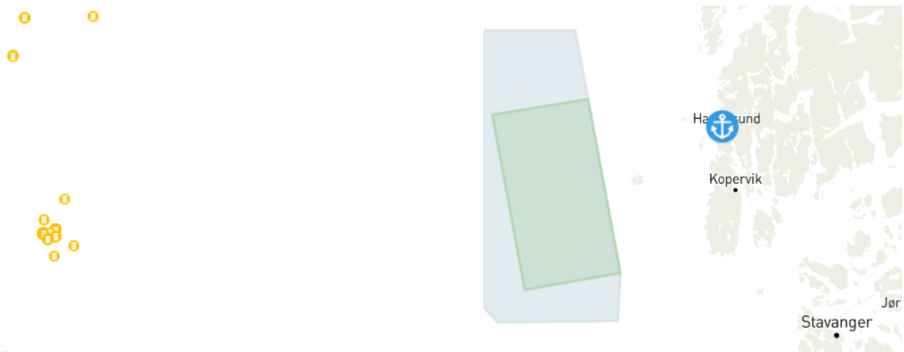


Figure 6.4: Map of Utsira Nord (green) and Vestavind F (blue) areas

6.1.4 Nordvest B

The Nordvest B area is the only area in this case study situated in the Norwegian Sea. The capacity was assumed to be similar to the Utsira Nord case with 750 MW. In order to make the wind farm more compact, the case study only considered the northern-most part of the area shown in Figure 6.5. The O&M port selected for Nordvest B was Rørvik, situated 204 km away from the wind farm. Nordvest B is situated in the proximity of a cluster of gas installations, with many different production installations close by as seen in Appendix D. The semi-submersible platform Åsgard B in the Åsgard field was deemed the closest platform suitable to be repurposed as an OMB. It is situated 34 km away from the centre of the northern part of Nordvest B. A map of Nordvest B and the boundaries used in the case study is shown in Figure 6.5.

Figure 6.5: Map of Nordvest B (blue) and the area considered for this case study (green)

6.2 Vessel selection

For this case study, operations using AHTS and CLV vessels were excluded in contrast to the Scotwind NE8 case. This was deemed unimportant for the comparison between the different cases, as the results would have been similar regardless of the maintenance base option. In order to fully represent the total O&M costs, a factor was therefore included to cover the costs of the AHTS and CLV operations. Three CTVs and one SOV were selected for the floating wind farms with an OMB. It was doubled for the bottom-fixed wind farms due to the doubling of the capacity. Two SOVs were chosen for the vessel scenario without an OMB in the floating wind farm, while three SOVs were selected for the bottom-fixed wind farms.

Data for the SOVs considered in the case study were assumed based on typical values for existing vessels. In addition, it was assumed that the operational limit of the gangway for the SOV was 3.5 meters, even though most existing vessels have an operational limit of 3.0 meters or less. The characteristics of the CTV were selected using typical values displayed in Table 3.1, excluding the TRI SWATH. The operational wave limit of both transit and transfer for the CTV was selected to be 2.5 meters. This was selected due to the unavailability of the CTVs shown in the code-to-code comparison of Scotwind NE8 and an expectation of new technology. The vessel characteristics for the transfer vessels are shown in Table 6.2.

Table 6.2: Characteristics for transfer vessels considered in the case study

		CTV	**SOV**
$L_{OA,\,\text{typical}}$	**[m]**	20	85
V	**[kn]**	20	12
Technicians	**[-]**	12	40
$H_{s,\,\text{max}}$	**[m]**	2.5	3.5

In addition to conducting simulations for different OMB options in the case study, the case study investigated the effects of exchanging the T2S operation with SSCVs. This will be performed by utilising SSCVs for the major replacement operations in the SOV case for Utsira Nord and Nordvest B. Vessel specifications for the SSCV and the other vessels considered in the case study are shown in Appendix H.

6.3 Weather data

The weather data considered in this case study consisted of data gathered from the Copernicus ERA5 database and NORA3. The data from ERA5 were gathered from 1998 to 2022, the same amount of years as the estimated lifespan of the wind farm. The data were the mean values of the areas of the wind farm. Data from the last couple of years were not available from the NORA3 database. In order to have a 25-year interval, the reanalysis data were gathered from 1996 to 2020. The NORA3 data were gathered from the centre of the areas in contrast to the ERA5 data.

6.4 Assumptions

Some assumptions were still needed in order to run the NOWIcob software with the case study. According to Statistics Norway (2023), O&G technicians in Norway had a monthly average salary of 79 700 NOK in 2022. It was assumed that similar salaries will be used for technicians for offshore wind production in Norway. In addition to salary, the cost of an employee in Norway is around 30% of the yearly salary which accounts for holiday pay, worker insurance and pension costs (Altinn, 2021). Converted to GBP this equivalated to a yearly fixed cost of technicians of 93 250 GBP (Xe, 2023).

The study of Barthelmie et al. (2009) revealed that wake effects accounted for between 10 and 20 % of power losses in a wind farm. A factor of 10% was assumed for this simulation. According to Siemens Power Transformers, electrical losses accounts for 2 to 3% of power generated on onshore wind farms (Colmenar-Santos et al., 2014). Due to it being offshore wind production, a higher percentage of 4% was assumed. Additionally, a discount rate of 5% was assumed for the project. The fuel price was assumed to be 0.42 GBP/liter (Ship&Bunker, 2023), assuming the usage of very low sulphur oil (VLSFO) due to its commonality and low sulphur content. This was important as the North Sea is an emission control area where SOx emissions are strict. The electricity price was assumed to be 0.15 GBP/kWh.

As previously discussed, to account for the lack of maintenance tasks with AHTSs and CLVs, a factor of 1.093 was multiplied by the simulated costs for the floating wind farms. For the bottom-fixed wind farms, the factor was adjusted to 1.029 to account for only the repair of cables. This was based on an estimate of the input values for ATHS and CLV operations used for the code-to-code comparison. Even though the maintenance tasks for AHTS and CLV in the estimate accounted for only 1 % of the expected maintenance tasks each year, the cost components and durations made it account for 8,5 % of the costs. Additionally, a factor of 1.19 was added to account for license fees and other costs associated with OPEX which accounts for 15.8 % of the total OPEX (BVG Associates, 2010).

Table 6.3: Updated default values for NOWIcob used in the case study

Input		**Value**
Wake loss	[%]	9,0
Electrical losses	[%]	4,0
Lost production due to downtime of electrical infrastructure	[%]	1,0
Discount rate	[%]	5
Fixed costs of technicians	[GBP]	93 250
Fuel price vessels	[GBP/l]	0,6
Constant electricity price	[GBP/kWh]	0,34

7 | Results

This chapter will present the results of the case study of the cases presented in Chapter 6. It will consist of a convergence study, a presentation of the simulation results and an overall summary of the different cases. The results of the investigation of SSCV utilisation will also be presented.

7.1 Convergence study

The convergence study was performed to see the required number of Monte Carlo iterations to achieve an error lower than the acceptance level of 2%. It was calculated through the python program shown in Appendix G, and the individual results are shown in Appendix J.2-M.2.

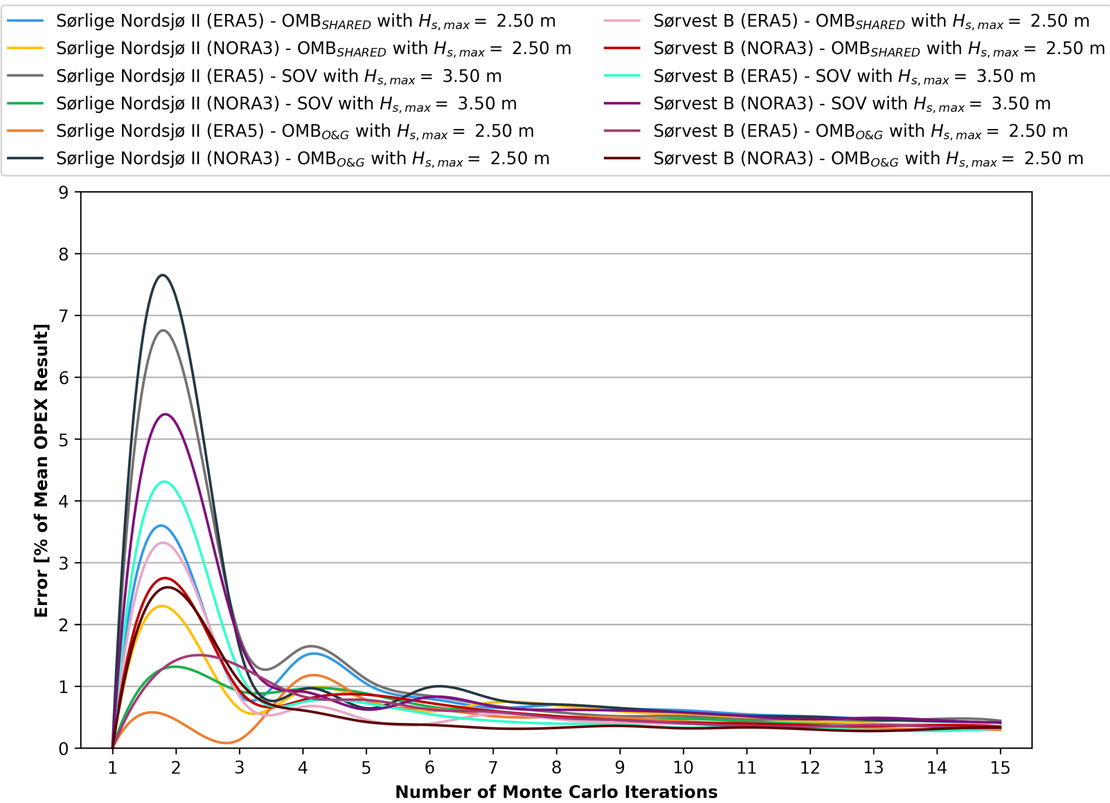


Figure 7.1: Convergence of the bottom-fixed wind farms

Figure 7.1 shows the errors of mean OPEX for all of the vessel scenarios of the bottom-fixed wind farms. It shows that the different vessel scenarios converge at around 11 Monte Carlo iterations. The error rate is also below 1%, meaning that the simulations are significantly below the required acceptance level. This indicates that the number of Monte Carlo iterations could be lower than the 15 iterations that were simulated.

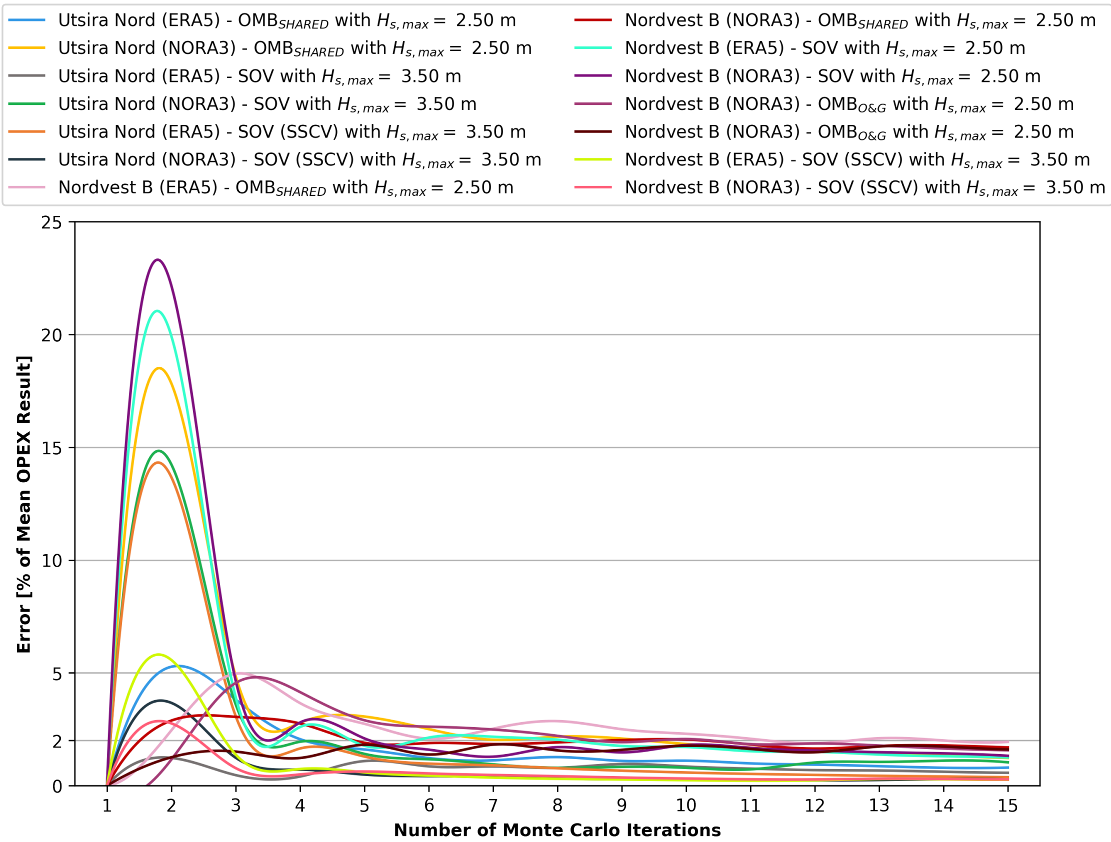


Figure 7.2: Convergence of the floating wind farms

The convergence study of the cases regarding the floating offshore wind farms in Figure 7.2, shows that all of the cases are below the acceptance level of 2% standard error. All of the wind farms converge, and 15 Monte Carlo iterations are sufficient enough to achieve the acceptance level even though the errors are considerably higher than the errors of the bottom-fixed wind farms.

The difference in the size of the errors between the floating and bottom-fixed wind farms can be explained by the increased complexity of the simulation due to the increased size of the wind farm. Typically, a less extensive simulation generates more errors in the output resulting in an increased number of Monte Carlo iterations. The number of Monte Carlo iterations versus the complexity of the simulation is a balancing art, and it is important to have a thorough investigation of the convergence to avoid unnecessary time consumption.

In summary, the convergence study shows that 15 Monte Carlo iterations provide acceptable errors for both the bottom-fixed and floating wind farms. Even though an increased number of Monte Carlo iterations would provide more accurate results, it would have been unnecessary and more time-consuming. Therefore, the analysis of the simulation results of the offshore wind farms could continue based on the 15 Monte Carlo iterations.

7.2 Simulation results

The simulation of the case studies consisted of 26 individual simulations with a total runtime of 986 063 seconds in the final iteration. The simulations were conducted on a six-core processor with a general clock speed of 3.90 GHz, with a maximum turbo speed of 4.5 GHz.

The O&M cost and lost income due to downtime shown in the following tables are calculated through the second part of Equation 4.2, while the estimated OPEX are calculated based on the entire Equation 4.2. The k_{other} was set to 1.22 for the bottom-fixed wind farms and 1.30 for the floating wind farms.

7.2.1 Sørlige Nordsjø II

Table 7.1: Results of the Sørlige Nordsjø II area

		OMB (substation) $H_{s,max} = 2.50m$		**SOV** $H_{s,max} = 3.50m$		**OMB (O&G platform)** $H_{s,max} = 2.50m$	
		ERA5	**NORA3**	**ERA5**	**NORA3**	**ERA5**	**NORA3**
O&M Cost from simulation	**[GBP/kW]**	67.94	68.24	72.75	72.64	68.54	68.52
OPEX estimate	**[GBP/kW]**	83.24	83.61	89.14	89.00	83.98	83.95
Lost income due to downtime	**[GBP/kW]**	14.09	14.77	12.66	13.59	14.77	15.59
Energy produced	**[TWh/year]**	7.296	7.479	7.321	7.498	7.285	7.465

Table 7.1 shows the simulation results for the Sørlige Nordsjø II case, with detailed results being accessible in Appendix J. As expected, the SOV case is 4-5 GBP/kW more costly than the OMB options. There is a relatively small and consistent difference between the OPEX estimations for the ERA5 and NORA3 data, with the biggest difference being 0.40 GBP/kW. However, there is a significant difference between the weather data in the lost income due to downtime and the annual energy produced. Overall, the differences between the produced energy between the three vessel scenarios are relatively small even though the lost income is greater for the OMB options.

Figure 7.3 shows the O&M cost split for the different cases. The Δ on top of the bar plots depicts the difference between the ERA5 and NORA3 results. The difference between the results of the different weather data was low for all of the cost categories, corresponding to the results shown in Table 7.1. The biggest difference between the two weather datasets is the vessel fuel costs. The simulation does not consider increased fuel consumption due to bad weather, meaning that the cases with NORA3 data have an increased number of travels.

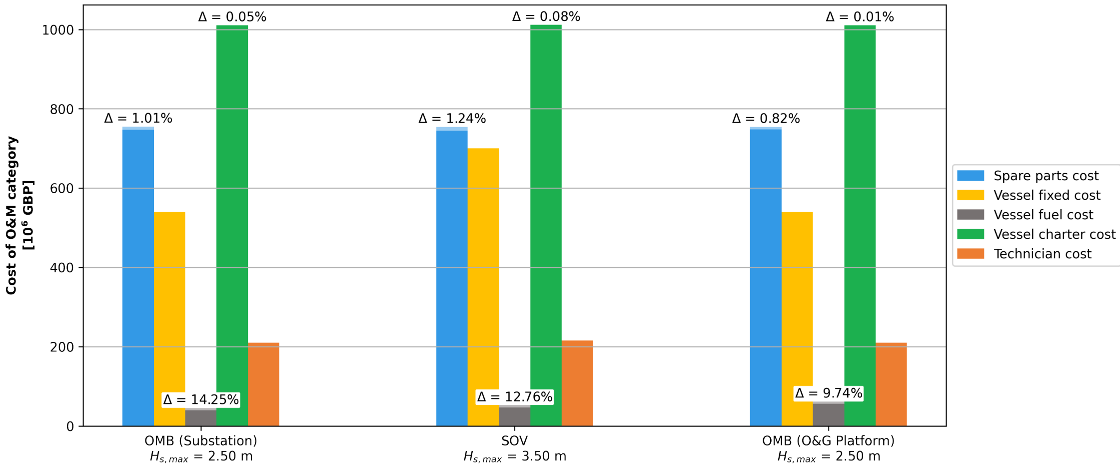


Figure 7.3: O&M cost split of Sørlige Nordsjø II with Δ showing the relative difference of the ERA5 and NORA3 results

7.2.2 Sørvest B

Table 7.2: Results of the Sørvest B area

		OMB (substation) $H_{s,max} = 2.50m$		**SOV** $H_{s,max} = 3.50m$		**OMB (O&G platform)** $H_{s,max} = 2.50m$	
		ERA5	**NORA3**	**ERA5**	**NORA3**	**ERA5**	**NORA3**
O&M Cost from simulation	**[GBP/kW]**	68.04	68.13	72.71	72.92	68.19	68.15
OPEX estimate	**[GBP/kW]**	83.36	83.47	89.09	89.34	83.55	83.50
Lost income due to downtime	**[GBP/kW]**	14.39	15.09	12.58	13.54	14.66	15.28
Energy produced	**[TWh/year]**	7.032	7.318	7.063	7.345	7.028	7.315

Table 7.2 shows the simulation results for the Sørvest B cases, with detailed results shown in Appendix K. Similar to the Sørlige Nordsjø II case, the difference is relatively small and consistent between the OPEX estimations of the ERA5 data and NORA3 data. Moreover, the differences between the annual energy produced and lost income due to downtime are also comparable to the results of Sørlige Nordjsø II.

Overall, the results of the different vessel scenarios are comparable to the results of Sørlige Nordsjø II. This was expected since both of the wind farms are of similar size and have approximately equal distances to the O&M ports. However, there is a significant difference between the two wind farms in the annual produced energy and lost income due to downtime. This suggests that the wind simulation of Sørlige Nordsjø II provides better weather conditions for generating electricity for the power curve of the 15MW turbine shown in Appendix E.

