DELFT UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering, Mathematics & Computer Science
MSc Sustainable Energy Technology

Master Thesis Project

Techno-economic analysis of the installation and O&M of far-offshore floating wind turbines

Author:
Apostolos Reppas (5382939)

Thesis Committee:
Associate Professor Dr.Ir. Axelle Viré (Chairman and Supervisor)
Assistant Professor Dr.Ir. Antonio Jarquin Laguna (Committee)
Ir. Matteo Baudino Bessone (Daily Supervisor)

September 9, 2022

Delft University of Technology

Preface

This report was written as fulfillment of my thesis project in order to obtain the MSc Sustainable Energy Technology offered at Delft University of Technology (TU Delft). Over the course of the project, I enriched my knowledge on offshore wind industry and its opportunities and limitations, as far as its implementation is concerned.

I would like to thank my supervisor, Axelle Viré, for giving me the opportunity to work on such an interesting topic and for guiding me during its execution.

I would also want to express my regards to Matteo Baudino Bessone for his daily guidance and extensive feedback throughout this project. The knowledge and information I obtained from him during our weekly meetings were vital for the completion of this project and for my future career endeavours.

Moreover, I feel the need to express my gratitude to my family for their unconditional support throughout the years. Finally, cheers to all my friends, either in close geographical proximity or not, who played a vital role in keeping a healthy work-life balance throughout the past two years.

Summary

In 2015, 196 countries signed the Paris Agreement as an organised effort to mitigate the adverse effects of climate change. Ever since, renewable forms of energy, and especially wind energy, have become an integral part of the energy infrastructure around the globe. However, the constant increase of installed wind capacity has put a strain on the selection of potential onshore locations for wind turbine installation. As a result, the wind industry is focusing on offshore applications, mainly with the use of bottom-fixed sub-structures. Nevertheless, research community has started shifting their interest in floating wind turbine designs to harvest the abundant wind potential of far-offshore locations, sited in water depths where monopiles and jacket sub-structures are not economically feasible. Despite the progress on the design of such floating units, there is still no consensus upon their optimum installation and maintenance strategies, activities which comprise one third of the lifetime cost of a floating wind farm.

The aim of this research is to gain understanding on the optimum installation and maintenance strategies for semi-submersible and spar buoy floating units based on their cost and duration. Towards this direction, four different installation strategies are investigated: semi-submersible installation with wind turbine assembly at quayside, semi-submersible installation with wind turbine assembly at wind farm site, spar buoy installation with wind turbine - spar buoy assembly in a single lift with a Heavy Lift Vessel (HLV) and spar buoy installation with wind turbine assembly on the spar buoy with multiple lifts with a crane barge. Furthermore, based on the type of the required maintenance activities, the onsite minor and major repairs of wind turbines with the use of a Crew Transfer Vessel (CTV) or a Walk-to-Work vessel (W2W) are examined, as well as the onsite or offsite replacement of major wind turbine components for wind turbines installed on both semi-submersible and spar buoy floating sub-structures. In the context of this thesis, a deterministic installation and Operation and Maintenance (O&M) model was developed. This model relies on various input data, including weather time series for near-shore and far-offshore locations, vessels and facilities costs, personnel and components costs as well as an electricity price for the calculation of the lost revenue due to downtime.

The analysis of the installation and maintenance strategies is based both on a base case scenario and a sensitivity analysis of the main factors influencing the cost and duration of offshore activities: distance from shore/port and weather limits of activities. The results show that semi-submersible installation with wind turbine assembly at quayside is the most cost-effective and fastest of all implemented strategies, followed by the spar buoy installation with HLV. The spar buoy installation with a crane barge and the semi-submersible installation with wind turbine assembly at wind farm site are characterised by higher installation cost and duration, due to the increased number of trips and the adverse weather conditions at site, respectively. Furthermore, the use of a CTV for onsite repairs is more cost-effective, albeit slower, approach than the W2W one, for all examined distances and weather limits. Finally, the offsite major replacement strategy for semi-submersibles is the most cost-effective of the examined strategies. No definitive conclusion can be drawn on the best major component replacement strategy for spar buoys, as the cost difference between the onsite and offsite approach is small. When the cost difference of different installation and maintenance strategies is low, the final choice depends on the volatile vessel rates and the electricity market prices.

Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
AHV	Anchor Handling Vessel
CAPEX	Capital Expenditure
CLV	Cable Laying Vessel
CTV	Crew Transfer Vessel
DC	Direct Current
EEZ	Exclusive Economic Zone
EU	European Union
HLV	Heavy Lift Vessel
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
LCOE	Levelised Cost of Energy
O&M	Operation and Maintenance
PEM	Proton Exchange Membrane
ROV	Remotely Operated Vehicle
TLP	Tension Leg Platform
W2W	Walk-to-Work vessel

1 | Introduction

In this Chapter, the current development trends of the wind industry are introduced, leading to the formulation of the research questions for this thesis. The structure of this Chapter follows; section 1.1 provides an overview of the current wind energy industry trends, section 1.2 gives an overview of the main components within floating wind farms, section 1.3 introduces the installation and O&M of floating wind farms, and section 1.4 presents the main research question and sub-questions of this thesis.

1.1 Background

In 2015, 196 countries signed the Paris Agreement as an organised effort to mitigate the adverse effects of climate change [1]. Ever since, the integration of renewable energy technologies in the current energy mix has increased in a fast rate around the globe, with wind turbines being one of the most mature renewable technologies. In 2015, the cumulative installed wind capacity was 433 GW, while in 2020, it increased up to 743 GW [2]. This trend of new wind installations is expected to continue in the following years, with a total new installed capacity of 469 GW forecast for the next five years. In 2019, wind energy accounted for 5.3% of the global electricity production and 20.3% of the global renewable electricity production, when also accounting for hydroelectric power among the renewable electricity sources [3].

The constant increase of installed wind capacity has made the selection of potential onshore locations for wind turbine installation a more difficult procedure. This is mainly due to wind farms' visual and acoustic constraints near populated areas, as well as the need to preserve and protect areas of high natural significance [4]. All these reasons, together with the high wind potential of offshore sites, have pushed the research towards offshore installations. Offshore sites are characterised by higher average wind speeds and lower turbulence, which result in higher energy yields and lower fatigue for the wind turbines, respectively [4]. In addition, larger wind turbines can be deployed, since sea transportation imposes less stringent restrictions on the turbine size.

Nevertheless, offshore wind energy has also various disadvantages compared to onshore installations. Marine environments are harsh and wind turbines have to withstand high wind speeds and also wave loading. Furthermore, due to distance from shore and harsh weather conditions, installation and O&M phases of offshore wind farms are characterised by restricted weather windows, resulting in longer downtime, lower availability and higher cost. Moreover, installation and O&M of offshore wind turbines require the deployment of specialised vessels and equipment compared to onshore ones, resulting in higher installation and O&M costs [4].

From 2015 until 2020, offshore wind installations increased by almost 200%, from 12 GW to 35.3 GW [2]. This trend is expected to remain, with 70 GW of offshore wind projected to be installed in the next five years [2]. European countries have been the pioneers towards harvesting offshore wind, as almost 70% of total installed offshore wind capacity is found in Europe. China has also invested in offshore wind, with a total share of 28%, while the rest of the installations are scattered around the globe [2]. From the current and future installations, it is apparent that offshore wind will take a larger share in the energy mix. Offshore commercial projects have predominantly focused on bottom-fixed solutions in shallow waters near shore. Most offshore wind farms implement monopile and jacket sub-structures, which are currently economically viable for depths up to 60 m [5].

For water depths greater than 60 m, floating sub-structures emerge as the most economically viable option, as bottom-fixed solutions would require extra production costs and higher structural properties [6]. The load handling capabilities of the mooring lines of the floating units are most effective between 80-150 m depth [6]. It is worth mentioning that bottom-fixed solutions might also not be feasible in shallow waters as well, depending on the sea-bed conditions, which might hinder such an installation. In this case, floating wind can also emerge as an ideal candidate to harvest the wind potential at these sites. However, when both solutions are feasible in such depths, the Capital Expenditure (CAPEX) of floating wind farms is expected to be around 15% higher than the bottom-fixed ones, mainly due to the requirement of mooring and anchoring systems as well as dynamic electrical cables [6]. This cost advantage of bottom-fixed solutions ceases to exist at water depths greater than 60 m, as aforementioned. In general, the integration of floating wind farms is highly facilitated if the following conditions apply in the site of interest: high wind potential, adequate water depths, proximity to ports and population centres, grid infrastructure and renewable incentives [7]. According to projections, floating wind could cover around 5% to 15% of the total offshore installations by 2050 [5].