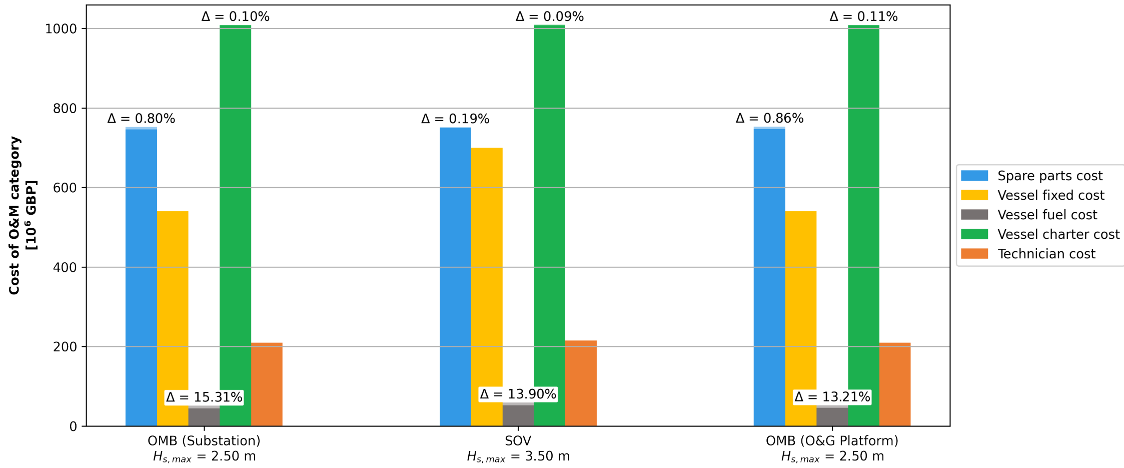


Figure 7.4: O&M cost split of Sørvest B with Δ showing the relative difference in the ERA5 and NORA3 results

Figure 7.4 shows the O&M cost split for the different cases. The O&M cost split shows that the difference between the two types of weather data is similar to the Sørlige Nordsjø II area with fuel costs having the greatest difference. The biggest contributor to O&M costs for Sørvest B and Sørlige Nordsjø II is the charter cost of the jack-up vessels, which is expected due to the costly estimated day rate of 253 987 GBP.

7.2.3 Utsira Nord

Table 7.3: Results of the Utsira Nord area

		OMB (substation) $H_{s,max} = 2.50m$		SOV $H_{s,max} = 3.50m$	
		ERA5	**NORA3**	**ERA5**	**NORA3**
O&M Cost from simulation	**[GBP/kW]**	44.51	46.74	58.25	60.46
OPEX estimate	**[GBP/kW]**	57.90	60.81	75.78	78.66
Lost income due to downtime	**[GBP/kW]**	13.51	15.79	11.47	12.97
Energy produced	**[TWh/year]**	3.253	3.403	3.270	3.427

The results of the simulation for the Utsira Nord case are shown in Table 7.3, with the detailed results shown in Appendix L. The difference in the OPEX estimations between the ERA5 simulations and the NORA3 simulations is significantly higher compared to the bottom-fixed wind farms. The OPEX estimations of the NORA3 simulations are around 7% greater than the ERA5 simulations for the vessel scenarios, compared to a 2-3% increase of the OPEX estimates in the bottom-fixed wind farms.

Overall, the results of Utsira Nord are significantly different to the bottom-fixed wind farms in the difference between the vessel scenarios. The O&M costs and subsequently the OPEX estimates have a significant increase of 15-18 GBP/kW from the OMB scenario to the SOV scenario, compared to around 5 GBP/kW for the bottom-fixed wind farms. Additionally, the relative difference in the annual produced energy between the different vessel scenarios is smaller compared to the bottom-fixed wind farms.

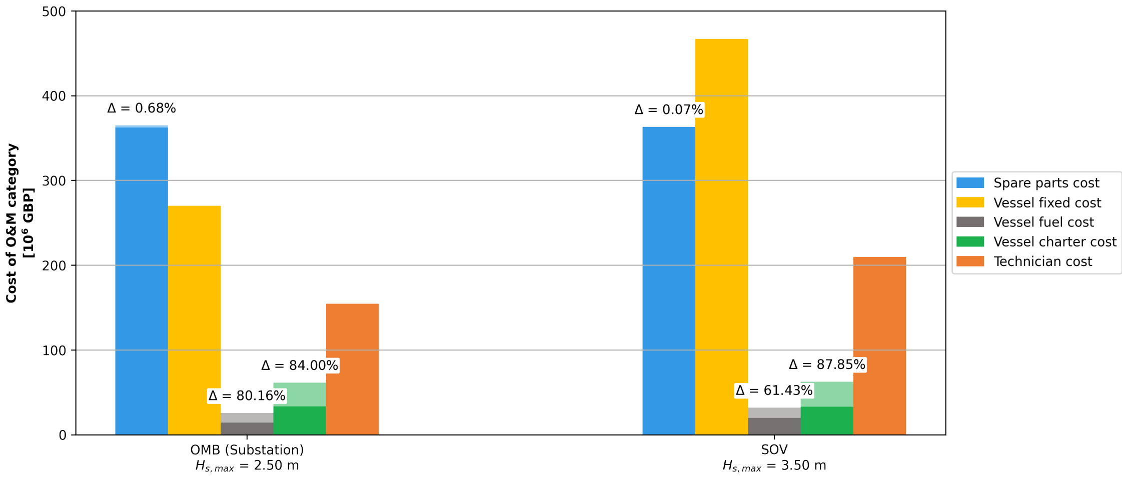


Figure 7.5: O&M cost split of Utsira Nord with Δ showing the relative difference in the ERA5 and NORA3 results

According to the O&M cost split shown in Figure 7.5, the difference between the charter and fuel costs for the different weather inputs is between 60% and 90%. This is significantly higher than the difference in the bottom-fixed wind farms. However, the two cost components contribute to a lesser extent to the total O&M costs than the results of the bottom-fixed wind farms.

7.2.4 Nordvest B

Table 7.4: Results of the Nordvest B area

		OMB (substation) $H_{s,max} = 2.50m$		SOV $H_{s,max} = 3.50m$		OMB (O&G platform) $H_{s,max} = 2.50m$	
		ERA5	NORA3	ERA5	NORA3	ERA5	NORA3
O&M Cost from simulation	**[GBP/kW]**	51.45	53.58	65.73	69.91	53.90	58.68
OPEX estimate	**[GBP/kW]**	66.94	69.71	85.52	90.95	70.13	76.34
Lost income due to downtime	**[GBP/kW]**	22.01	20.69	13.08	13.54	22.33	20.72
Energy produced	**[TWh/year]**	3.082	3.138	3.158	3.197	3.080	3.138

Table 7.4 shows the simulation results for the Nordvest B cases, with detailed results shown in Appendix K. The O&M results follow a similar trend to the results of Utsira Nord. However, the O&M costs are around 7 GBP/kW higher than the results of Utsira Nord. Additionally, the lost income due to downtime is significantly higher compared to Utsira Nord. The annual produced energy is also different in comparison to the other three wind farms. The Nordvest B area has an increased annual produced energy of around 76 GWh per year from the OMB case to the SOV case, which is over a doubling of the biggest increase of the other three wind farms.

Figure 7.6 shows how the different cost components compromise the simulated O&M costs for Nordvest B. The fuel costs are, as expected, higher than those of the Utsira Nord area due to the increased distance to the O&M port. Similar to the O&M cost split of Utsira Nord, the charter costs are significantly smaller than the charter costs of the bottom-fixed wind farms. This is because the day rates of tugboats are considerably less costly than for the jack-up vessels used in bottom-fixed wind farms.

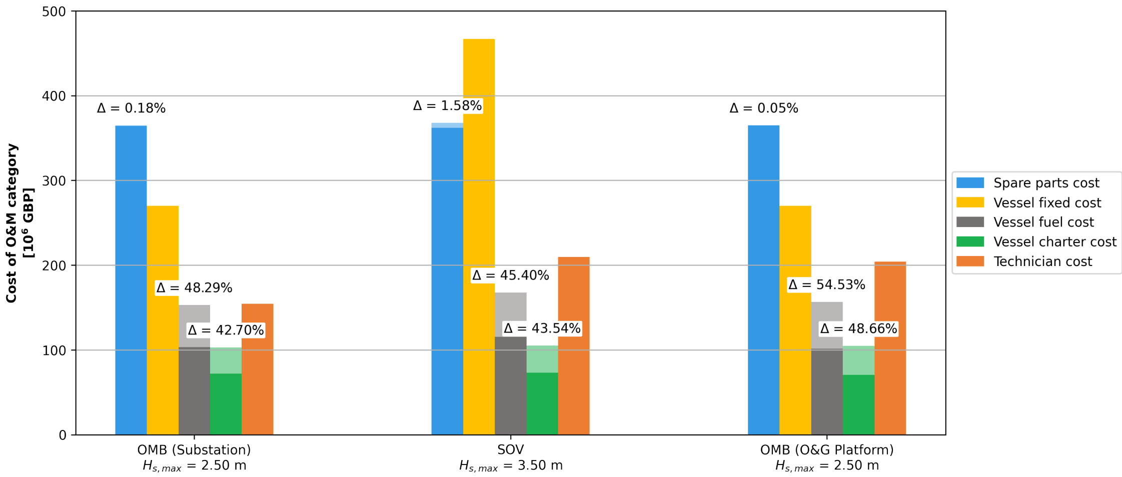


Figure 7.6: O&M cost split of Nordvest B with Δ showing the relative difference in the ERA5 and NORA3 results

7.3 Overall results of case study

As previously stated, verification of the simulation is important. Table 7.5 shows the results of other case studies investigating the cost of O&M of offshore wind. The case study by Dinwoodie et al. (2015) investigated a bottom-fixed wind farm consisting of 80 3 MW turbines situated approximately 50 km from the O&M port. The case study by Martin et al. (2016) investigated a bottom-fixed wind farm consisting of 8 MW turbines constructed in two stages, with 1A being the first stage and 1C being both stages as a single wind farm. The OPEX values were gathered from histograms provided in the research article, and may not be a detailed representation of the actual results.

The case study by Musial et al. (2020) investigated a floating wind farm using semisubmersible OWTs where the 2022 scenario had 10 MW turbines and the 2032 scenario had 15 MW turbines. The data of the previously discussed case study by Avanessova et al. (2022), are a mean value of the weather inputs of the case with an OMB with a CTV with $H_{s,max}$ = 2.50 m and the SOV case.

Table 7.5: Reference case studies

Case study	Size of wind farm [MW]	Distance to shore [km]	OPEX [GBP/kW]
Dinwoodie et al. (2015) - Base case	240	50	104.88
Martin et al. (2016) - 1A (Interpreted)	496	30	30.38
Martin et al. (2016) - 1C (Interpreted)	968	50	23.44
Musial et al. (2020) - 2022 scenario	600	91	49.60
Musial et al. (2020) - 2032 scenario	600	91	30.40
Avanessova et al. (2022) - OMB with CTV	990	100	45.65
Avanessova et al. (2022) - SOV	990	100	48.79

The results of the case study of this thesis were therefore plotted against the reference cases, shown in Figure 7.7. The results of the simulation of this thesis are a mean between the ERA5 and NORA3 results. It was expected that the O&M would increase with an increased distance to the O&M port. However, it shows that the reference case of Dinwoodie et al. (2015) approximates a significantly higher O&M cost than the case studies of this thesis. Additionally, the costs of Utsira Nord are significantly higher than the costs of the similar floating wind farms of Musial et al. (2020) and Avanessova et al. (2022).

Overall, there is a lack of consistency between the O&M cost and the distance to port between the case studies of this thesis and the case studies of the references. Understandably, the different reference case studies have different focuses on O&M cost in their studies. The O&M cost results of Utsira Nord are between 44 and 60 GBP/kW, which would have made the results more similar to the case studies of the 2023 scenario of Musial et al. (2020) and the results of Avanessova et al. (2022). This suggests that the k_{other} of 1.31, which covers costs not accounted for in the simulation, might have been too high or that the reference case studies not have accounted for these costs.

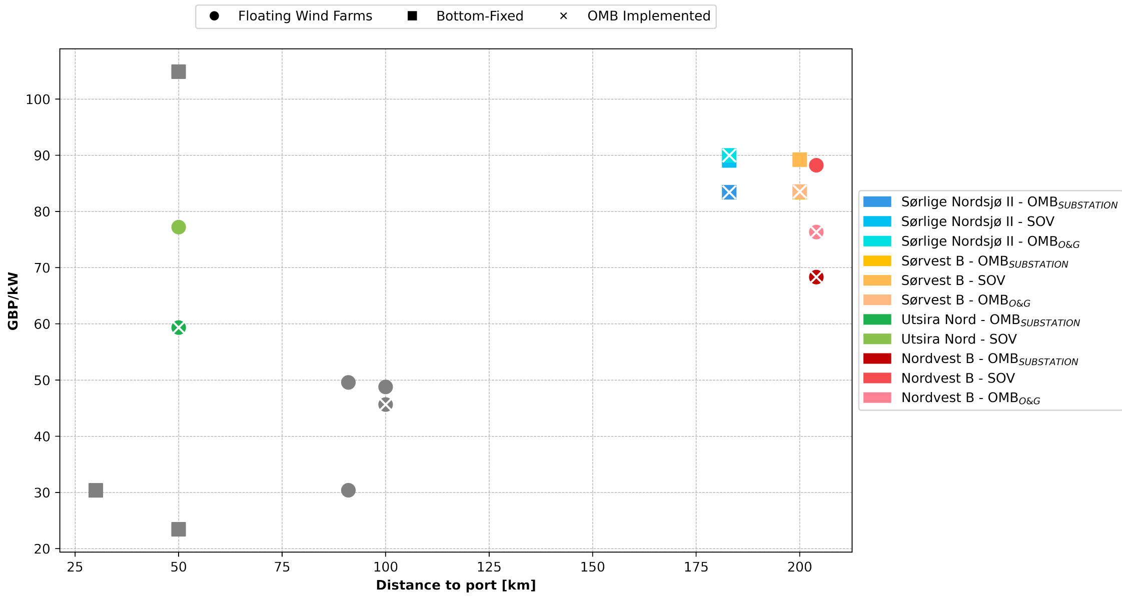


Figure 7.7: Scatter plot with reference case studies depicted in grey markers

7.3.1 Sensitivity analysis

A sensitivity analysis was carried out for the different wind farms in the case study in order to understand the effects of different inputs in the simulation. Sensitivity analysis is a valuable method to assess the impact of variables of a simulation, which shows how sensitive the simulation model is to changes in specific variables, such as discount rates or costs. The following sensitivities were gathered from the sensitivity functionality of the NOWIcob tool.

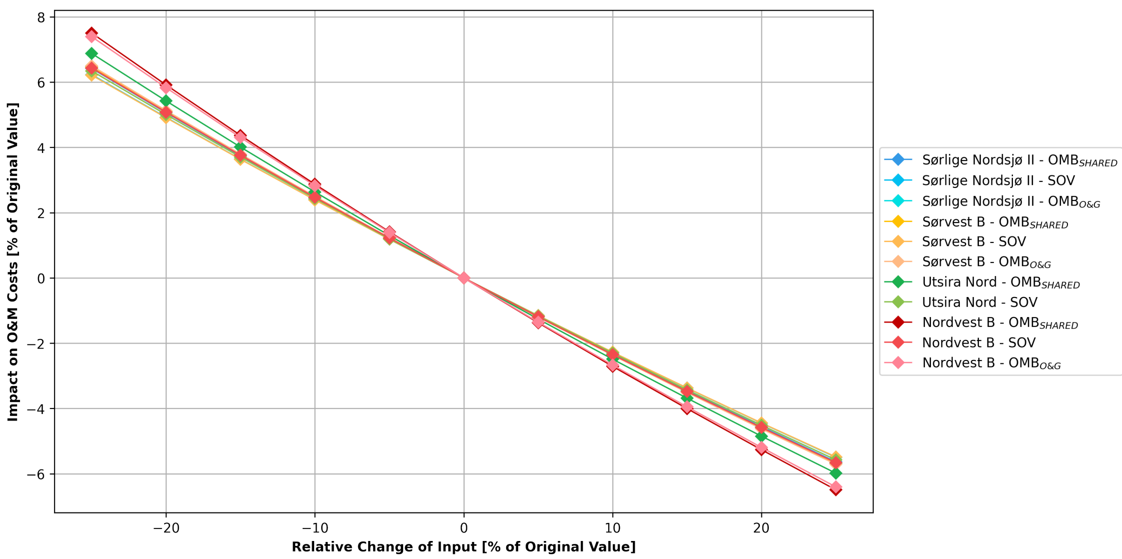


Figure 7.8: Sensitivity of the discount rate

The establishment of the discount rate and electricity price was not given much attention in the case development, being 5% and 0.15 GBP/kWh respectively. Figure 7.8 shows the discount rate sensitivity for the different wind farms and their associated vessel scenarios. As seen in Figure 7.8, the different simulations are similarly affected by the changes in the discount rate. A 25% decrease in the discount rate affects the O&M cost results by around 7%. A 25% increase affects the O&M costs by around 6%. These changes may seem small at first, but they have a significant impact on the costs considering the 25 years of accumulated costs. For instance, the summarised simulated O&M costs for the case with a shared OMB and substation at Sørlige Nordsjø II are around 2 554 million GBP. A 7% decrease in the O&M costs equivalates to 179 million GBP, showing that the discount rate has a significant impact on the costs.

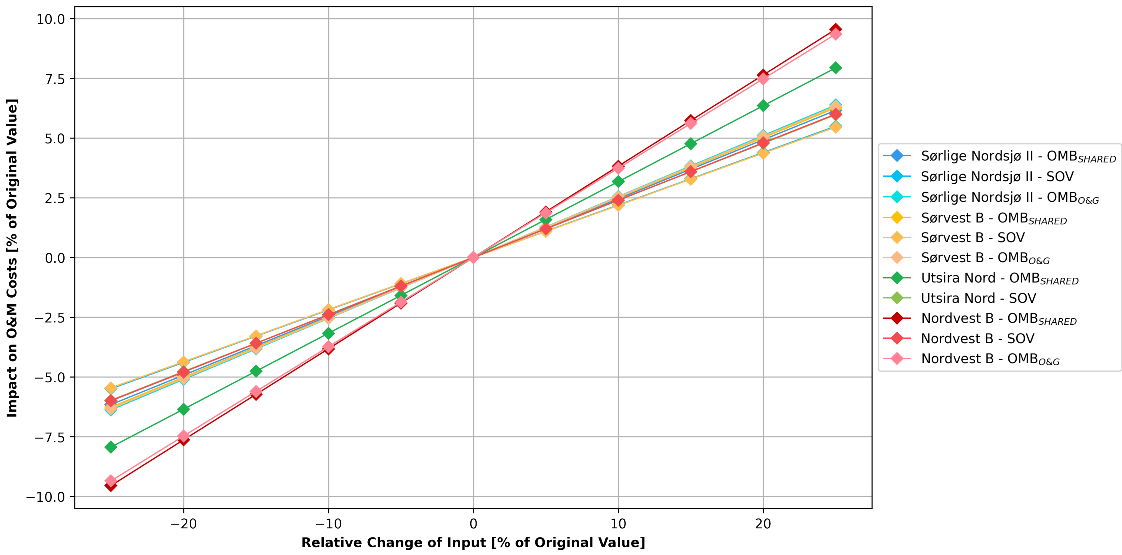


Figure 7.9: Sensitivity of the electricity price

The sensitivity of the electricity price is shown in Figure 7.9. The electricity price is not directly connected to the O&M cost, but it is a large contributor to the lost income due to downtime. As seen in the figure, there is some variation in the different cases compared to the sensitivity of the discount rate. The change in electricity prices has the greatest effect on the vessel scenarios of Nordvest B. This comes as a result of the increase in lost income due to downtime of the Nordvest B area compared to the other wind farms, which is significantly higher with the worst case having over 22 GBP/kW in lost income due to downtime.

All of the simulated scenarios utilise a SOV for some or all of the minor and major repairs. Figure 7.10 shows the sensitivity of the day rate of the SOVs. The day rates for the SOVs contribute significantly to the total O&M cost results, compromising most of the fixed vessel costs shown in the previously discussed bar plots of all the cases. The SOV cases for the floating wind farms have the highest sensitivity, as a 25% change in the day rate for the SOV results in a 12% increase or decrease in the total O&M costs. Generally, the change of the day rate of the SOV changes the O&M cost result significantly almost regardless of the level of SOV utilisation.

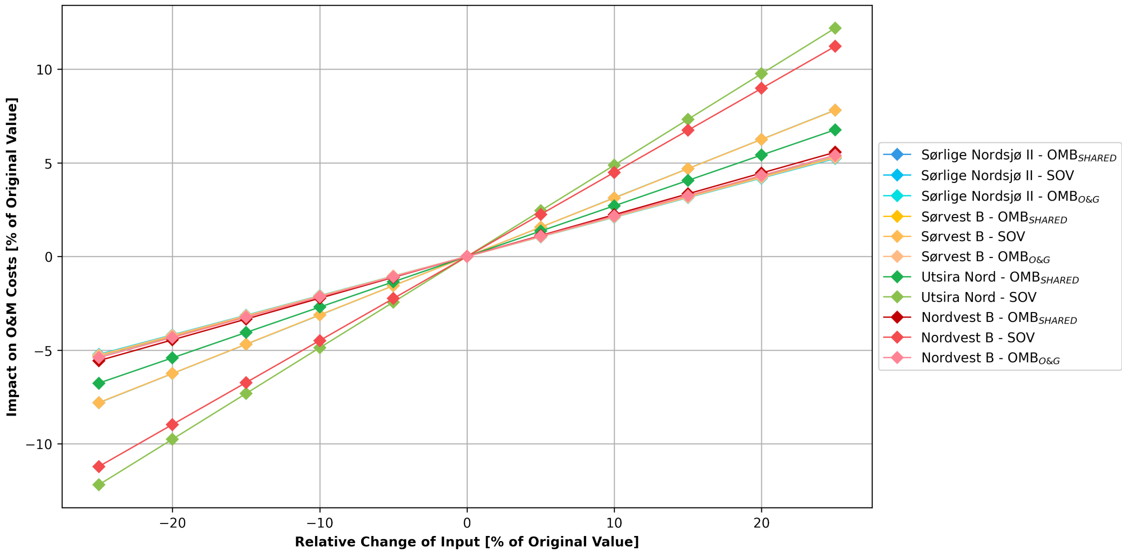


Figure 7.10: Sensitivity of the day rate of SOV

The day rate used for the jack-up vessels is over five times greater than the day rate for the SOV. This makes it the greatest contributor to O&M costs for the bottom-fixed wind farms. The day rate is based on short-term charter rates from the works of Dalgic et al. (2013) adjusted for inflation. A lot has changed in the offshore wind industry in the past decade, and basing the day rates from 2013 solely on inflation might have given an incorrect conception of the current situation. The sensitivity of the day rate is therefore important to investigate. Figure 7.11 shows that the sensitivities of the day rates are similar and linear for all of the bottom-fixed cases. For the jack-up vessel, a 25 % change in the day rate affects the total O&M costs by around 11 %.

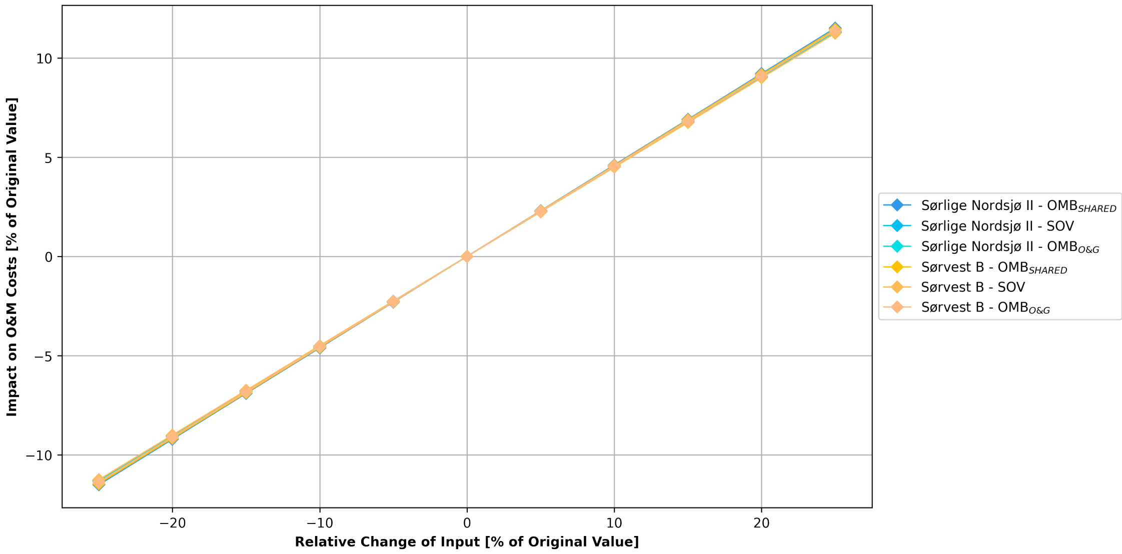


Figure 7.11: Sensitivity of the day rate of the jack-up vessel

The floating wind farm cases did not utilise a jack-up vessel, and the impact of changing the day rate for its replacement, tugboats, was too low for the NOWIcob to consider for the sensitivity analysis. However, an input which only affected the floating wind farms was the repair cost of the semi-submersible OWT. The repair cost was based on the input data utilised in Avanessova et al. (2022), and may have been too high and unrealistic. The sensitivity analysis of the repair cost for semi-submersible OWTs is shown in Figure 7.12. The sensitivity analysis shows that the Utsira Nord cases are affected by the change in repair cost to a greater extent compared to the Nordvest B cases. A 25 % change in repair cost equivalates approximately to a 9-10% change to the total O&M costs for Utsira Nord, while the change equivalates to approximately 8% for Nordvest B.

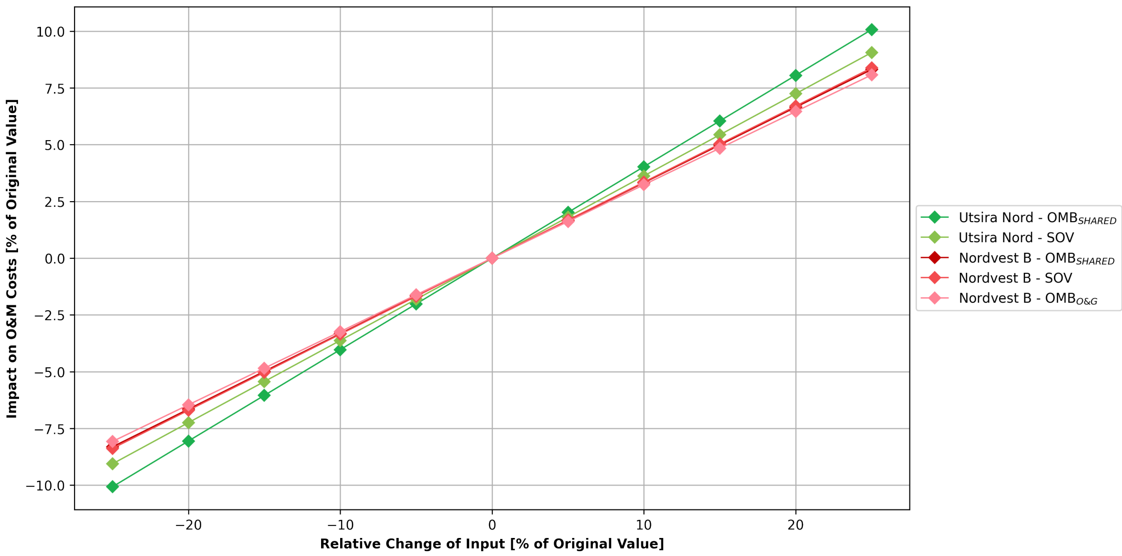


Figure 7.12: Sensitivity of the repair cost of the semi-submersible OWT

7.3.2 Additional cost of OMB

In order to investigate if the implementation of OMBs had any impact on cost reduction, it was important to investigate the full impact of it on CAPEX, OPEX and the generated electricity. The OPEX component of the LCOE was therefore investigated for the different wind farms and vessel scenarios. The $LCOE_{OPEX}$ were calculated through Equation 4.3 which has been described in section 4.1. The results were displayed as a function of the topside weight of the OMB modules. The weight of the topside substation is also considered, which is assumed to be 2 500 tonnes. However, the substation weight is constant and consequently not included in the weight variable in the following plots.

The chart displayed in Figure 7.13 shows the OPEX component of the LCOE for the six simulated vessel scenarios in the Sørlige Nordsjø II wind farm. Overall, it shows that the OMB scenarios have a higher $LCOE_{OPEX}$ than the SOV scenarios. As expected, the $LCOE_{OPEX}$ of the OMB scenario with a shared foundation with a substation increase at a higher rate than the scenarios considering the repurposing of O&G platforms. This is expected as the O&G option only considers the costs of the topside OMB modules, while the shared foundation considers the additional structural costs in addition to the topside costs.

According to the simulations and calculations of this thesis, OMBs should not be considered for the Sørlige Nordsjø II area. The results of the SOV scenarios show that it is consistently around 1.00 GBP/MWh less costly with the SOV case than the OMB options for both the ERA5 and NORA 3 simulations.

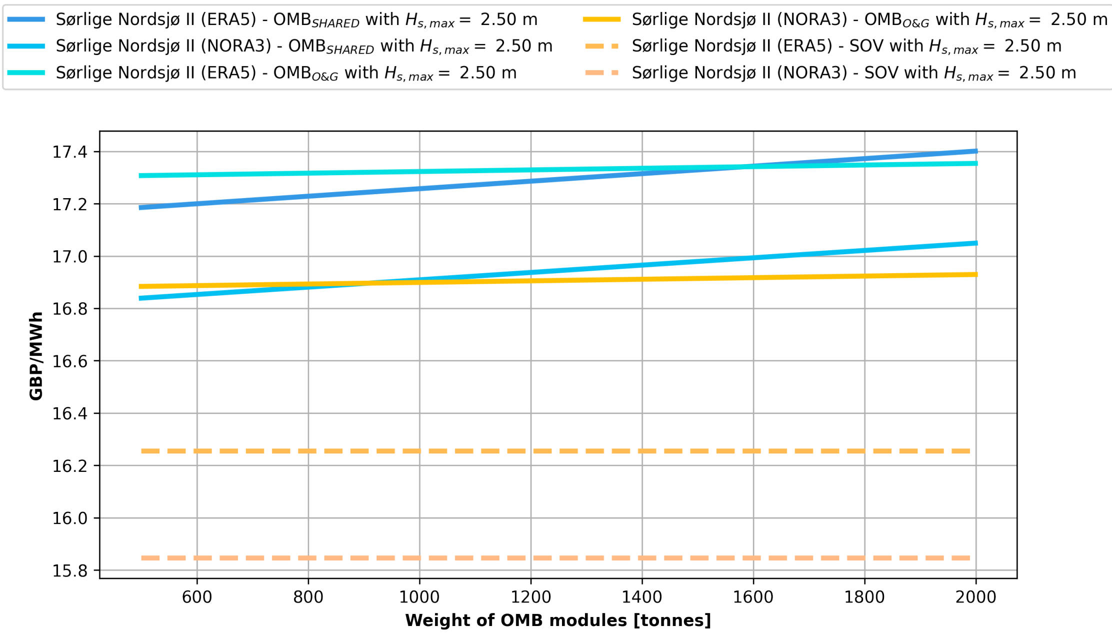


Figure 7.13: $LCOE_{OPEX}$ of Sørlige Nordsjø II

Figure 7.14 displays a chart showing the $LCOE_{OPEX}$ of all the cases simulated for the Sørvest B area. Even though the two bottom-fixed areas of Sørlige Nordsjø II and Sørvest B have similar characteristics, the differences between the $LCOE_{OPEX}$ results are quite substantial. The alteration of positions of the SOV scenarios and OMB scenarios appear to have changed to a near-complete reversal compared to the results of Sørlige Nordsjø II.

According to the simulation and calculations, the Sørvest B area benefits from the implementation of an OMB. The difference between the case with the shared OMB with a substation and the SOV case is over 1.00 GBP/MWh for both the ERA5 and NORA3 results. The cost estimate for the shared substation and OMB increases at a rate per tonne similar to the case of the Sørlige Nordsjø II area, indicating that the increased water depth of Sørvest B of 5 meters does not affect the additional structural costs to a notable extent.

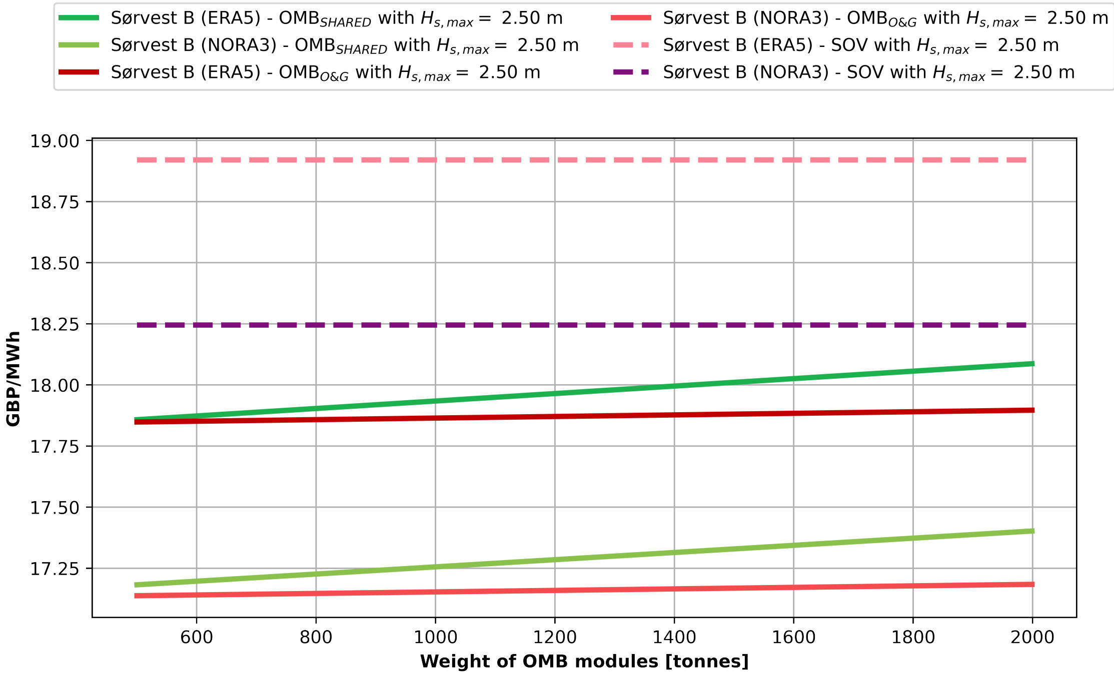


Figure 7.14: $LCOE_{OPEX}$ of Sørvest B

The $LCOE_{OPEX}$ of the vessel scenarios in Utsira Nord area are shown in Figure 1.1. The chart shows that there is some large contrast compared to the bottom-fixed cases. The difference between the SOV scenario and the OMB scenario is around 3.00-3.50 GBP/MWh. Additionally, the differences between the ERA5 and NORA3 results are negligible.

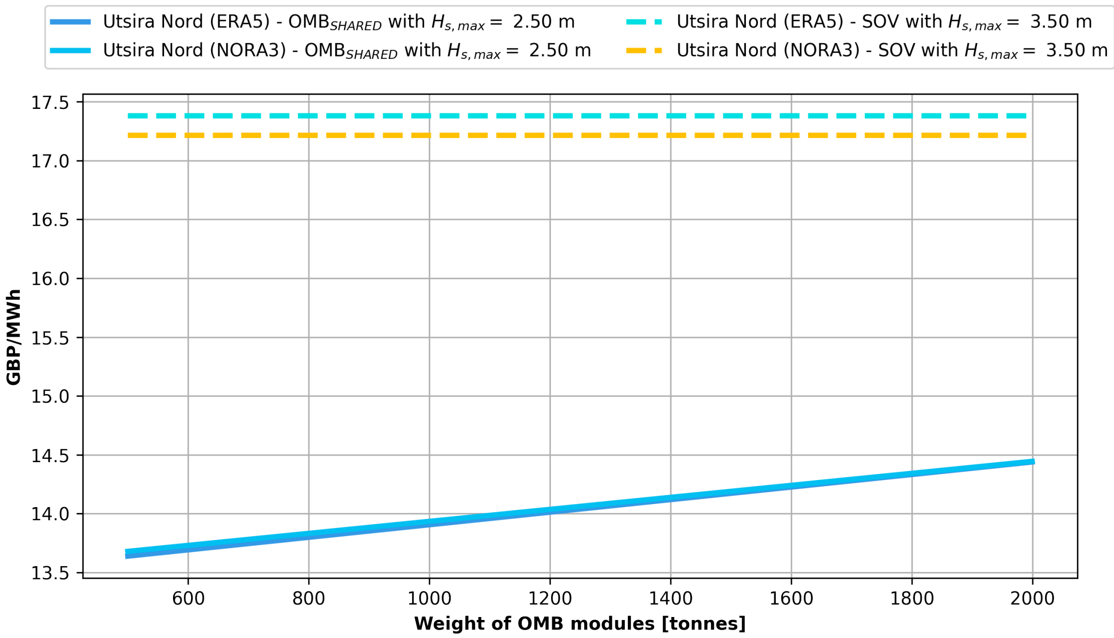


Figure 7.15: $LCOE_{OPEX}$ of Utsira Nord

According to the simulations and calculations of this thesis, OMBs should be considered for the Utsira Nord area as there are clear benefits of its implementation. However, this is unexpected as the Utsira Nord area is only situated 50 km from the O&M port. This is closer than the 70 km boundary set by Hu and Yung (2020) where solutions with accommodation are recommended.

The chart shown in Figure 7.16 depicts the $LCOE_{OPEX}$ for the vessel scenarios in Nordvest B. The differences between the ERA5 and NORA3 are not negligible, as the difference between the vessel scenarios is around 1.00 GBP/MWh. Similarly to Utsira Nord, the difference between the OMB options and SOV cases is considerably large compared to the bottom-fixed wind farms, being over 3.00 GBP/MWh. However, all the costs in general are around 3.00 GBP/MWh more expensive than the scenarios of Utsira Nord. This is expected as the travel distance to O&M port is over four times greater compared to the Utsira Nord area.

Even though the costs are generally higher than for Utsira Nord, the least costly option is still the OMB with a shared foundation with a substation, following the same trend as in the Utsira Nord area. However, repurposing an O&G platform to a shared O&G platform and OMB might be less costly if the weight of the topside OMB modules surpasses 1 100 tonnes.

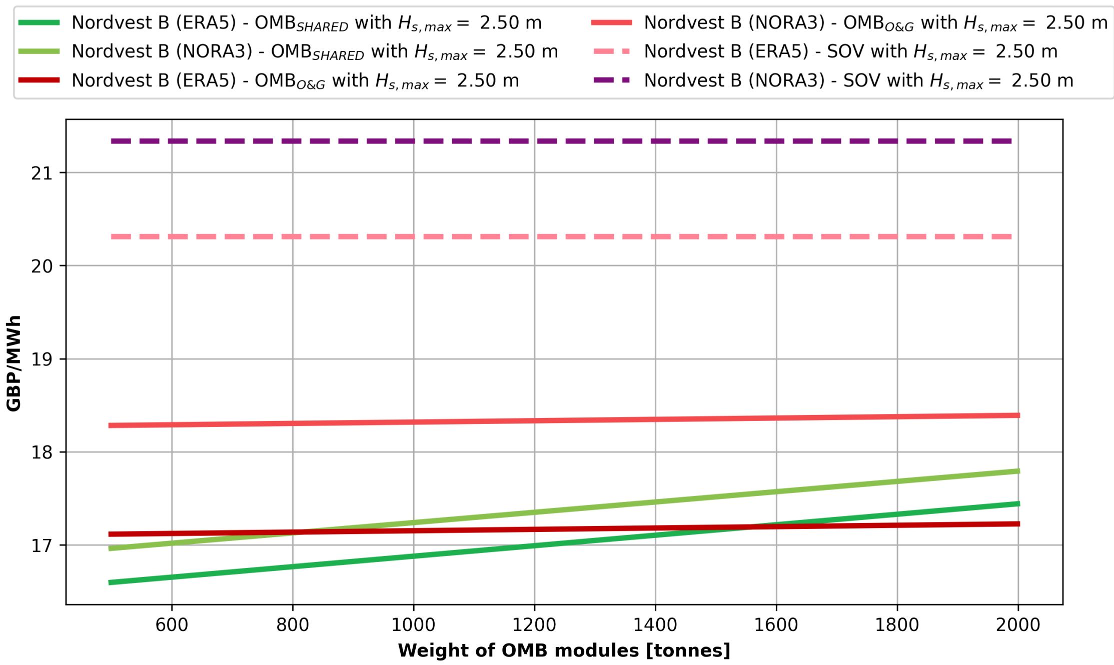


Figure 7.16: $LCOE_{OPEX}$ of Nordvest B

7.4 Results of SSCV implementation

The effects of implementing a SSCV for heavy lifts were investigated to see if its implementation could lower costs. Table 7.6 and 7.7 shows the simulation results of the SOV case with T2S operations and an identical SOV case where the T2S operations are replaced by utilisation of SSCV. It was investigated for the previously investigated floating wind farms of Utsira Nord and Nordvest B.