It should be noted, however, that the high capital costs of floating wind farms might hinder their development, even if there is considerable Levelised Cost of Energy (LCOE) reduction potential [8]. Therefore, policy support for the development of floating wind is essential for its cost reduction and increased competitiveness [4, 6]. Through such financial support, high volume production, development of supply chains and learning-by-doing can result into cost reduction and increase of installed capacity.

As aforementioned, far-offshore locations are ideal for achieving high capacity factors with larger wind turbines. Offshore wind farms are connected to the onshore substation with export cables, which directly transmit electricity to the grid. Nevertheless, challenges may arise due to the wind farm's intermittent, non-dispatchable electricity output. This volatility puts an extra strain on the constant balance between electricity supply and demand, a prerequisite for the smooth operation of the electricity sector. In addition, further strengthening of the electricity grid, possibly in remote areas, is needed to integrate offshore wind farms [9].

These challenges can be alleviated by coupling hydrogen production, through the addition of an electrolyser, with the offshore wind farm. The produced green hydrogen could act as a storage mechanism, which could be exploited in cases of low wind availability and thus contribute to the balance of the grid. Moreover, a far-offshore wind farm could solely produce hydrogen which could be further utilised upon request for different energy requirements, like heating, transport, or onshore electricity production when the demand is high [9]. Acknowledging all these benefits, European Union (EU) has proposed an ambitious plan to install 40 GW of electrolysers in EU countries by 2030. Furthermore, EU aims to support the construction of another 40 GW of electrolysers in neighbouring countries to import the produced hydrogen [10].

1.2 Floating wind farm components

Floating wind farms consist of different main subsystems: the wind turbine, the floating sub-structure, the anchoring and mooring system and the electrical Balance of Plant. If the wind farm is partially or totally dedicated to the production of hydrogen, the installation of additional components is essential, including electrolysers, desalination and compression units. These subsystems are introduced in this section in the following structure; wind turbines for floating applications are presented in subsection 1.2.1, characteristics of floating sub-structures are introduced in subsection 1.2.2 and the main anchoring and mooring systems are presented in section 1.2.3. Finally, information about the electrical balance of plant and hydrogen production components of floating wind is presented in subsections 1.2.4 and 1.2.5, respectively.

1.2.1 Floating wind turbines

As aforementioned, large wind turbines can be introduced in offshore applications as there are lower constraints for their transportation. Typical are the examples of the Hywind Tampen spar-buoy-based floating wind farm, which will comprise 11 wind turbines with a nominal capacity of 8.6 MW each [11], and of the Kincardine semi-submersible-based floating wind farm, which comprises five wind turbines with a nominal capacity of 9.5 MW each, as well as a 2 MW wind turbine [12]. To match the trend that sees offshore wind turbines become larger and larger, International Energy Agency (IEA) has proposed a reference wind turbine of 15 MW nominal power output [13]. This reference wind turbine is a Class IB direct-drive turbine, with a rotor diameter of 240 m and a hub height of 150 m. In general, direct-drive wind turbine generators are characterised by several advantages compared to the geared drivetrains, including lower complexity, fewer parts, higher reliability and additional flexibility in designing, characteristics of high importance for far-offshore applications, where the accessibility of the structure is reduced due to the harsh weather conditions.