Table 7.6: Results of SSCV implementation for the Utsira Nord area

		SOV with T2S $H_{s,max}$ **= 3.50 m**		**SOV with SSCV** $H_{s,max}$ **= 3.50 m**	
		ERA5	**NORA3**	**ERA5**	**NORA3**
O&M Cost from simulation	**[GBP/kW]**	58.25	60.46	137.05	136.41
OPEX estimate	**[GBP/kW]**	75.78	78.66	178.31	177.47
Lost income due to downtime	**[GBP/kW]**	11.47	12.97	11.48	12.89
Energy produced	**[TWh/year]**	3.270	3.427	3.270	3.428

Table 7.7: Results of SSCV implementation for the Nordvest B area

		SOV with T2S $H_{s,max}$ **= 3.50 m**		**SOV with SSCV** $H_{s,max}$ **= 3.50 m**	
		ERA5	**NORA3**	**ERA5**	**NORA3**
O&M Cost from simulation	**[GBP/kW]**	65.73	69.91	134.20	135.38
OPEX estimate	**[GBP/kW]**	85.52	90.95	174.60	176.13
Lost income due to downtime	**[GBP/kW]**	13.08	13.54	13.11	13.60
Energy produced	**[TWh/year]**	3.158	3.197	3.158	3.197

Overall, the results of the costs are significantly higher than for the T2S operation. The day rate of the SSCV is the largest contributor to these costs, which was set at 50% more expensive than the day rate of jack-up vessels. Considering the sensitivity of the day rate of jack-up vessels shown in Figure 7.11, one could suspect the day rate of the SSCV having similar or greater sensitivity on the total O&M costs. Unexpectedly, the lost income due to downtime and the annual produced energy were similar between the two cases. This was unexpected since the SSCV operations were modelled with shorter durations than the T2S operations.

8 | Discussion

The objective of this thesis was to investigate whether the implementation of OMBs could lower costs for Norwegian offshore wind. After conducting a quantitative case study of several areas suggested for development of offshore wind, the overall results showed that OMBs have a significant potential within Norwegian offshore wind. This was based on the simulations and calculations of this thesis, which must be interpreted with caution. The simulation became very time-consuming for the case study due to the complexity of the subassemblies of the internal components and the number of different hypothetical wind farms and their associated vessel scenarios. The quantitative approach conducted in the case study might have subjugated the importance of qualitative assessment of the input variables and analysis of each case. The idea behind the quantitative approach was to include several wind farms as the different areas proposed for offshore wind development in Norway are not homogeneous. This was done to avoid drawing any conclusions for OMBs based on the conditions of a single area.

The NOWIcob tool could only utilise a single core of the processor for the simulation. This made the NOWIcob simulation utilise only 15% of the potential processor power of the computer used for the simulation on average. Selecting a more qualitative approach through investigating a single wind farm could have generated a more detailed and realistic investigation and utilised the true strength of the NOWIcob tool. Another possible method could be to decrease the number of subassemblies of the internal components of the OWT. The control study utilising the maintenance tasks used by Dinwoodie et al. (2015) in the code-to-code comparison showed that the runtime decreased significantly with less extensive modelling of the maintenance tasks. These adjustments would have decreased the time of each iteration of the simulation and simultaneously increased the number of simulation iterations to enhance the output of the simulations.

The simulations of the vessel scenarios suffer from a lack of vessel optimisation for the different wind farms. Initially, the number of CTVs and SOVs was based on the case study conducted by Avanessova et al. (2022) and adjusted for the size of the wind farm. Vessel optimisation is an essential part of the planning of offshore wind farms, and this creates relatively unrealistic O&M costs as the vessel utilisation varies for each wind farm. However, the number of vessels is similar for all the individual offshore wind farms in the case study making the relative difference in the results accurate even though the generated costs are inaccurate.

The NOWIcob tool has the ability to consider condition-based maintenance. This was not considered for this case study due to a lack of available data for the subassemblies of the internal components of the OWT. Condition-based maintenance is vital to increase availability and reduce the number of required maintenance visits in an offshore wind farm, and its implementation in the simulation would have had an impact on the availability. This would have impacted the number of visits using CTVs and SOVs, making it important to include condition-based maintenance in eventual further investigations of OMBs.

The vessel suggestion shown in Table 2.1 for major replacements are assumed to be a mix of SOVs, jack-up vessels and T2S operations. This is based on the cost and the complexity of the components and their affiliated tasks. Originally, the subdivision of failures in the works of Carroll et al. (2015) was solely based on the cost of the repairs. If some of the assumptions for major replacements turn out to be incorrect, there would be considerable consequences in the generated O&M costs for the bottom-fixed wind farms as the utilisation of the costly jack-up vessels would increase.

After conducting the code-to-code comparison, it was decided to remove the operations utilising AHTS and CLVs from the simulation and separately add them to the costs after the simulation. As seen in the results, the removal of these operations in the simulations generated more consistent results between the vessel scenarios as intended. However, the k_{other} factor of 1.22 and 1.30 might not represent the actual costs associated with the operations of AHTS and CLVs. The eventual downtime due to the removed operations was not accounted for either, but it would be insignificant in order to analyse the performance of OMBs with the utilisation of CTVs compared to the exclusive utilisation of SOVs. This is because the number of maintenance tasks using ATHS and CLVs would be roughly the same for every vessel scenario.

Additionally, the k_{other} factor includes other costs such as license fees. This was included in order to obtain realistic OPEX values and be comparable to the reference case studies. There are many aspects concerning O&M of offshore wind farms that were not included in the simulation such as maintenance of export cables and substations. Generally, the computed cost results were higher compared to most of the reference case studies. However, it seems that the case study of this thesis considered similar aspects of O&M compared to the reference case studies.

The fuel considered for the case study was VLSFO, as the North Sea is an emission control area with restrictions on SOx emissions. This could differ from the actual fuel utilised in the future, as fuel conversion and newbuilds with alternative fuels are a high priority within the maritime industry. Alternative fuels such as liquefied natural gas, ammonia and hydrogen have a high prosperity within the maritime industry and their implementation in Norwegian offshore wind are not unrealistic from a long-term perspective. However, alternative fuels would be required to be easily available and accessible at the OMB in order to refuel the CTVs. Several companies have investigated the possibility of offshore power hubs to refuel vessels, and integrating this with an OMB could solve this issue and potentially save costs.

Overall, the two weather data of ERA5 and NORA3 consistently produced similar results. The results from the simulations using NORA3 created slightly higher results. This indicates that the NORA3 data are somewhat more conservative in their reanalysis. According to its documentation by Haakenstad et al. (2021), the NORA3 provide a more detailed reanalysis compared to ERA5. Therefore, the usage of NORA3 data should be used in eventual further investigations as it provides a detailed and conservative weather reanalysis of the Norwegian shelf.

Generally, the cost results of the spare parts are relatively consistent throughout all the vessel scenarios, as shown in Figure 7.3, 7.4, 7.5 and 7.6. This indicates that the number of failures is similar for all the vessel scenarios, which is important to assess the real effect of the OMB implementation compared to conventional usage of SOVs. It would have been problematic if the scenarios using OMBs and CTVs generated fewer or greater numbers of failures, as its implementation would have directly influenced the failures and consequently the availability of the wind farm.

In addition, the differences between the OMB and SOV options were consistent throughout all the vessel scenarios. The small difference between the annual produced energy showed that the increased wait time due to weather did not have a significant impact on the availability. Additionally, the OMB option turned out to be the best option for three of the wind farms. The difference in costs was consistent for all wind farms and vessel scenarios, making a correction of the cost estimates relatively straightforward in order to improve the analysis, e.g. to reduce the SOV costs if the costs are higher than actual values.

The sensitivity analysis showed that some of the input values have a significant impact on the total O&M costs. The sensitivity analysis only considered the most cost-sensitive input values, which was the reason why inputs such as the day rate of CTVs were not included. The discount rate was set to 5% which is an optimistic assumption taking the current global economic situation in 2023. In retrospect, a discount rate of at least 10% should have been considered in the case study as this is closer to typical values for maritime engineering projects. A 100% increase in the discount rate would have significantly decreased the total O&M costs, as seen in Figure 7.8.

The sensitivity analysis also presented the sensitivities to the day rates of jack-up vessels and SOVs. In general, the day rate of the SOV contributes significantly to the total costs of O&M as SOVs are an integral part of the O&M regardless of the type of vessel scenario. The day rate of the jack-up vessels was the largest contributor to the bottom-fixed wind farms. It was assumed that the jack-up vessels were individually chartered for a 30-day period with the day rates presented in the works of Dalgic et al. (2013), adjusted for inflation. These day rates are based on works dating back to 2013, and the adjustment with the inflation rate might not realistically represent the current situation. A change in the day rate of jack-up vessels would significantly change the total O&M costs for the bottom-fixed wind farms.

In the case study of Avanessova et al. (2022) the general costs of a shared substation and OMB were considered. This thesis specifically considered the additional structural costs and topside OMB costs as the additional cost associated with an OMB implementation. The substation must be built either way in the offshore wind farm, and the general costs of the substation were therefore subtracted from the cost of the shared substation and OMB. The cost estimations suffered especially from a lack of available cost data for floaters of semi-submersible substations, and it is therefore important to analyse the results with caution.

Additionally, it is important to mention that the results for the repurposing of O&G platforms shown in Figure 7.15 and 7.16 consider the cost of the topside components of the OMB. The costs of potentially decreasing the profitability of the O&G platform or the costs of taking the platform out of production and physically refitting it into a shared O&G platform and OMB are not included in the results as it is hard to determine. These costs must be considered in order to properly investigate the actual effect of repurposing O&G platforms.

The $LCOE_{OPEX}$ was investigated in order to see the combined effects of OMB implementation on the costs and the produced electricity. At first sight, this could have been investigated by using the lost income due to downtime shown in the results. However, this parameter is based on the electricity costs which is uncertain and not given much attention throughout the case study. There is not any straightforward approach to estimating electricity prices in the future. Using the built-in electricity price generator in NOWIcob or utilising a binomial lattice model approach would give reasonable estimates of the electricity prices. However, the inclusion of it in the analysis of the results generated in the case study would increase the uncertainty which is already high enough.

The investigation of the SSCV was difficult to perform as data for the costs of such vessels are not available in the current literature. The day rate was based on a 50% increase in the day rate of jack-up vessels, which as previously mentioned is a highly sensitive input and might not represent the current situation. The 50% increase in the day rate was assumed since SSCVs are highly complex and rare vessels. The total costs are therefore even more sensitive to a change in the day rate than for the jack-up vessels, and the cost results of the investigation of the SSCV implementation must be interpreted with caution.

However, the results of the SSCV implementation show that the benefits of it are absent in regard to increased availability and energy production. According to the simulations, the implementation of SSCV would not benefit the wind farm compared to T2S operations unless the cost of SSCV decreases. It is plausible that the day rate of SSCV is lower compared to the day rates used in the simulation, however, it is unrealistic that the costs decrease to similar rates as the tugboats used in the T2S operations.

Lastly as mentioned earlier in the discussion and in the code-to-code comparison, some of the input values were gathered from literature dating back almost a decade. This coupled with the exponential growth of the offshore wind industry in recent years has made some of the assumptions taken in the case study different from the actual current values. The inflation rate does not strictly follow the offshore wind market, and basing some of the cost estimates solely on inflation may have oversimplified the current situation.

9 | Conclusion

This thesis aimed to investigate the effectiveness of the implementation of OMBs in Norwegian offshore wind through a case study of hypothetical wind farms in multiple suggested areas. The review of O&M of offshore wind farms showed how important O&M is for the costs of offshore wind, and it introduced multiple approaches to lower the costs of offshore wind. Additionally, the review and feasibility study of OMBs in Norwegian offshore wind showed that OMBs could have a significant impact on Norwegian offshore wind if the conditions are suitable.

The quantitative case study tested the implementation of OMBs for several different conditions at the Norwegian Continental Shelf. This was important in order to avoid drawing any conclusions based on the conditions of a specific location. The Norwegian geography and bathymetry provide a range of different conditions for upcoming wind farms on the Norwegian shelf.

The NOWIcob tool provided the opportunity to simulate the entire lifespan of the different hypothetical wind farms through a discrete event simulation utilising Monte Carlo iterations. This was important in order to understand the impact OMBs had on the entire lifespan of the wind farm. The case study utilised the subassembly in the works of Carroll et al. (2015) for failure rates of wind turbine, which is more detailed compared to subassemblies used in previous and similar studies.

The results of the case study showed that the implementation of OMBs has great potential within Norwegian offshore wind for areas suitable for floating and bottom-fixed development. The results of the hypothetical floating wind farms of Utsira Nord and Nordvest B showed that OMBs generated the least costly option for O&M. The case study also showed that OMBs significantly impact the costs of bottom-fixed wind farms. However, the effectiveness of OMBs is greatly affected by the local conditions at each wind farm as demonstrated in the results of Sørlige Nordsjø II.

The case study also included an investigation of the usage of SSCVs for the investigated floating wind farms. The investigation showed that the effect SSCVs have on the availability and energy production is minimal, even though the generated costs presumably were too high compared to realistic O&M costs. The day rates of SSCVs would have to be significantly lower than the day rates used in this case study in order to become a real alternative to T2S operations in floating offshore wind.

In conclusion, the case study shows that OMBs have great potential within offshore wind and should be investigated further in the development of actual upcoming offshore wind farms in Norway. The results of the case study must be interpreted with caution, as the input values used are based on literature dating back almost a decade and recent advancements in the offshore wind market. This thesis and the case study present several topics for further investigation of the implementation of OMBS in Norwegian offshore wind, which are important in order to understand the full impact of OMBs in Norway.

9.1 Contribution

As intended, this thesis has made an effort to lower costs within O&M in Norwegian offshore wind. Previous studies have used a narrow scope of subassemblies of the OWT. The work of this study included a more detailed subassembly of the OWT and provided a suggestion for vessel selection for the different detailed maintenance tasks. Additionally, the work consisted of the construction of a map displaying points of interest for Norwegian offshore wind in addition to active oil and gas installations. The map, shown in Appendix D, functions as an interactive encyclopedia of Norwegian offshore wind. Lastly, this thesis investigated the usage of SSCVs which proved to have similar efficiency as the usage of T2S operations for maintenance tasks requiring heavy lifts.

9.2 Further work

As previously mentioned, this thesis introduces several topics for further investigation of OMBs in Norwegian offshore wind. Ideally, the investigation of this thesis would have included some of these topics. However, the case study turned out to be more time-consuming than anticipated. The following list shows a suggestion of topics for further investigation of the effectiveness of OMBs in Norwegian offshore wind.

- Include emissions as a KPI and investigate the effects of different fuels on the vessels used in O&M
- Perform a vessel optimisation for the investigated hypothetical wind farms to increase vessel utilisation and generate more realistic O&M costs
- Investigate the design of a shared substation with an OMB in detail to be able to understand the additional costs of OMBs
- Investigate all additional costs associated with repurposing an O&G platform to a shared O&G platform and OMB
- Investigate the capital expenditures of the hypothetical wind farms, which results in a complete LCOE analysis
- Investigate the operational limits of vibrations of the OWT, to ensure safe operation for technicians during maintenance tasks
- Investigate the usage of abandoned O&G platforms and foundations for OMBs to reduce construction costs and to recycle old infrastructure

References

Aborgela, T., Shehata, A. S., Kotb, M., & Radwan, A. (2022). Heavy Lift Semi-Submersible Ships Utilization in Offshore Wind Turbines Industry [Technologies and Materials for Renewable Energy, Environment and Sustainability]. *Energy Reports*, *8*, 834–847. https://doi.org/https://doi.org/10.1016/j.egyr.2022.07.097

Ahn, D., Shin, S.-c., Kim, S.-y., Kharoufi, H., & Kim, H.-c. (2017). Comparative evaluation of different offshore wind turbine installation vessels for Korean west–south wind farm. *International Journal of Naval Architecture and Ocean Engineering*, *9*(1), 45–54. https://doi.org/https://doi.org/10.1016/j.ijnaoe.2016.07.004

Aker Solutions. (2022, November 22). *Subsea Substation – Unlocking the potential of floating offshore wind*. Retrieved 13th December 2022, from https://www.akersolutions.com/news/news-archive/2022/subsea-substation--unlocking-the-potential-of-floating-offshore-wind/

Alicat Workboats. (2017). Alicat Workboats Receives MCS SWATH 2 CTV Order. *offshoreWIND.biz*. Retrieved 12th May 2023, from https://www.offshorewind.biz/2017/09/04/alicat-workboats-receives-mcs-swath-2-ctv-order/

Altinn. (2021). What does an employee cost? https://www.altinn.no/en/start-and-run-business/working-conditions/employment/what-does-an-employee-cost/

Ampelmann. (2023). *Ampelmann - History*. Retrieved 8th May 2023, from https://www.ampelmann.nl/history

Anderson, F., Dawid, R., Cava, D. G., & McMillan, D. (2021). Operational Metrics for an Offshore Wind Farm & Their Relation to Turbine Access Restrictions and Position in the Array. *Journal of Physics: Conference Series*, *2018*(1), 012002. https://doi.org/10.1088/1742-6596/2018/1/012002

Arabian-Hoseynabadi, H., Oraee, H., & Tavner, P. (2010). Failure Modes and Effects Analysis (FMEA) for Wind Turbines. *International Journal of Electrical Power & Energy Systems*, *32*(7), 817–824. https://doi.org/https://doi.org/10.1016/j.ijepes.2010.01.019

Aslesen, S., Basso, M., Erraia, J., Foseid, H., Hernes, S., Jakobsen, E., & Winje, E. (2022). *FLYTENDE HAVVIND - Analyse av markedet og norske aktøreres omsetningspotensial*. Menon Economics. Retrieved 5th December 2022, from https://offshore-wind.no/wp-content/uploads/2019/10/Menon-Economics-Havvindanalyse-2022_digital.pdf

Auestad, Ø. F., Gravdahl, J. T., Perez, T., Sørensen, A. J., & Espeland, T. H. (2015). Boarding control system for improved accessibility to offshore wind turbines: Full-scale testing. *Control Engineering Practice*, *45*, 207–218. https://doi.org/https://doi.org/10.1016/j.conengprac.2015.09.016

Austrheim, E. H., & Nesse, A. (2021, June 15). *Leveransemodeller for havvind - Delrapport – Kartlegging av norske kompetansemiljøer innen havvind*. The Federation of Norwegian Industries. Retrieved 1st December 2022, from https://www.nors kindustri.no/siteassets/dokumenter/rapporter-og-brosjyrer/leveransemodeller-havvind/leveransemodeller-havvind_juni_kartlegging-av-norske-kompetansemiljoer.pdf

Avanessova, N., Gray, A., Lazakis, I., Thomson, R. C., & Rinaldi, G. (2022). *Analysing the effectiveness of different offshore maintenance base options for floating wind farms*. Wind Energy Science.

Aziz Biabani, M. A. K., & Mohsin Ahmed, S. R. (2016). Maintenance of EHV substation. *2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES)*, 2105–2116. https://doi.org/10.1109/SCOPES.2016.7955819

Babicz, J. (2015). *WÄRTSILÄ - ENCYCLOPEDIA OF SHIP TECHNOLOGY* (2nd ed.). Wärtsilä.

Bank of England. (2023). *Inflation calculator*. Retrieved 26th April 2023, from https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

Barthelmie, R., Hansen, K. S., Frandsen, S., Rathmann, O., Schepers, J., Schlez, W., Phillips, J., Rados, K., Zervos, A., Politis, E., & Chaviaropoulos, P. (2009). Modelling and Measuring Flow and Wind Turbine Wakes in Large Wind Farms Offshore. *Wind Energy*, *12*, 431–444. https://doi.org/10.1002/we.348

Behrens, A., & Günther, H. (2009). Operational Wave Prediction of Extreme Storms in Northern Europe. *Natural Hazards*, *49*, 387–399. https://doi.org/10.1007/s11069-008-9298-3

Besnard, F., Patriksson, M., Strömberg, A.-B., Wojciechowski, A., & Bertling, L. (2009). An optimization framework for opportunistic maintenance of offshore wind power system. *2009 IEEE Bucharest PowerTech*, 1–7. https://doi.org/10.1109/PTC.2009.5281868

Bessone, M. B., Zaaijer, M., von Terzi, D., Dykes, K., Jump, E., & Viré, A. (2022). Including Installation Logistics Costs in the Optimal Sizing of Semi-Submersibles for Floating Wind Farms. *Journal of Physics: Conference Series*, *2265*(4), 042018. https://doi.org/10.1088/1742-6596/2265/4/042018

Boskalis. (2018). *Equipment sheet - Ndurance*. Retrieved 1st May 2023, from https://boskalis.com/media/wbanffyp/ndurance_clv.pdf

Breivik, Ø., Carrasco, A., Haakenstad, H., Aarnes, O. J., Behrens, A., Bidlot, J.-R., Björkqvist, J.-V., Bohlinger, P., Furevik, B. R., Staneva, J., & Reistad, M. (2022). The Impact of a Reduced High-Wind Charnock Parameter on Wave Growth With Application to the North Sea, the Norwegian Sea, and the Arctic Ocean [e2021JC018196 2021JC018196]. *Journal of Geophysical Research: Oceans*, *127*(3), e2021JC018196. https://doi.org/https://doi.org/10.1029/2021JC018196

Buljan, A. (2021). Vard to Build North Star SOVs for Dogger Bank OWF. *offshoreWIND.biz*. Retrieved 1st May 2023, from https://www.offshorewind.biz/2021/04/06/vard-to-build-north-star-sovs-for-dogger-bank-owf/

Bull, S., & Bringsværd, S. (2020, December 16). *The next wave in renewables: Equinor's path towards an offshore wind major*. Equinor. Retrieved 21st November 2022, from https://www.equinor.com/content/dam/statoil/documents/ir/events-and-presentations/equinor-offshore-and-floating-wind-16-december.pdf

BVG Associates. (2010). Value breakdown for the offshore wind sector. *RAB (2010) 0365*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48171/2806-value-breakdown-offshore-wind-sector.pdf

BVG Associates. (2023). Wind farm costs. *ORE Catapult*. Retrieved 15th May 2023, from https://guidetoanoffshorewindfarm.com/wind-farm-costs

Carroll, J., McDonald, A., & Mcmillan, D. (2015). Failure rate, Repair Time and Unscheduled O&M Cost Analysis of Offshore Wind Turbines. *Wind Energy*, *19*. https://doi.org/10.1002/we.1887

Caselitz, P., Giebhardt, J., & Mevenkamp, M. (1997a). Application of Condition Monitoring Systems in Wind Energy Convertors. *Proceedings of the European Wind Energy Conference, EWEC'97, Dublin, Ireland*, 579–582.

Caselitz, P., Giebhardt, J., & Mevenkamp, M. (1997b). Online Fault Detection and prediction in Wind Energy Convertors. *Proceedings of the European Wind Energy Conference, EWEC'97, Dublin, Ireland*, 623–627.

Chen, Q., Liang, C., Wang, Z., & Zhang, B. (2023). Design of Semi-Submersible Offshore Power Generation Platform based on Green Energy Utilization. *Highlights in Science, Engineering and Technology*, *29*, 12–24.

Chitteth Ramachandran, R., Desmond, C., Judge, F., Serraris, J.-J., & Murphy, J. (2022). Floating Wind Turbines: Marine Operations Challenges and Opportunities. *Wind Energy Science*, *7*(2), 903–924. https://doi.org/10.5194/wes-7-903-2022

Colmenar-Santos, A., Campíñez-Romero, S., Enriquez-Garcia, L., & Pérez-Molina, C. (2014). Simplified Analysis of the Electric Power Losses for On-Shore Wind Farms Considering Weibull Distribution Parameters. *Energies*, *7*, 6856–6885. https://doi.org/10.3390/en7116856

Copernicus. (2023). ERA5 hourly data on single levels from 1940 to present [Accessed: 20-04-2023]. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview

Cotton, I., Jenkins, N., & Pandiaraj, K. (2001). Lightning Protection for Wind Turbine Blades and Bearings. *Wind Energy*, *4*(1), 23–37. https://doi.org/https://doi.org/10.1002/we.44

Dai, L., Ehlers, S., Rausand, M., & Utne, I. B. (2013). Risk of Collision between Service Vessels and Offshore Wind Turbines. *Reliability Engineering & System Safety*, *109*, 18–31. https://doi.org/https://doi.org/10.1016/j.ress.2012.07.008

Dai, L., Stålhane, M., & Utne, I. B. (2015). Routing and Scheduling of Maintenance Fleet for Offshore Wind Farms. *Wind Engineering*, *39*(1), 15–30. https://doi.org/10.1260/0309-524X.39.1.15

Dalgic, Y., Lazakis, I., & Turan, O. (2013). Vessel Charter Rate Estimation for Offshore Wind O&M Activity. https://doi.org/10.1201/b15813-113

Dankowski, H., & Dilger, H. (2013). Investigation of the Mighty Servant 3 Accident by a Progressive Flooding Method [V001T01A018], *Volume 1: Offshore Technology*. https://doi.org/10.1115/OMAE2013-10342

Dervos, C. T., & Vassiliou, P. (2000). Sulfur hexafluoride (SF6): Global Environmental Effects and Toxic Byproduct Formation. *Journal of the Air & Waste Management Association*, *50*, 137–141. https://doi.org/https://doi.org/10.1080/10473289.2000.10463996

Díaz, H., Rodrigues, J. M., & Guedes Soares, C. (2016). Preliminary Cost Assessment of an Offshore Floating Wind Farm Installation on the Galician Coast, 843–850. https://doi.org/10.1201/9781315229256-99

Dinwoodie, I., Endrerud, O.-E. V., Hofmann, M., Martin, R., & Sperstad, I. B. (2015). Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms. *Wind Engineering : The International Journal of Wind Power*, *39*, 1–14. https://doi.org/10.1260/0309-524X.39.1.1

Dippel, M. (2022, May 31). *30 partners join DNV to start Joint Industry Project for floating offshore wind substations*. DNV. Retrieved 23rd November 2022, from https://www.dnv.com/news/30-partners-join-dnv-to-start-joint-industry-project-for-floating-offshore-wind-substations-222575

Dresser, B., & Tetra Tech, Inc. (2021). Offshore Wind Submarine Cabling Overview. *NYSERDA Report 21-14*, 46–49. https://www.nyftwg.com/wp-content/uploads/2021/05/Offshore-Wind-Submarine-Cable-Report.pdf

ECMWF. (2023). ERA5: data documentation [Digital encyclopedia of the data documentation of ERA5]. https://confluence.ecmwf.int/display/CKB/ERA5%5C%3A+data+documentation

Emeis, S., & Turk, M. (2007). Comparison of Logarithmic Wind Profiles and Power Law Wind Profiles and their Applicability for Offshore Wind Profiles. https://doi.org/10.1007/978-3-540-33866-6_11

Energi Norge. (2022). *Høringssvar – "Høyring av forslag til inndeling av dei opna områda i utlysingsområde for fornybar energiproduksjon til havs"*. Retrieved 14th November 2022, from https://www.regjeringen.no/no/dokumenter/hoyring-av-forslag-til-inndeling-av-dei-opna-omrada-i-utlysingsomrade-for-fornybar-energiproduksjon-til-havs/id2900420/Download/?vedleggId=2ded2a40-f4d3-4d94-92d9-6778709e03c2

Equinor. (2023). *Hywind Tampen*. Retrieved 2nd May 2023, from https://www.equinor.com/energy/hywind-tampen

Fauli, M., Keppler, M., & Revheim, P. P. (2022, January 27). *Tidslinje havvind - Sørlige Nordsjø II*. Sweco & Energi Norge. Retrieved 8th November 2022, from https://www.energinorge.no/contentassets/c947a7e6ccd64760ba723f6f5c234bdf/sweco_tidslinjehavvind_2022-01_27_final.pdf

Foxwell, D. (2019). Day rates for SOVs likely to continue upward course. https://www.rivieramm.com/news-content-hub/news-content-hub/day-rates-for-sovs-likely-to-continue-upward-course-54572

Fred. Olsen Windcarrier. (2016a). Fred Olsen unveils O&M study. *renews.biz*. Retrieved 12th May 2023, from https://renews.biz/42045/fred-olsen-unveils-om-study/

Fred. Olsen Windcarrier. (2016b, June 28). *Fred. Olsen Ocean AS and Shoreline AS simulate best O&M solution for bigger offshore wind farms*. Retrieved 15th November

2022, from https://windcarrier.com/media/news/fred-olsen-ocean-as-and-shoreline-as-simulate-best-o-m-solution-for-bigger-offshore-wind-farms/

Fred. Olsen Windcarrier. (2023). *Hornsea One*. Retrieved 7th May 2023, from https://windcarrier.com/track-record/case-studies/hornsea-one/

Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Witold Skrzypinski, G. S., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., & Viselli, A. (2020). Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine. https://www.nrel.gov/docs/fy20osti/75698.pdf

GL Gaarrad Hassan. (2013, June). *A Guide to UK Offshore Wind Operations and Maintenance*. Retrieved 5th December 2022, from http://csmres.co.uk/cs.public.upd/article-downloads/Offshore-wind-guide-June-2013-updated.pdf

Gray, A. (2021). *SETTING A BENCHMARK FOR DECARBONISING O&M VESSELS OF OFFSHORE WIND FARMS*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2021/02/VesselEmissionsOM_Final.pdf

Guachamin, W., Li, L., Gao, Z., & Moan, T. (2016). Methodology for Assessment of the Operational Limits and Operability of Marine Operations. *Ocean Engineering*, *125*, 308–327. https://doi.org/10.1016/j.oceaneng.2016.08.015

Guanche, R., Martini, M., Jurado, A., & Losada, I. J. (2016). Walk-to-work accessibility assessment for floating offshore wind turbines. *Ocean Engineering*, *116*, 216–225. https://doi.org/https://doi.org/10.1016/j.oceaneng.2016.03.013

Haakenstad, H., Breivik, Ø., Furevik, B. R., Reistad, M., Bohlinger, P., & Aarnes, O. J. (2021). NORA3: A Nonhydrostatic High-Resolution Hindcast of the North Sea, the Norwegian Sea, and the Barents Sea. *Journal of Applied Meteorology and Climatology*, *60*(10), 1443–1464. https://doi.org/https://doi.org/10.1175/JAMC-D-21-0029.1

Hagen, B., Simonsen, I., Hofmann, M., & Muskulus, M. (2013). A multivariate Markov Weather Model for O&M Simulation of Offshore Wind Parks [Conference paper on the development and benchmarking of the multi-parameter weather model subsequently implemented in NOWIcob]. *Energy Procedia*, *35*, 137–147. http://web.phys.ntnu.no/~ingves/Downloads/MyPapers/EnergyProcedia_35_137_2013.pdf

Halvorsen-Weare, E. E., Gundegjerde, C., Halvorsen, I. B., Hvattum, L. M., & Nonås, L. M. (2013). Vessel Fleet Analysis for Maintenance Operations at Offshore Wind Farms [DeepWind'2013 – Selected papers from 10th Deep Sea Offshore Wind R&D Conference, Trondheim, Norway, 24 – 25 January 2013]. *Energy Procedia*, *35*, 167–176. https://doi.org/https://doi.org/10.1016/j.egypro.2013.07.170

Hansen, M. How hard can it be to pitch a wind turbine blade? [11th Danish Center for Applied Mathematics and Mechanics, DCAMM ; Conference date: 19-03-2007 Through 21-03-2007]. English. In: 11th Danish Center for Applied Mathematics and Mechanics, DCAMM ; Conference date: 19-03-2007 Through 21-03-2007. 2007. http://www.fam.web.mek.dtu.dk/dcamm05/index.php?navigate=symposia

Harrison, J., Garrad, A., Warren, T., & Powell, J. (2020). Floating Offshore Wind: Installation, Operation & Maintenance Challenges. https://www.blackfishengineering.com/post/floating-offshore-wind-installation-operation-maintenance-challenges

Harrison, R. L. (2010). Introduction To Monte Carlo Simulation. *AIP conference proceedings*, *1204*, 17–21. https://doi.org/https://doi.org/10.1063/1.3295638

Hasager, C., Stein, D., Courtney, M., Peña, A., Mikkelsen, T., Stickland, M., & Oldroyd, A. (2013). Hub Height Ocean Winds over the North Sea Observed by the NORSEWInD Lidar Array: Measuring Techniques, Quality Control and Data Management. *Remote Sensing*, *5*, 4280–4303. https://doi.org/10.3390/rs5094280

Heerema Marine Contractors. (2022). *Sleipnir*. Retrieved 8th May 2023, from https://www.heerema.com/heerema-marine-contractors/fleet/sleipnir

Helal, M. (2008). *A Hybrid System Dynamics-Discrete Event Simulation approach To Simulating The Manufacturing Enterprise* (PhD dissertation). University of Central Florida.

Hofmann, M., Sperstad, I. B., & Lorentzen, M. (2017). *Technical documentation of version 3.3 of the NOWIcob tool*. SINTEF Energi AS. https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2620579

Hu, B., & Yung, C. (2020). *Offshore Wind Access Report 2020*. TNO. http://resolver.tudelft.nl/uuid:d6cefbf6-2916-42fc-bb3d-b2d713938e09

Indrevær, N. E., Enervold, K., & Kolsnes, T. (2021, June 15). *Delivery methods for offshore wind - Norwegian ports, yards and construction sites for offshore wind*. The Federation of Norwegian Industries. Retrieved 12th November 2022, from https://www.norskindustri.no/siteassets/dokumenter/rapporter-og-brosjyrer/leveransemodeller-havvind/leveransemodeller-havvind_juni_havner-verft-og-byggesteder.pdf

James, R., & Ros, M. C. (2015). Floating Offshore Wind: Market and Technology Review. https://dokumen.tips/documents/floating-offshore-wind-market-and-technology-review.html?page=1

Jansen, M., Staffel, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., & Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. *Nature Energy*, *5*, 614–622. https://doi.org/https://doi.org/10.1038/s41560-020-0661-2

Jiang, Z. (2021). Installation of Offshore Wind Turbines: A Technical Review. *Renewable and Sustainable Energy Reviews*, *139*, 110576. https://doi.org/https://doi.org/10.1016/j.rser.2020.110576

Kabbabe Poleo, K., Crowther, W. J., & Barnes, M. (2021). Estimating the Impact of Drone-based Inspection on the Levelised Cost of Electricity for Offshore Wind Farms. *Results in Engineering*, *9*, 100–201. https://doi.org/https://doi.org/10.1016/j.rineng.2021.100201

Kaltschmitt, M., Streicher, W., & Wiese, A. (2007). Basics of Renewable Energy Supply. In M. Kaltschmitt, W. Streicher & A. Wiese (Eds.), *Renewable energy: Technology, and environment economics* (pp. 52–55). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-70949-5_2

Karyotakis, A., & Bucknall, R. (2010). Planned intervention as a maintenance and repair strategy for offshore wind turbines. *Journal of Marine Engineering & Technology*, *9*(1), 27–35. https://doi.org/10.1080/20464177.2010.11020229

Levander, K. (2017). *Compendium TMR4254: System Based Ship Design*. NTNU.

Li, H., & Guedes Soares, C. (2022). Assessment of Failure Rates and Reliability of Floating Offshore Wind Turbines. *Reliability Engineering & System Safety*, *228*, 108777. https://doi.org/https://doi.org/10.1016/j.ress.2022.108777

Li, M., Kang, J., Sun, L., & Wang, M. (2019). Development of Optimal Maintenance Policies for Offshore Wind Turbine Gearboxes Based on the Non-homogeneous Continuous-Time Markov Process. *Journal of Marine Science and Application*, *18*. https://doi.org/10.1007/s11804-019-00075-9

Liu, Y., Li, S., Yi, Q., & Chen, D. (2016). Developments in Semi-Submersible Floating Foundations Supporting Wind Turbines: A Comprehensive Review. *Renewable and Sustainable Energy Reviews*, *60*, 433–449. https://doi.org/https://doi.org/10.1016/j.rser.2016.01.109

Lloyd's Register of Shipping. (2022). *Sea-web : The register of ships and list of shipowners on the internet*.

Louis Dreyfus Armateurs. (2022). *INNO'VENT - The first Crew Transfer Vessel designed and manufactured in France*. Retrieved 7th May 2023, from https://www.lda.fr/en/innovent-the-first-crew-transfer-vessel-designed-and-manufactured-in-france/

Lu, B., Li, Y., Wu, X., & Yang, Z. (2009). A Review of Recent Advances in Wind Turbine Condition Monitoring and Fault Diagnosis. *Proceedings of IEEE Conference on Power Electronics and Machines in Wind Application*, 1–7. https://doi.org/10.1109/PEMWA.2009.5208325

Luengo, M. M., & Kolios, A. (2015). Failure Mode Identification and End of Life Scenarios of Offshore Wind Turbines: A Review. *Energies*, *8*(8), 8339–8354. https://doi.org/10.3390/en8088339

Ma, K.-T., Luo, Y., Thomas Kwan, C.-T., & Wu, Y. (2019). *Mooring System Engineering for Offshore Structures*. Elsevier.

Marineregions.org. (2019). *Shapefiles - Download*. Retrieved 17th April 2023, from https://www.marineregions.org/downloads.php#eez

Márquez-Domínguez, S., & Sørensen, J. D. (2012). Fatigue Reliability and Calibration of Fatigue Design Factors for Offshore Wind Turbines. *Energies*, *5*(6), 1816–1834. https://doi.org/10.3390/en5061816

Martin, R., Lazakis, I., Barbouchi, S., & Johanning, L. (2016). Sensitivity Analysis of Offshore Wind Farm Operation and Maintenance Cost and Availability. *Renewable Energy*, *85*, 1226–1236. https://doi.org/https://doi.org/10.1016/j.renene.2015.07.078

McMorland, J., Collu, M., McMillan, D., & Carroll, J. (2022). Operation and maintenance for floating wind turbines: A review. *Renewable and Sustainable Energy Reviews*, *163*, 112499. https://doi.org/https://doi.org/10.1016/j.rser.2022.112499

McNiff, B. (2007). The gearbox reliability. *Proceedings of the 2nd Sandia National Laboratories Wind Turbine Reliability Workshop*, 623–627.

Montoya, F. S. (2022). *Operations planning (O2M) for offshore wind farms*. DNV. Retrieved 14th December 2022, from https://www.dnv.com/services/operations-planning-o2m-for-offshore-wind-farms-5158

Moubray, J. (1997). *Reliability-centred Maintenance*. Butterworth-Heinemann.

Musial, W., Beiter, P., & Nunemaker, J. (2020). *Cost of Floating Offshore Wind Energy Using New England Aqua Ventus Concrete Semisubmersible Technology* (Technical report). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75618.pdf

Myhr, A., Bjerkseter, C., Ågotnes, A., & Nygaard, T. A. (2014). Levelised Cost of Energy for Offshore Floating Wind Turbines in a Life Cycle Perspective. *Renewable Energy*, *66*, 714–728. https://doi.org/https://doi.org/10.1016/j.renene.2014.01.017

Na, W.-B., & Kundu, T. (2002). Underwater Pipeline Inspection Using Guided Waves. *Journal of Pressure Vessel Technology*, *124*(2), 196–200. https://doi.org/10.1115/1.1466456

National Ocean Industries Association. (2023). *THE BASICS OF OFFSHORE OIL & GAS*. Retrieved 16th May 2023, from https://www.noia.org/basics-offshore-oil-gas/

Nejad, A. R., Keller, J., Guo, Y., Sheng, S., Polinder, H., Watson, S., Dong, J., Qin, Z., Ebrahimi, A., Schelenz, R., Gutiérrez Guzmán, F., Cornel, D., Golafshan, R., Jacobs, G., Blockmans, B., Bosmans, J., Pluymers, B., Carroll, J., Koukoura, S., … Helsen, J. (2022). Wind Turbine Drivetrains: State-of-the-Art Technologies and Future Development Trends. *Wind Energy Science*, *7*(1), 387–411. https://doi.org/10.5194/wes-7-387-2022

Nejad, A. R., & Torsvik, J. (2021). Drivetrains on floating offshore wind turbines: Lessons learned over the last 10 years. *Forschung im Ingenieurwesen*, *85*(2), 335–343. https://doi.org/10.1007/s10010-021-00469-8

Nejad, A. R., Gao, Z., & Moan, T. (2014). Fatigue Reliability-based Inspection and Maintenance Planning of Gearbox Components in Wind Turbine Drivetrains [EERA DeepWind' 2014, 11th Deep Sea Offshore Wind R&D Conference]. *Energy Procedia*, *53*, 248–257. https://doi.org/https://doi.org/10.1016/j.egypro.2014.07.234

Norwegian Petroleum Directorate. (2023). *Factpages - Facility*. Retrieved 17th April 2023, from https://factpages.npd.no/en/facility/TableView/Fixed

Norwegian Water Resources and Energy Directorate (NVE). (2023). *Identifisering av utredningsområder for havvind*. https://veiledere.nve.no/havvind/identifisering-av-utredningsomrader-for-havvind/

NREL. (2020). *IEA_15MW_240_RWT*. Retrieved 18th April 2023, from https://nrel.github.io/turbine-models/IEA_15MW_240_RWT.html

OEG Offshore. (2023). Topside installation complete at 500MW Fecamp. Retrieved 12th May 2023, from https://www.oegoffshore.com/products/accommodation-modules

Oh, K.-Y., Nam, W., Ryu, M., Kim, J.-Y., & Epureanu, B. (2018). A Review on the Foundation of Offshore Wind Energy Convertors: Current Status and Future Perspectives. *Renewable and Sustainable Energy Reviews*, *88*. https://doi.org/10.1016/j.rser.2018.02.005

Ørsted A/S. (2022). *Horns Rev 2 Havmøllepark*. Retrieved 15th November 2022, from https://orstedcdn.azureedge.net/-/media/www/docs/corp/com/our-business/wind-power/wind-farm-project-summary/horns-rev-2_da_2018.ashx?rev=3c62237cbf854e569aa3162e18f0d172

Patricksson, Ø. (2012). *Semi-Submersible Platform Design to Meet Uncertainty in Future Operating Scenarios* (Master's Thesis). Norwegian University of Technology and Science.