1.2.2 Floating sub-structures

Despite the novelty of floating wind farms, various types of sub-structures have already been developed. Typical floating support structures are the spar buoy, semi-submersible, and Tension Leg Platform (TLP), as it is shown in Figure 1.1. Hybrid designs combining the advantages of different concepts are also under development (e.g. GICON or TetraSpar). Semi-submersibles mainly maintain their stability through displaced buoyancy, spar buoys through a gravity-based righting moment and TLPs through tensioned mooring lines [6]. The main characteristics of these three types of sub-structures follow [6, 14]:

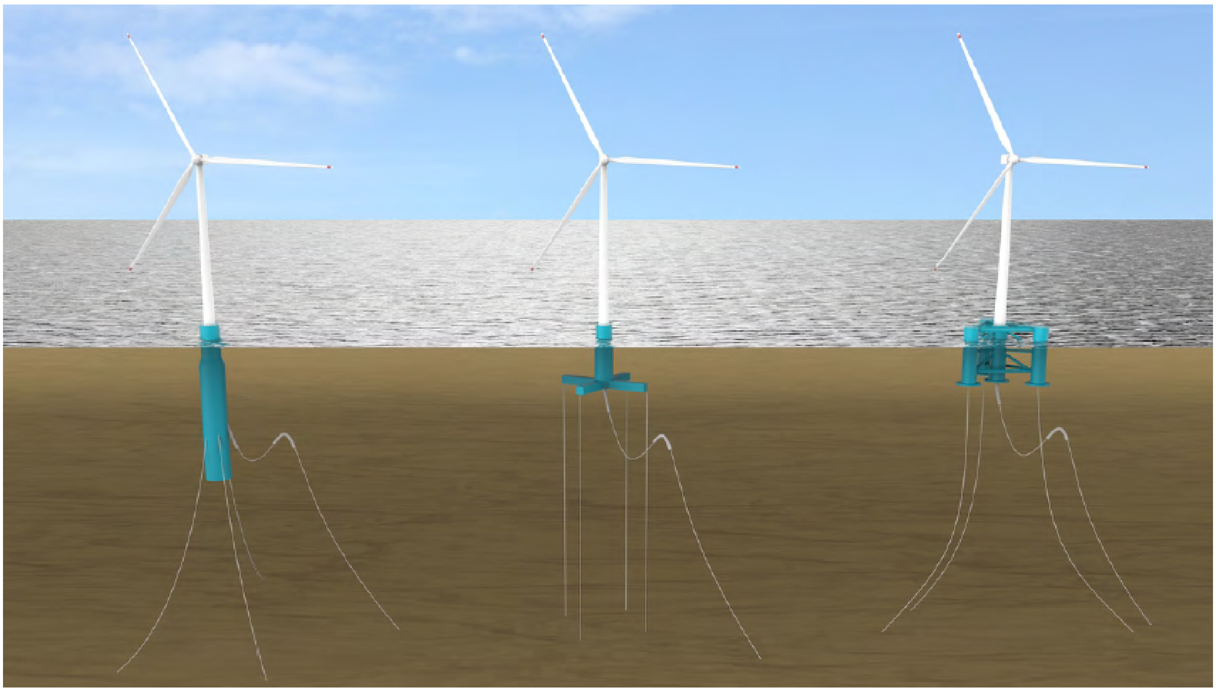


Figure 1.1: Schematic overview of the most common floating sub-structure concepts. From left to right: spar buoy, TLP, semi-submersible [15].

- The ballasted mass of a semi-submersible, designed to support a 15 MW wind turbine, is in the order of 30,000 tons. Semi-submersibles are characterised by low draft which simplifies towing operations. The outer columns can be filled with sea water to reach the operational draft at site. Due to their buoyant and stable structure, they are able to withstand increased wave loading and offer a lively dynamic performance of the whole structure. Semi-submersibles are supposed to perform better for applications in water depths around 30-300 m.

- The ballasted mass of a spar buoy, designed to support a 15 MW wind turbine, is in the order of 40,000 tons. Due to their high draft, spar buoys are ideal for locations with water depths above 100 m and moderate wave loads and gusts.
- The dry mass of a TLP, designed to support a 15 MW wind turbine, is in the order of 5,000 tons and no ballast is required, resulting in a low-mass structure. TLP's stability is achieved by vertical lines in tension, the fatigue life of which is yet to be fully understood in respect to turbine loading. This sub-structure is suitable for severe wave environments, as the increase in tower loads, due to installing the wind turbine on a floating sub-structure, is expected to be lower than for the other floater concepts. They are ideal for applications in water depths around 40-350 m.