Piotrowski, P. J., Robak, S., Polewaczyk, M., & Raczkowski, R. (2016). Offshore Substation Workers' Exposure to Harmful Factors - Actions Minimizing Risk of Hazards. *Medycyna pracy*, *67*, 51–72. https://doi.org/https://doi.org/10.13075/mp.5893.00320

PMI Underwater Cable Solutions. (2015). When it comes to subsea cable repair, time is of the essence. *Cable Hardware Solutions*. Retrieved 25th April 2023, from https://pmiind.com/when-it-comes-to-subsea-cable-repair-time-is-of-the-essence/

Popa, L. M., Jensen, B.-B., Ritchie, E., & Boldea, I. (2003). Condition monitoring of Wind Generators. *Proceedings of the 38th IAS Annual Meeting on Industry Applications Conference, Salt Lake City, UT, USA*, 1839–1846.

Prest, A. R., & Turvey, R. (1966). Cost-Benefit Analysis: A Survey. In *Surveys of economic theory: Resource allocation* (pp. 155–207). Palgrave Macmillan UK. https://doi.org/10.1007/978-1-349-00210-8_5

Rangel Ramírez, J., & Sørensen, J. (2012). Risk-based Inspection Planning Optimisation of Offshore Wind Turbines. *Structure and Infrastructure Engineering*, *8*, 473–481. https://doi.org/10.1080/15732479.2010.539064

Reliawind. (2007). Reliability focused research on optimizing wind energy systems design, operation and maintenance: tools, proof of concepts, guidelines & methodologies for a new generation. *Reliawind, Rep. 2007*.

Ren, Z., Verma, A. S., Li, Y., Teuwen, J. J., & Jiang, Z. (2021). Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, *144*, 110886. https://doi.org/https://doi.org/10.1016/j.rser.2021.110886

Rizzo, P. (2014). 17 - Sensing solutions for assessing and monitoring underwater systems. In M. Wang, J. Lynch & H. Sohn (Eds.), *Sensor technologies for civil infrastructures* (pp. 525–549). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9781782422433.2.525

Royal IHC. (2023). *Service operation vessels*. Retrieved 7th May 2023, from https://www.royalihc.com/offshore-energy/offshore-vessels/service-operation-vessels

Royal Norwegian Ministry of Trade and Industry. (2022a, June 23). *Roadmap – The green industrial initiative*. https://www.regjeringen.no/contentassets/1c3d3319e6a946f2b57633c0c5fcc25b/roadmap_the-green-industrial-initiative_singlepages_web.pdf

Royal Norwegian Ministry of Trade and Industry. (2022b, December 1). *Havvind blir Norges neste eksporteventyr*. Retrieved 1st December 2022, from https://www.regjeringen.no/no/aktuelt/havvind-blir-norges-neste-eksporteventyr/id2949198/

Sanford, W. (2015). Achieve Comprehensive Reliability by Combining RBI and RCM. *Inspectioneering Journal - April/March 2015*.

Schull, P. J. (2002). Nondestructive Evaluation: Theory, Techniques, and Applications.

Searoutes.com. (2023). Retrieved 5th May 2023, from https://app.searoutes.com/

Sevan SSP. (2023). *Sevan Floating Substation - Offshore wind and power hubs*. Retrieved 13th May 2023, from https://sevanssp.com/floating-substation/

Shafiee, M. (2015). Maintenance logistics organization for offshore wind energy: Current progress and future perspectives. *Renewable Energy*, *77*, 182–193. https://doi.org/https://doi.org/10.1016/j.renene.2014.11.045

Ship&Bunker. (2023). *Rotterdam bunker prices*. Retrieved 5th May 2023, from https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam

Sivalingam, K., Sepulveda, M., Spring, M., & Davies, P. (2018). A Review and Methodology Development for Remaining Useful Life Prediction of Offshore Fixed and Floating Wind turbine Power Converter with Digital Twin Technology Perspective. *2018 2nd International Conference on Green Energy and Applications (ICGEA)*, 197–204. https://doi.org/10.1109/ICGEA.2018.8356292

Slette, H. T. (2022). Lecture notes in Discrete Event Simulation.

Sørensen, J. D. (2015). Reliability Assessment of Wind Turbines. *12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12*. https://open.library.ubc.ca/media/stream/pdf/53032/1.0076166/4

Spinato, F., Tavner, P., van Bussel, G., & Koutoulakos, E. (2009). Reliability of Wind Turbine Subassemblies IET Proceedings. *IET Renewable Power Generation*, *3*. https://doi.org/10.1049/iet-rpg.2008.0060

Stålhane, M., Halvorsen-Weare, E. E., Nonås, L. M., & Pantuso, G. (2019). Optimizing Vessel Fleet Size and Mix to Support Maintenance Operations at Offshore Wind Farms. *European Journal of Operational Research*, *276*(2), 495–509. https://doi.org/https://doi.org/10.1016/j.ejor.2019.01.023

Statistics Norway. (2023). *11419: Monthly earnings, by occupation, industry (SIC2007), contents, year and measuring method*. Retrieved 8th May 2023, from https://www.ssb.no/en/statbank/table/11419/tableViewLayout1/

Stehly, T., Beiter, P., & Duffy, P. (2020). *2019 Cost of Wind Energy Review*. National Renewable Energy Lab. (NREL) Golden, CO (United States).

Stehly, T., & Duffy, P. (2022). *2021 Cost of Wind Energy Review*. National Renewable Energy Lab. (NREL) Golden, CO (United States).

Stumpf, H. P., & Hu, B. (2018). *Offshore Wind Access Report 2018*. TNO. https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-E--17-071

Technical University of Denmark (DTU). (2021). *Global Wind Atlas*. Retrieved 15th May 2023, from https://globalwindatlas.info/en/

Thalemann, F., & Bard, J. (2012). Offshore Supply Chain Requirements for Ocean Energy in Europe - Results from the ORECCA Project. *4th International Conference on Ocean Energy*. https://publica-rest.fraunhofer.de/server/api/core/bitstreams/0df610b4-85ca-4940-a242-7a8738f397a5/content

The Norwegian Meteorological Institute. (2023). NORA3 [Accessed: 17-05-2023]. https://marine.met.no/node/19

Thomas, É., Levrat, É., & Iung, B. (2008). OVERVIEW ON OPPORTUNISTIC MAINTENANCE [9th IFAC Workshop on Intelligent Manufacturing Systems]. *IFAC Proceedings Volumes*, *41*(3), 245–250. https://doi.org/https://doi.org/10.3182/20081205-2-CL-4009.00044

Tran, T., & Kim, D.-H. (2015). The Platform Pitching Motion of Floating Offshore Wind Turbine: A Preliminary Unsteady Aerodynamic Analysis. *Journal of Wind Engineering and Industrial Aerodynamics*, *142*. https://doi.org/10.1016/j.jweia.2015.03.009

Ulstein Ship design. (2023). *Anchor Handling Tug Supply*. Retrieved 1st May 2023, from https://ulstein.com/ship-design/ahts

United Nations. (2023). *THE 17 GOALS*. Retrieved 2nd May 2023, from https://sdgs.un.org/goals

Utne, I. B. (2020). *TMR4335 Marine Technology – Propulsion Systems, Safety and Environment*. Department of Marine Technology, NTNU.

van Bussel, G., & Zaaijer, M. (2001). Reliability, Availability and Maintenance Aspects of large-scale Offshore Wind Farms, a concepts study. *Proceedings of MAREC*, *113*.

Vard Ship design. (2023). *Vard 4 12 - Service Operatrion Vessel*. Retrieved 1st May 2023, from https://www.vard.com/ship-design/vard-4-series-offshore-renewables/vard-4-12-service-operation-vessel

Vattenfall AB. (2022). *Dantysk – climate-friendly electricity from the German North Sea*. Retrieved 15th November 2022, from https://powerplants.vattenfall.com/dantysk/

Vestas Wind Systems. (2023). V236-15.0 MW Brochure [Accessed: 20-05-2023]. https://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/OffshoreProductBrochure/v236-150-mw-brochure/?page=1

Walgern, J., Peters, L., & Madlener, R. (2017). Economic Evaluation of Maintenance Strategies for Offshore Wind Turbines Based on Condition Monitoring Systems. *FCN Working Paper*, *08*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3240555

Wilcken, S. (2012). *Alpha factors for the calculation of forecasted operational limits for marine operations in the Barents Sea* (Master's Thesis). University of Stavanger.

Williams, A. (2011, July). *HVDC vs. HVAC cables for offshore wind*. Retrieved 27th November 2022, from https://www.reutersevents.com/renewables/wind-energy-update/hvdc-vs-hvac-cables-offshore-wind

Windspider. (2022). *Windspider - Products*. Retrieved 3rd December 2022, from https://windspider.com/products/

Wiser, R., Rand, J., Seel, J., Beiter, P., Baker, E., Lantz, E., & Gilman, P. (2021). Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nature Energy*, *6*, 555–565. https://doi.org/https://doi.org/10.1038/s41560-021-00810-z

Wood Mackenzie. (2019, November 18). *Europe to spearhead renewable energy cost reductions for offshore wind through 2028*. Retrieved 21st November 2022, from https://www.woodmac.com/press-releases/europe-to-spearhead-renewable-energy-cost-reductions-for-offshore-wind-through-2028/

Xe. (2023). *Xe Currency Converter*. Retrieved 26th April 2023, from https://www.xe.com/currencyconverter/

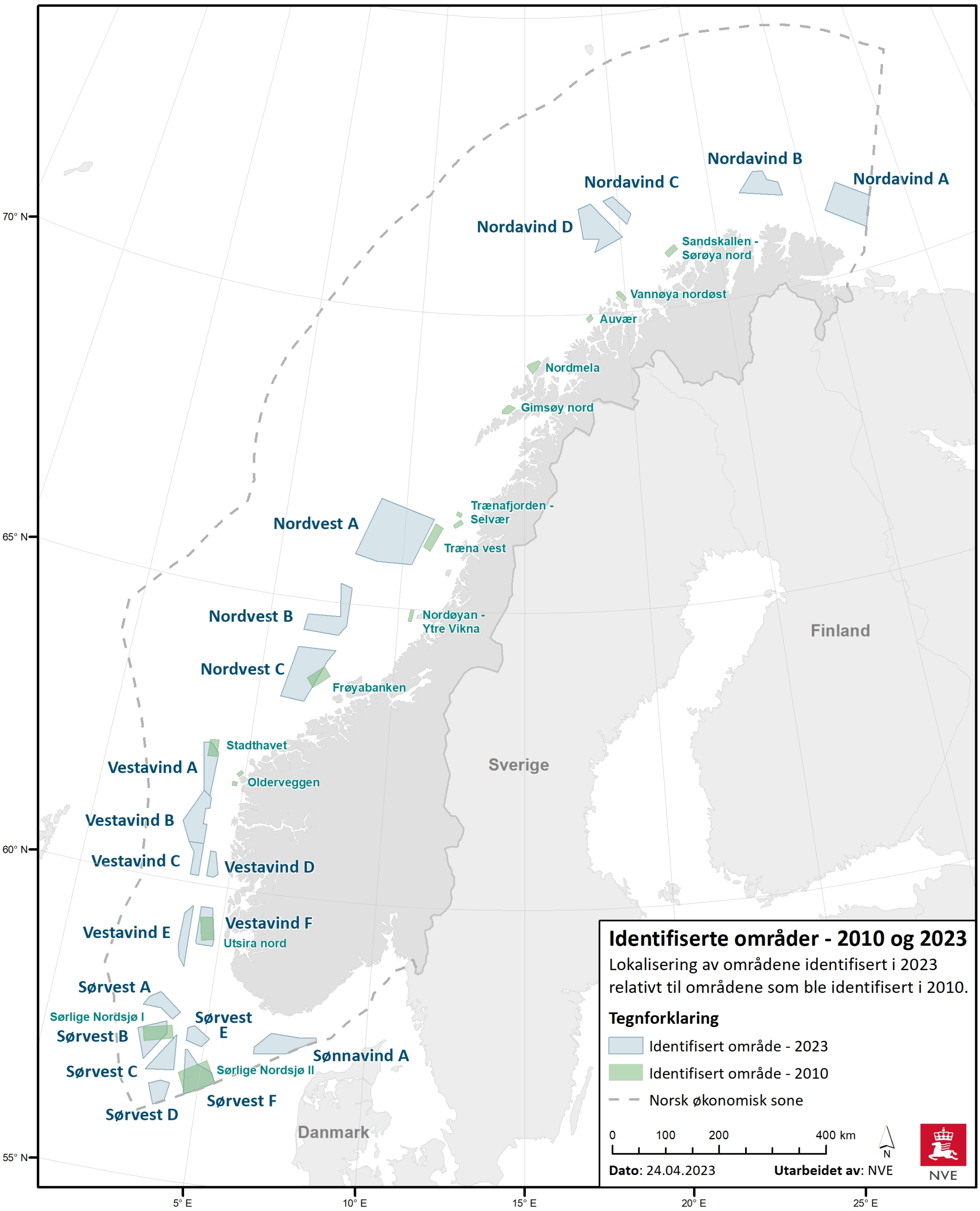
Zhang, C., Gao, W., Guo, S., Li, Y., & Yang, T. (2017). Opportunistic Maintenance for Wind Turbines Considering Imperfect, Reliability-based Maintenance. *Renewable Energy*, *103*, 606–612. https://doi.org/https://doi.org/10.1016/j.renene.2016.10.072

Zhao, M., Chen, Z., & Blaabjerg, F. (2007). Generation Ratio Availability Assessment of Electrical Systems for Offshore Wind Farms. *Energy Conversion, IEEE Transactions on*, *22*, 755–763. https://doi.org/10.1109/TEC.2006.881391

Appendix

A Map of proposed areas for offshore wind

A map of the proposed areas for development of offshore wind in the Norwegian economic zone, developed by Norwegian Water Resources and Energy Directorate (NVE) (2023).



B Failure rates for OWT components

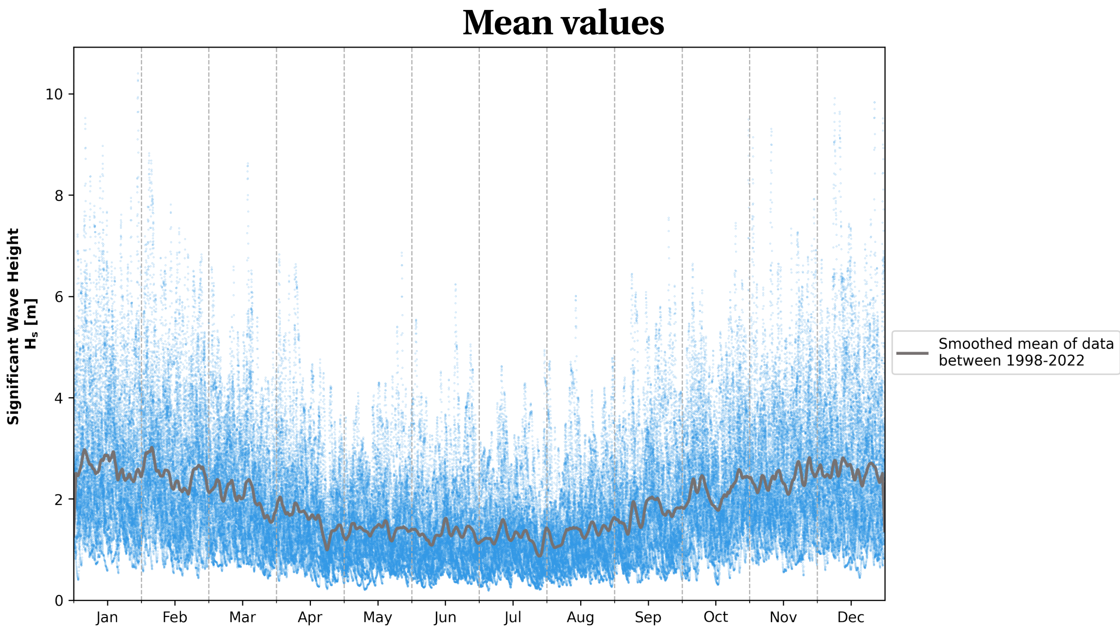
A table displaying failure rates of components ($\boldsymbol{\lambda}$) together with durations ($\boldsymbol{r}$), number of technicians ($\boldsymbol{n}$) and costs of material ($\boldsymbol{C_{SP}}$) of unscheduled maintenance tasks gathered from Carroll et al. (2015). The data are generated by analysing over 350 OWTs with a nominal power between 2 and 4 MW. The cost data from the study are displayed in euros (€), and a conversion rate to GBP (£) of 0.90 is used (Xe, 2023). In addition, the costs have been adjusted for inflation from 2015 to 2023 with a total rate of 29% (Bank of England, 2023).

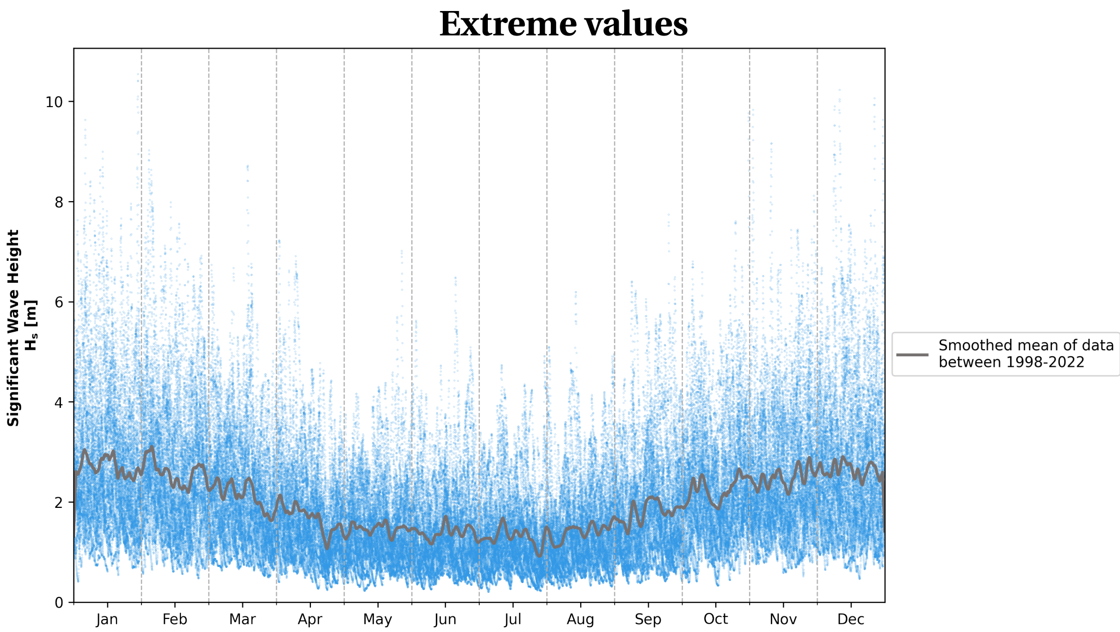
Component	**Minor Repair**				**Major Repair**				**Major Replacement**				**No Cost Data**		
	λ [-]	r [h]	n [-]	C_{SP} [GBP]	λ [-]	r [h]	n [-]	C_{SP} [GBP]	λ [-]	r [h]	n [-]	C_{SP} [GBP]	λ [-]	r [h]	n [-]
Pitch/ Hydraulics	0.824	9	2.3	244	0.179	19	2.9	2 206	0.001	25	4.0	16 254	0.072	17	2.8
Generator	0.485	7	2.2	186	0.321	24	2.7	4 064	0.095	81	7.9	69 660	0.098	13	2.4
Gearbox	0.395	8	2.2	145	0.038	22	3.2	2 903	0.154	231	17.2	267 030	0.046	7	2.2
Blades	0.456	9	2.1	197	f0.010	21	3.3	1 742	0.001	288	21.0	104 490	0.053	28	2.6
Electrical components	0.358	5	2.2	116	0.016	14	2.9	2 322	0.002	18	3.5	13 932	0.059	7	2.4
Contactor/ Circuit breaker/ Relay	0.326	4	2.2	302	0.054	19	3.0	2 670	0.002	150	8.3	15 674	0.048	5	2.0
Hub	0.182	10	2.3	186	0.038	40	4.2	1 742	0.001	298	10.0	104 490	0.014	8	2.4
Yaw system	0.162	5	2.2	163	0.006	20	2.6	3 483	0.001	49	5.0	14 513	0.020	9	2.4
Power supply/ Converter	0.076	7	2.2	279	0.081	14	2.3	6 153	0.005	57	5.9	15 093	0.018	10	2.7
Transformer	0.052	7	2.5	110	0.003	26	3.4	2 670	0.001	1	1.0	81 270	0.009	19	2.8
Controls	0.355	8	2.2	232	0.054	14	3.1	2 322	0.001	12	2.0	15 093	0.018	17	3.2
Grease/ Oil/ Cooling Liq.	0.407	4	2.0	186	0.006	18	3.2	2 322	-	-	-	-	0.058	3	2.0
Safety	0.373	2	1.8	151	0.004	7	3.3	2 786	-	-	-	-	0.015	2	2.0
Sensors	0.247	8	2.3	174	0.070	6	2.2	2 903	-	-	-	-	0.029	8	2.7
Pumps/ Motors	0.278	4	1.9	383	0.043	10	2.5	2 322	-	-	-	-	0.025	7	2.5
Heaters/ Coolers	0.190	5	2.3	540	0.007	14	3.0	1 509	-	-	-	-	0.016	5	2.7
Tower/ Foundation	0.092	5	2.6	163	0.089	2	1.4	1 277	-	-	-	-	0.004	6	2.3
Service items	0.108	7	2.2	93	0.001	-	-	1 393	-	-	-	-	0.016	9	2.2
Other components	0.812	5	2.0	128	0.042	21	3.2	2 786	0.001	36	5.0	11 610	0.150	8	2.3

C Wave data for Sørlige Nordsjø II and Utsira Nord

Data analysis of significant wave heights of the two opened areas for development of offshore wind in Norway. The weather data are gathered from the ERA5 database from Copernicus (2023) and consist of data from 1998 to 2022. A smoothed mean of the yearly data sets is displayed in grey.

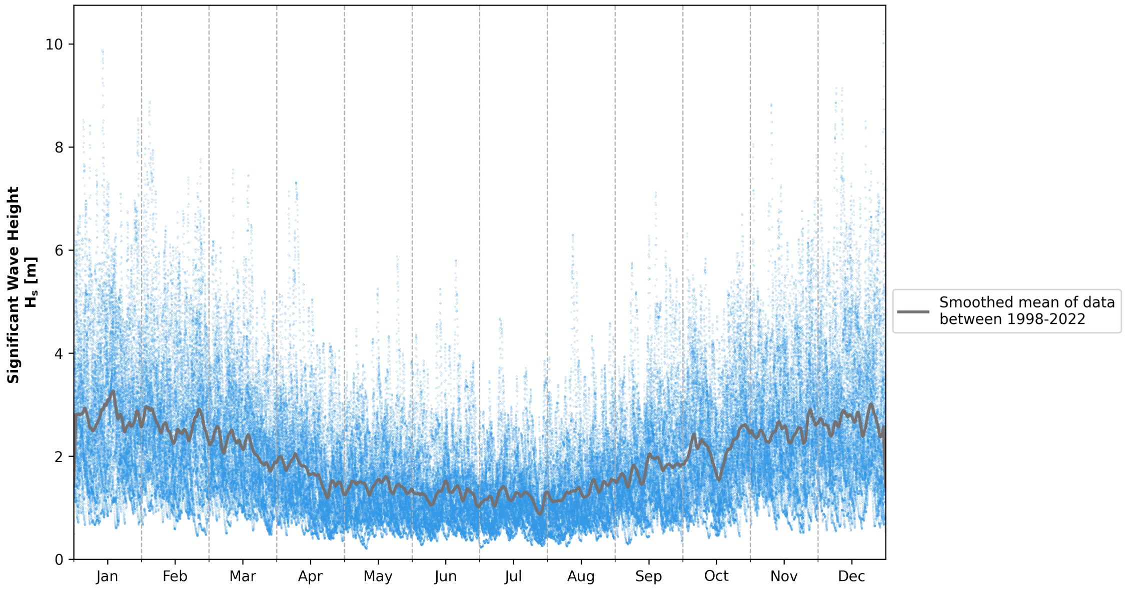
C.1 Sørlige Nordsjø II



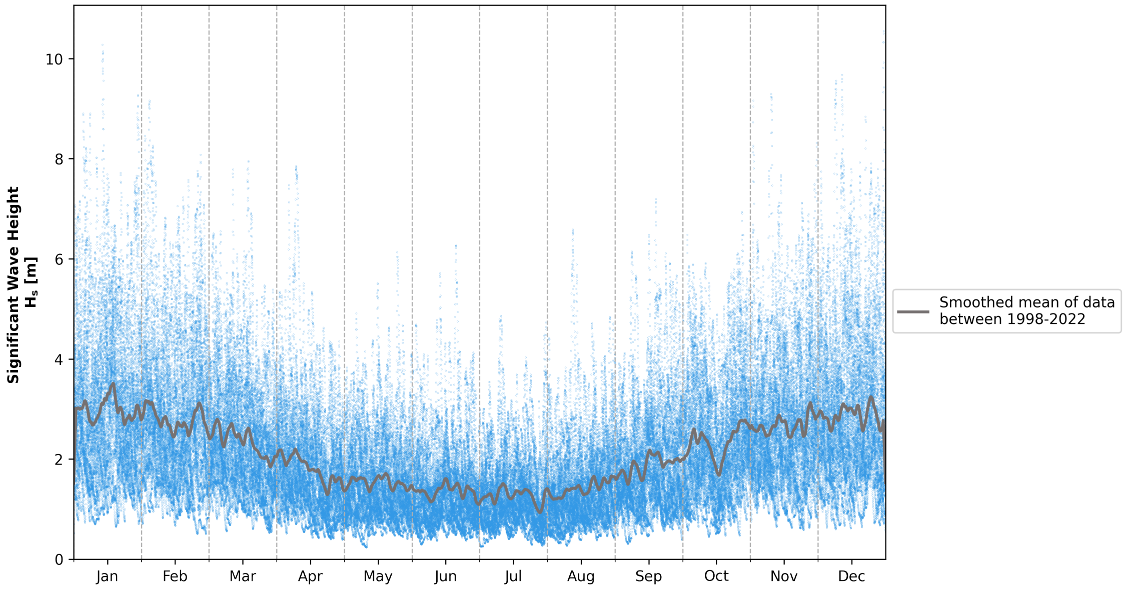


C.2 Utsira Nord

Mean values

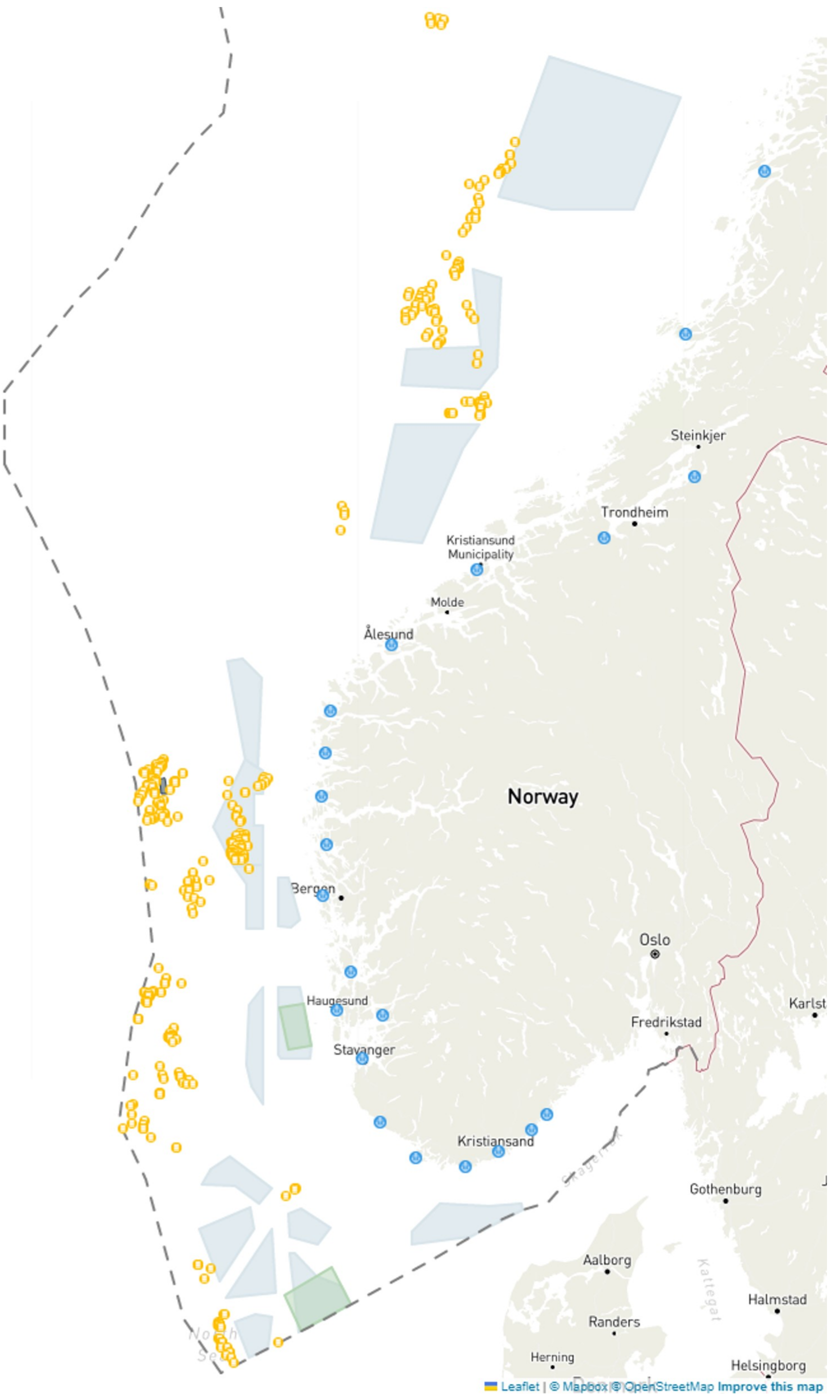


Extreme values



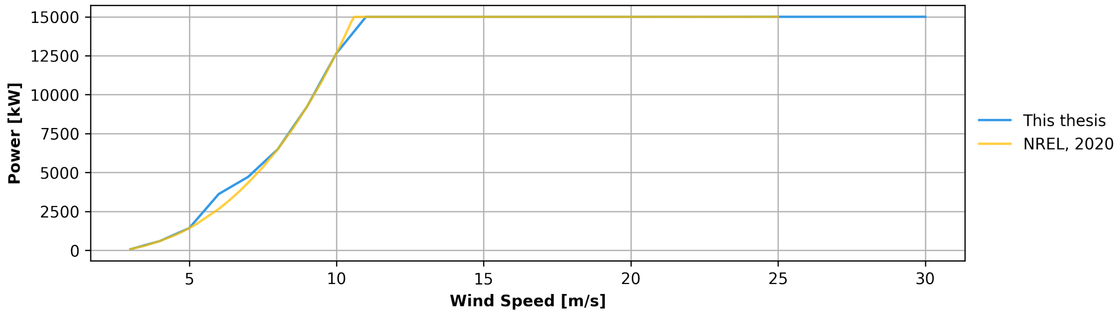
D Map of active oil and gas installations and potential wind farms in the North Sea

A map created for this thesis using data of oil and gas installations gathered from Norwegian Petroleum Directorate (2023). The data of areas for development are gathered from Norwegian Water Resources and Energy Directorate (NVE) (2023) and the EEZ boundaries are gathered from Marineregions.org (2019). The map is accessible through the QR-code or the url https://map-10051.vercel.app/.



E Power curve for 15 MW turbine

The power curve of the IEA Wind 15-MW Turbine (Gaertner et al., 2020) gathered from the study NREL (2020), is displayed below where the values are adjusted to integers for wind speed through interpolation. The graph displays the different power curves compared to one another. The cut-out wind speed is extended from 25 m/s to 30 m/s to be similar to the Vestas V236-15.0 MW turbine (Vestas Wind Systems, 2023).



Wind speed [m/s]	Power [kW]	Power production [% of rated]
3	70	0.47 %
4	595	3.97 %
5	1 429	9.53 %
6	3 615	24.10 %
7	4 719	31.46 %
8	6 481	43.21 %
9	9 229	61.53 %
10	12 661	84.41 %
11	14 994	99.96 %
12	14 995	99.97 %
13	14 995	99.97 %
14	14 995	99.97 %
15	14 995	99.97 %
16	14 995	99.97 %
17	14 995	99.97 %
18	14 995	99.97 %
19	14 995	99.97 %
20	14 995	99.97 %
21	14 997	99.98 %
22	14 997	99.98 %
23	14 997	99.98 %
24	14 999	99.99 %
25	15 000	100.00 %
26	15 000	100.00 %
27	15 000	100.00 %
28	15 000	100.00 %
29	15 000	100.00 %
30	15 000	100.00 %

F Cost calculation of OMB

```python
import numpy as np
"""
m- weight of accommodation[tonnes]
d - depth [m]

x_og - True if repurposing of oil and gas platforms to OMB
x_shared - True if shared foundation between OMB and substation
"""
def additional_cost_omb(m, d, x_og, x_shared):
    if x_og and x_shared or not x_og and not x_shared:
        return 'Wrong input!'
    m_substation_topside = 2500                                  #[tonnes]
    cost_omb = m*(7240*0.5+5000*0.35+2000*0.15)/pow(10,6)    #[mGBP]
    # Weight ratio for bottom-fixed
    k_w_bf = 14286                                               #[GBP/tonne]
    # Weight ratio for floating
    k_w_fl = 37738                                               #[GBP/tonne]
    # Depth ratio for bottom fixed
    depth_ratio = (1+((-181.5291+55.0358*np.log(d))/100))    #[-]
    # Mooring adjusted for depth
    cost_mooring = (2131*d + 1323540)/pow(10,6)               #[mGBP]
    # Bottom-fixed, regression of estimate (Oh et al., 2018)
    if d <= 70:
        cost_foundation_base = (k_w_bf*(m_substation_topside)*depth_ratio)/pow(10,6)
        if x_shared:
            cost_foundation = (k_w_bf*(m_substation_topside+m)*depth_ratio)/pow(10,6)
            return cost_omb + cost_foundation - cost_foundation_base
        else:
            return cost_omb
    # Floating foundation based on Windfloat (Bjerkseter and Agotnes, 2013)
    else:
        cost_floater_base = (k_w_fl*(m_substation_topside))/pow(10,6)
        if x_shared:
            cost_floater = (k_w_fl*(m_substation_topside+m))/pow(10,6)
            return cost_omb + cost_floater + cost_mooring - cost_floater_base
        else:
            return cost_omb
```

G Calculation of error of mean OPEX

```python
import pandas as pd
import numpy as np
from scipy.stats import t

# Read the csv file, with structure: MonteCarloIteration,OPEX_sc1,...,OPEX_scN
df = pd.read_csv('simulation_data.csv', delimiter=';')

# Extract the data for the scenarios
scenario_data = df.iloc[:, 1:].to_numpy()

# Calculate the OPEX error as a percentage of the mean for each scenario
num_iterations, num_scenarios = scenario_data.shape
opex_errors = np.zeros((num_iterations, num_scenarios))
for i in range(num_scenarios):
    scenario_opex = scenario_data[:, i]
    means = []
    stds = []
    for j in range(num_iterations):
        subset = scenario_opex[:j+1]
        mean = subset.mean()
        std = subset.std(ddof=1)
        # Critical t-value for 95% confidence level
        t_value = t.ppf(0.975, j)
        standard_error = t_value * std / np.sqrt(j+1)
        means.append(mean)
        stds.append(100 * standard_error / mean)
    opex_errors[:, i] = np.array(stds)

# Set NaN values to 0
opex_errors = np.nan_to_num(opex_errors, nan=0)

# Store the raw data in a pandas DataFrame
iterations = np.arange(1, num_iterations+1)
scenario_names = ['Scenario {}'.format(i+1) for i in range(num_scenarios)]
data = np.zeros((num_iterations, num_scenarios*2))
data[:, ::2] = opex_errors
data[:, 1::2] = scenario_data
df_raw_data = pd.DataFrame(data, index=iterations, columns=pd.MultiIndex.from_product([scenario_names, ['Error', 'OPEX']]))
```

H Vessel characteristics for simulation

The table below displays the vessel characteristics used for the different simulation scenarios. CTV 1 and CTV 2 are the vessel characteristics used in the code-to-code comparison, while CTV 3 is the characteristics for the simulation of the case study. The SOV and Mother vessel were based upon the VARD 4 12 design (Vard Ship design, 2023), with day rates gathered from Foxwell (2019) adjusted for inflation. Missing values were found by using data from similar vessels from Lloyd's Register of Shipping (2022). Day rates for the tugboat, ATHS and CLV were gathered from various sources such as J. Harrison et al. (2020), and averaged by Bessone et al. (2022). Ulstein Ship design (2023) was used for values for ATHS vessels, while Boskalis (2018) was used for values for the CLV. Vessel characteristics for the jack-up vessel were gathered from Dinwoodie et al. (2015) and Dalgic et al. (2013). The SSCV was modelled after the jack-up vessel with the day rate having a 50% increase. Missing values were interpreted from works of Dinwoodie et al. (2015) together with base values implemented in the Nowicob software.

Vessel name	V_{service} **[kn]**	$f_{c,\text{propulsion}}$ **[l/h]**	$f_{c,\text{auxiliary}}$ **[l/h]**	$n_{\text{personell}}$ **[−]**	$H_{S,\text{max transit}}$ **[m]**	**Access ability**	$H_{S,\text{max access}}$ **[m]**	**Day rate [GBP]**
CTV 1	20	400	50	12	1.75	Yes	1.75	2 258
CTV 2	20	400	50	12	2.50	Yes	1.75	2 258
CTV 3	20	400	50	12	2.50	Yes	2.50	2 258
SOV	13.5	2 000	200	40	5	Yes	3.50	43 200
Mother vessel	13.5	2 000	200	40	5	Yes	3.50	43 200
Daughter craft	20	400	50	12	1.75	Yes	1.75	-
Jack-up vessel	12	3 000	300	100	5	No	-	253 987
SSCV	12	3000	300	100	5	No	-	380 981
Tugboat	12	1500	150	12	5	No	-	25 489
ATHS	17	2 000	200	35	5	No	-	35 902
CLV	11	2 000	200	70	5	No	-	91 109

I Results of Scotwind NE8

I.1 Simulation results

		OMB with CTV $H_{s,max}$ = 1.75 m	OMB with CTV $H_{s,max}$ = 2.50 m	SOV $H_{s,max}$ = 3.50 m
OPEX	[**GBP/kW**]	43.90	65.16	55.24
OPEX error	[%]	4.00	2.72	2.81
Lost income due to downtime	[**GBP/kW**]	111.76	76.48	44.43
Energy produced	[**TWh/year**]	4.51	4.68	4.84
Time availability	[%]	89.84	92.97	95.83
TA error	[%]	0.09	0.07	0.02
Energy availability	[%]	89.04	92.53	95.68
EA error	[%]	0.11	0.07	0.03
Wait time due to weather	[**hours/year**]	39 231	23 888	8 602
Vessel utilisation of CTVs	[**% of all offshore shifts**]	20.40	26.63	-
Vessel utilisation of SOVs	[**% of all working shifts**]	43.80	43.80	51.60
Runtime	[**s**]	52 415	47 731	46 123

Control study

		OMB with CTV $H_{s,max}$ = 1.75 m	OMB with CTV $H_{s,max}$ = 2.50 m	SOV $H_{s,max}$ = 3.50 m
OPEX	[**GBP/kW**]	30.62	30.20	42.38
OPEX error	[%]	4.00	2.72	2.81
Lost income due to downtime	[**GBP/kW**]	111.76	76.48	44.43
Energy produced	[**TWh/year**]	4.51	4.68	4.84
Time availability	[%]	89.84	92.97	95.83
TA error	[%]	0.09	0.07	0.02
Energy availability	[%]	89.04	92.53	95.68
EA error	[%]	0.11	0.07	0.03
Wait time due to weather	[**hours/year**]	39 231	23 888	8 602
Vessel utilisation of CTVs	[**% of all offshore shifts**]	20.40	26.63	-
Vessel utilisation of SOVs	[**% of all working shifts**]	43.80	43.80	51.60
Runtime	[**s**]	52 415	47 731	46 123

I.2 Convergence results

Iteration	OMB with CTV $H_{s,max}$ = 1.75 m		OMB with CTV $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m	
	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]
1	NaN	994	Nan	1 614	Nan	1 287
2	4.89	1 002	19.64	1 665	28.77	1 347
3	21.57	1 156	8.97	1 734	20.26	1 505
4	16.52	902	5.74	1 604	15.14	1 204
5	12.29	1.118	3.88	1 655	10.25	1 363
6	11.25	1 200	2.97	1 673	8.23	1 436
7	9.18	1 121	2.52	1 620	6.64	1 386
8	7.74	1 115	3.71	1 485	5.56	1 373
9	7.07	984	3.19	1 633	5.03	1 285
10	6.31	1 020	3.38	1 498	4.42	1 349
11	5.62	1 070	3.41	1 749	3.94	1 354
12	5.19	1 003	3.17	1 565	3.59	1 317
13	4.76	1 030	3.28	1 781	3.37	1 288
14	5.03	1 234	3.02	1 613	3.17	1 410
15	4.65	1 087	2.88	1 561	2.98	1 304
16	4.43	1 155	2.68	1 619	2.91	1 441
17	4.45	1 223	2.50	1 629	2.95	1 482
18	4.37	1 210	3.03	1 369	3.03	1 508
19	4.11	1 107	2.88	1 565	2.88	1 422
20	4.00	1 001	2.72	1 622	2.81	1 284

Average O&M cost	1 086 539 653 GBP	1 612 690 358 GBP	1 367 133 151 GBP

I.3 Convergence results for reference cases

Iteration	OMB with CTV $H_{s,max}$ = 1.75 m		OMB with CTV $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m	
	Error [%]	**O&M Costs [10^6 GBP]**	**Error [%]**	**O&M Costs [10^6 GBP]**	**Error [%]**	**O&M Costs [10^6 GBP]**
1	NaN	710	NaN	710	NaN	1 003
2	2.24	712	58.54	779	32.96	1 056
3	9.67	760	11.90	763	6.54	1 038
4	5.38	745	6.22	752	3.64	1 049
5	7.58	822	4.28	741	2.55	1 025
6	6.26	797	3.52	774	2.53	1 074
7	5.17	785	4.37	827	2.16	1 063
8	4.36	749	3.78	741	2.17	1 087
9	3.75	757	3.44	729	2.42	1 114
10	3.29	760	3.02	752	2.45	1 001
11	3.07	795	2.75	738	2.41	1 106
12	2.80	783	2.67	716	2.43	995
13	2.72	809	2.43	751	2.28	1 019
14	2.50	774	2.44	802	2.10	1 065
15	2.37	741	2.51	698	1.95	1 065
16	2.22	783	2.34	764	1.96	993
17	2.28	710	2.20	762	1.83	1 045
18	2.14	771	2.08	737	1.72	1 050
19	2.40	676	2.26	676	1.67	1 086
20	2.35	717	2.15	734	1.58	1 042

Average O&M cost	757 874 053 GBP	747 363 798 GBP	1 048 834 835 GBP

J Results of Sørlige Nordsjø II

J.1 Simulation results

ERA5				
		OMB (Substation) $H_{s,max}$ **= 2.50 m**	**SOV** $H_{s,max}$ **= 3.50 m**	**OMB (O&G Platform)** $H_{s,max}$ **= 2.50 m**
O&M Cost	**[GBP/kW]**	67.94	72.75	68.54
O&M Cost error	[%]	0.41	0.44	0.30
Lost income due to downtime	**[GBP/kW]**	14.09	12.66	14.77
Energy produced	[**TWh/year**]	7.296	7.321	7.285
Time availability	[%]	96.91	97.22	96.70
TA error	[%]	0.01	0.00	0.01
Energy availability	[%]	96.84	97.16	96.69
EA error	[%]	0.01	0.01	0.01
Wait time due to weather	[**hours/year**]	4 982	1 642	5 102
Runtime	[**s**]	60 696	54 179	63 324
NORA3				
		OMB (Substation) $H_{s,max}$ **= 2.50 m**	**SOV** $H_{s,max}$ **= 3.50 m**	**OMB (O&G Platform)** $H_{s,max}$ **= 2.50 m**
OPEX	**[GBP/kW]**	68.27	72.64	68.52
OPEX error	[%]	0.33	0.34	0.41
Lost income due to downtime	**[GBP/kW]**	14.77	13.59	15.59
Energy produced	[**TWh/year**]	7.479	7.498	7.465
Time availability	[%]	96.83	97.12	96.59
TA error	[%]	0.01	0.01	0.01
Energy availability	[%]	96.77	97.03	96.59
EA error	[%]	0.01	0.01	0.01
Wait time due to weather	[**hours/year**]	5 663	2 257	5 911
Runtime	[**s**]	60 709	57 812	63 981

J.2 Convergence results for ERA5

Iteration	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		OMB (O&G Platform) $H_{s,max}$ = 2.50 m	
	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]
1	NaN	2 550	NaN	2722	NaN	2566
2	3.38	2 564	6.48	2 750	0.46	2 568
3	0.86	2 547	1.82	2 712	0.13	2 568
4	1.48	2 509	1.62	2 683	1.14	2 604
5	1.04	2 529	1.12	2 727	0.77	2 574
6	0.80	2 547	0.84	2 717	0.64	2 561
7	0.65	2 532	0.69	2 727	0.52	2 578
8	0.70	2 577	0.58	2 713	0.50	2 552
9	0.64	2 568	0.52	2 706	0.49	2 548
10	0.61	2 573	0.52	2 748	0.43	2 572
11	0.55	2 555	0.46	2 714	0.39	2 564
12	0.51	2 530	0.47	2 753	0.35	2 565
13	0.47	2 556	0.44	2 740	0.32	2 567
14	0.43	2 545	0.47	2 767	0.30	2 580
15	0.41	2 530	0.44	2 741	0.30	2 587

Average O&M cost	2 547 596 000 GBP	2 728 045 667 GBP	2 570 244 933 GBP

J.3 Convergence results for NORA3

Iteration	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		OMB (O&G Platform) $H_{s,max}$ = 2.50 m	
	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]
1	NaN	2 549	NaN	2 727	NaN	2564
2	2.18	2 558	1.32	2 733	7.30	2 594
3	0.64	2 562	0.92	2 713	1.65	2 565
4	0.94	2 585	0.96	2 696	0.95	2 561
5	0.78	2 542	0.88	2 746	0.64	2 571
6	0.59	2 562	0.67	2 718	0.99	2 520
7	0.74	2 601	0.58	2 740	0.80	2 557
8	0.69	2 539	0.49	2 728	0.71	2 582
9	0.59	2 561	0.46	2 706	0.65	2 586
10	0.53	2 549	0.47	2 753	0.58	2 554
11	0.48	2 553	0.43	2 715	0.52	2 576
12	0.43	2 562	0.39	2 719	0.50	2 592
13	0.39	2 560	0.37	2 742	0.46	2 572
14	0.36	2 560	0.36	2 704	0.44	2 587
15	0.33	2 558	0.34	2 719	0.41	2 562

Average O&M cost	2 560 262 733 GBP	2 723 975 333 GBP	2 569 613 867 GBP

K Results of Sørvest B

K.1 Simulation results

ERA5				
		OMB (Substation) $H_{s,max}$ **= 2.50 m**	**SOV** $H_{s,max}$ **= 3.50 m**	**OMB (O&G Platform)** $H_{s,max}$ **= 2.50 m**
O&M Cost	**[GBP/kW]**	68.04	72.71	68.19
O&M Cost error	[%]	0.42	0.32	0.33
Lost income due to downtime	**[GBP/kW]**	14.39	12.58	14.66
Energy produced	[**TWh/year**]	7.032	7.063	7.028
Time availability	[%]	96.76	97.15	96.68
TA error	[%]	0.02	0.01	0.01
Energy availability	[%]	96.66	97.08	96.60
EA error	[%]	0.02	0.01	0.01
Wait time due to weather	[**hours/year**]	6 307	2 125	6 402
Runtime	[**s**]	61 799	54 665	63 690

NORA3				
		OMB (Substation) $H_{s,max}$ **= 2.50 m**	**SOV** $H_{s,max}$ **= 3.50 m**	**OMB (O&G Platform)** $H_{s,max}$ **= 2.50 m**
O&M Cost	**[GBP/kW]**	68.13	72.92	68.15
O&M Cost error	[%]	0.35	0.42	0.33
Lost income due to downtime	**[GBP/kW]**	15.09	13.54	15.28
Energy produced	[**TWh/year**]	7.318	7.345	7.315
Time availability	[%]	96.68	97.07	96.62
TA error	[%]	0.02	0.01	0.02
Energy availability	[%]	96.63	96.99	96.59
EA error	[%]	0.02	0.01	0.01
Wait time due to weather	[**hours/year**]	6 797	2 717	6 822
Runtime	[**s**]	61 898	55 462	60 251

K.2 Convergence results for ERA5

Iteration	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		OMB (O&G Platform) $H_{s,max}$ = 2.50 m	
	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]
1	NaN	2 552	NaN	2 726	NaN	2 558
2	3.18	2 565	4.17	2 744	1.42	2 564
3	0.84	2 548	1.23	2 718	1.33	2 538
4	0.67	2 539	0.74	2 742	0.84	2 539
5	0.46	2 555	0.73	2 707	0.78	2 575
6	0.39	2 563	0.55	2 728	0.62	2 567
7	0.55	2 521	0.44	2 728	0.59	2 535
8	0.47	2 554	0.40	2 741	0.49	2 551
9	0.41	2 541	0.38	2 712	0.46	2 537
10	0.39	2 566	0.33	2 730	0.40	2 554
11	0.39	2 571	0.35	2 702	0.36	2 557
12	0.36	2 565	0.32	2 723	0.35	2 569
13	0.39	2 522	0.29	2 727	0.37	2 584
14	0.38	2 573	0.28	2 711	0.34	2 557
15	0.42	2 593	0.32	2 761	0.33	2 571

Average O&M cost	2 555 168 533 GBP	2 726 653 600 GBP	2 557 109 467 GBP

K.3 Convergence results for NORA3

Iteration	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		OMB (O&G Platform) $H_{s,max}$ = 2.50 m	
	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]
1	NaN	2 556	NaN	2 727	NaN	2 558
2	2.67	2 567	5.26	2 750	2.56	2 568
3	0.93	2 575	1.75	2 712	1.08	2 546
4	0.78	2 546	0.91	2 730	0.61	2 565
5	0.86	2 530	0.62	2 734	0.42	2 563
6	0.73	2 535	0.83	2 687	0.37	2 548
7	0.60	2 561	0.68	2 714	0.32	2 566
8	0.52	2 563	0.62	2 746	0.33	2 543
9	0.45	2 563	0.61	2 757	0.36	2 535
10	0.41	2 567	0.58	2 755	0.32	2 549
11	0.40	2 536	0.52	2 739	0.33	2 576
12	0.36	2 563	0.47	2 734	0.30	2 552
13	0.36	2 536	0.49	2 772	0.28	2 554
14	0.37	2 582	0.45	2 728	0.31	2 585
15	0.35	2 544	0.42	2 731	0.33	2 528

Average O&M cost	2 554 989 800 GBP	2 734 340 867 GBP	2 555 623 800 GBP

L Results of Utsira N

L.1 Simulation results

ERA5				
		OMB with CTV $H_{s,max}$ **= 2.50 m**	**SOV** $H_{s,max}$ **= 3.50 m**	**SOV with SSCV** $H_{s,max}$ **= 3.50 m**
O&M Cost	**[GBP/kW]**	44.51	58.25	137.05
O&M Cost error	[**%**]	0.80	0.57	0.38
Lost income due to downtime	[**GBP/kW**]	13.51	11.47	11.48
Energy produced	[**TWh/year**]	3.253	3.270	3.270
Time availability	[**%**]	96.74	97.19	97.19
TA error	[**%**]	0.01	0.01	0.01
Energy availability	[**%**]	96.61	97.12	97.12
EA error	[**%**]	0.01	0.01	0.02
Wait time due to weather	[**hours/year**]	3 182	1 080	1 069
Runtime	[**s**]	25 692	13 340	16 238

NORA3				
		OMB with CTV $H_{s,max}$ **= 2.50 m**	**SOV** $H_{s,max}$ **= 3.50 m**	**SOV with SSCV** $H_{s,max}$ **= 3.50 m**
O&M Cost	**[GBP/kW]**	46.74	60.46	136.41
O&M Cost error	[**%**]	1.23	1.03	0.27
Lost income due to downtime	[**GBP/kW**]	15.79	12.97	12.89
Energy produced	[**TWh/year**]	3.403	3.427	3.428
Time availability	[**%**]	96.23	97.00	97.02
TA error	[**%**]	0.02	0.01	0.01
Energy availability	[**%**]	96.23	96.91	96.63
EA error	[**%**]	0.02	0.02	0.01
Wait time due to weather	[**hours/year**]	4 565	1 764	1 680
Runtime	[**s**]	25 798	13 496	16 270

L.2 Convergence results for ERA5

	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		SOV with SSCV $H_{s,max}$ = 3.50 m	
Iteration	**Error [%]**	**O&M Costs [10^6 GBP]**	**Error [%]**	**O&M Costs [10^6 GBP]**	**Error [%]**	**O&M Costs [10^6 GBP]**
1	NaN	840	NaN	1 098	NaN	2 593
2	5.27	847	1.23	1 095	13.67	2 538
3	3.82	822	0.47	1 094	3.08	2 593
4	2.06	831	0.41	1 100	1.65	2 564
5	1.61	847	1.09	1 118	1.29	2 603
6	1.22	835	0.86	1 095	0.98	2 578
7	1.12	824	0.85	1 084	0.90	2 546
8	1.27	811	0.79	1 085	0.77	2 560
9	1.10	836	0.96	1 067	0.66	2 568
10	1.11	853	0.85	1 098	0.58	2 573
11	0.99	836	0.76	1 095	0.52	2 567
12	0.93	822	0.69	1 087	0.48	2 559
13	0.86	826	0.67	1 078	0.44	2 576
14	0.79	834	0.62	1 095	0.41	2 561
15	0.80	852	0.57	1 094	0.38	2 567
Average O&M cost	834 499 987 GBP		1 092 190 933 GBP		2 569 597 067 GBP	

L.3 Convergence results for NORA3

	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		SOV with SSCV $H_{s,max}$ = 3.50 m	
Iteration	**Error [%]**	**O&M Costs [10^6 GBP]**	**Error [%]**	**O&M Costs [10^6 GBP]**	**Error [%]**	**O&M Costs [10^6 GBP]**
1	NaN	873	NaN	1 131	NaN	2 579
2	17.83	898	14.24	1 157	3.67	2 565
3	4.85	865	3.60	1 126	1.24	2 554
4	2.79	866	1.95	1 131	0.71	2 557
5	3.06	914	1.41	1 126	0.49	2 559
6	2.51	864	1.17	1 121	0.42	2 550
7	2.03	887	0.94	1 130	0.38	2 549
8	2.17	842	0.79	1 134	0.32	2 556
9	2.09	845	0.83	1 111	0.28	2 566
10	1.85	882	0.79	1 145	0.29	2 543
11	1.68	889	0.72	1 123	0.26	2 558
12	1.52	883	1.02	1 180	0.24	2 552
13	1.43	894	1.05	1 168	0.25	2 538
14	1.33	866	1.11	1 097	0.29	2 586
15	1.23	875	1.03	1 124	0.27	2 553
Average O&M cost	876 332 808 GBP		1 133 658 667 GBP		2 557 612 067 GBP	

M Results of Nordvest B

M.1 Simulation results

ERA5					
		OMB (Substation) $H_{s,max} = 2.50$ **m**	**SOV** $H_{s,max} = 3.50$ **m**	**OMB (O&G Platform)** $H_{s,max} = 2.50$ **m**	**SOV with SSCV** $H_{s,max} = 3.50$ **m**
O&M Cost	**[GBP/kW]**	51.45	65.73	53.90	134.20
O&M Cost error	[**%**]	1.94	1.25	1.57	0.26
Lost income due to downtime	**[GBP/kW]**	22.01	13.08	22.33	13.11
Energy produced	[**TWh/year**]	3.082	3.158	3.080	3.158
Time availability	[**%**]	94.78	96.80	94.71	96.80
TA error	[**%**]	0.06	0.01	0.05	0.02
Energy availability	[**%**]	94.34	96.65	94.27	96.64
EA error	[**%**]	0.08	0.02	0.08	0.03
Wait time due to weather	[**hours/year**]	11 544	2 606	11 680	2 609
Runtime	[**s**]	25 301	11 669	25 048	14 571

NORA3					
		OMB (Substation) $H_{s,max} = 2.50$ **m**	**SOV** $H_{s,max} = 3.50$ **m**	**OMB (O&G Platform)** $H_{s,max} = 2.50$ **m**	**SOV with SSCV** $H_{s,max} = 3.50$ **m**
O&M Cost	**[GBP/kW]**	53.58	69.91	58.68	135.38
O&M Cost error	[**%**]	1.69	1.32	1.61	0.28
Lost income due to downtime	**[GBP/kW]**	20.69	13.54	20.72	13.60
Energy produced	[**TWh/year**]	3.138	3.197	3.138	3.197
Time availability	[**%**]	95.12	96.72	95.12	96.72
TA error	[**%**]	0.04	0.02	0.04	0.01
Energy availability	[**%**]	94.77	96.56	94.78	96.55
EA error	[**%**]	0.05	0.03	0.06	0.03
Wait time due to weather	[**hours/year**]	10 030	2 907	9 921	2 901
Runtime	[**s**]	25 374	12 858	25 093	16 849

M.2 Convergence results for ERA5

Iteration	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		OMB (O&G Platform) $H_{s,max}$ = 2.50 m		SOV with SSCV $H_{s,max}$ = 3.50 m	
	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]
1	NaN	958	NaN	1 220	NaN	1 008	NaN	2529
2	2.45	961	19.93	1 259	1.16	1 010	5.57	2 507
3	4.96	927	3.92	1 236	4.55	978	1.38	2 533
4	3.66	980	2.60	1 214	4.15	1 042	0.74	2 528
5	2.74	977	1.77	1 238	2.90	1 024	0.59	2 510
6	2.08	956	2.13	1 186	2.62	979	0.44	2 522
7	2.52	1 012	2.17	1 273	2.49	1 046	0.36	2 523
8	2.86	1 032	2.04	1 272	2.21	1 038	0.30	2 518
9	2.50	959	1.76	1 231	1.93	1 003	0.27	2 530
10	2.30	1 004	1.71	1 278	2.07	1 069	0.24	2 520
11	2.08	961	1.53	1 238	1.84	1 018	0.22	2 516
12	1.88	970	1.50	1 201	1.87	973	0.24	2 503
13	2.10	905	1.38	1 224	1.78	986	0.30	2 490
14	2.00	937	1.30	1 212	1.65	998	0.28	2 506
15	1.94	928	1.25	1 206	1.57	986	0.26	2 509
Average O&M cost	964 601 660 GBP		1 232 508 867 GBP		1 010 643 127 GBP		2 516 259 600 GBP	

M.3 Convergence results for NORA3

Iteration	OMB (Substation) $H_{s,max}$ = 2.50 m		SOV $H_{s,max}$ = 3.50 m		OMB (O&G Platform) $H_{s,max}$ = 2.50 m		SOV with SSCV $H_{s,max}$ = 3.50 m	
	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]	Error [%]	O&M Costs [10^6 GBP]
1	NaN	1 059	NaN	1 323	NaN	1 110	NaN	2 550
2	2.89	1 064	22.17	1 370	1.26	1 108	2.76	2 539
3	3.05	1 040	4.66	1 331	1.51	1 098	0.78	2 535
4	2.76	1 025	2.80	1 319	1.23	1 092	0.50	2 551
5	1.90	1 055	2.09	1 314	1.81	1 134	0.63	2 520
6	1.89	1 079	1.60	1 326	1.38	1 105	0.54	2 554
7	1.85	1 086	1.28	1 333	1.82	1 154	0.47	2 528
8	1.92	1 018	1.71	1 272	1.56	1 102	0.42	2 528
9	2.02	1 006	1.48	1 316	1.59	1 077	0.36	2 538
10	2.04	1 002	1.80	1 250	1.77	1 056	0.32	2 537
11	1.82	1 041	1.67	1 285	1.63	1 082	0.28	2 536
12	1.64	1 045	1.56	1 287	1.48	1 114	0.28	2 523
13	1.76	987	1.48	1 277	1.74	1 032	0.31	2 564
14	1.78	1 091	1.43	1 347	1.73	1 147	0.30	2 525
15	1.69	1 072	1.32	1 315	1.61	1 094	0.28	2 547
Average O&M cost	1 044 577 640 GBP		1 310 972 133 GBP		1 100 316 533 GBP		2 538 317 400 GBP	

NTNU
Norwegian University of
Science and Technology