1.2.3 Anchoring and mooring system

Catenary mooring lines are a suitable solution for semi-submersibles and spar buoys. Catenary moorings have a bigger sea-bed footprint [4] and are usually more expensive than the tendons required by TLPs, due to their higher weight and dimensions compared to the latter. On the other hand, TLPs make use of much more expensive anchors than the other two concepts, but their less expensive mooring lines lead to a lower overall mooring system cost [16]. Finally, steel chains are used for the catenary mooring lines of semi-submersibles and spar buoys, while synthetic fibres are viable in the case of TLPs [17].

In general, drag embedment anchors are a suitable choice in the case of catenary mooring systems, as slack catenary mooring systems are designed to avoid vertical loads at the anchor. On the other hand, the tendons of TLPs have to withstand vertical loads, thus disqualifying drag embedment anchors as an option. In that case, a suction pile anchor or a vertical load anchor should be preferred instead [4, 18]. However, the selection of the most appropriate anchors largely depends on the seabed conditions at the wind farm site [6].

1.2.4 Electrical balance of plant

The main electrical components of a floating wind farm are the inter-array cables, the offshore sub-station, the export cable and the onshore sub-station. Some characteristics of these components follow:

- Inter-array cables connect wind turbines within a string with each other and different strings with the offshore sub-station, in order to transfer the produced electricity. The fatigue of the electrical cables is one of the most important factors to be taken into consideration at the design phase of floating wind farms, primarily due to floating turbines motion. Therefore, the use of dynamic cables for floating wind turbines is essential. Moreover, marine growth on top of the cables should be taken into account, as it can significantly deteriorate their fatigue life [6].
- An offshore sub-station provides stability of voltage, usage of a single export cable and reduction of electrical losses for the transmission of electricity to shore, thus leading to substantial savings, which offset its high installation cost [19]. The decision of implementing one or more offshore sub-stations in a wind farm is determined by the capacity of the wind farm and by the distance from shore. Usually, sub-stations are considered for either capacities larger than 100 MW or far-offshore sites [20]. For deep-water applications, semi-submersible sub-structures for floating sub-stations can be considered [4].

- Export cables are responsible for the transmission of the produced electricity to the main electrical grid. For this purpose, both Alternating Current (AC) and Direct Current (DC) have been proposed in the literature. The latter possibility offers lower power losses at the expense of higher investment cost. Although High Voltage Alternating Current (HVAC) is a cost-competitive solution for offshore export cables near shore, there is a break-even distance beyond which High Voltage Direct Current (HVDC) emerges as the most appropriate solution. This distance has been reported to be between 55 and 100 km [21, 22].
- An onshore sub-station is used to connect the electricity supplied by the offshore wind farm to the national grid. The installation cost of the onshore sub-station, is mostly determined by the soil preparation, the foundation and the installation cost due to the use of cranes and excavators [20].

1.2.5 Hydrogen production components

The coupling of hydrogen production to a floating wind farm, is a novel idea, thus limited information about the optimum configuration exists in the literature. According to [9], three different configurations are the most promising ones: (i) onshore hydrogen production (centralised onshore), (ii) hydrogen production in an offshore sub-station (centralised offshore), and (iii) in-turbine hydrogen production (decentralised offshore). For these procedures, the installation of electrolysers, desalination and compression units, as well as pipelines is essential. However, in the case of onshore production, the offshore pipeline system can be omitted as well as the desalination unit, in case of clean water supply. Moreover, in the configurations of onshore and offshore centralised production, only one electrolyser and desalination unit need to be installed, whereas in the case of in-turbine hydrogen production, each wind turbine is equipped with its own electrolyser and desalination unit [9].

Furthermore, another important aspect to be taken into consideration, is whether the whole operation is expected to be hydrogen-driven or electricity driven [9]. In the former case, all the produced electricity is used for hydrogen production, while in the latter one only the excess of electricity is exploited for this purpose. However, this is an important aspect of the whole project, as it determines if the installation of an export cable is necessary. In addition, in the former case, if the produced electricity exceeds the electrolyser specifications, the possibility to install a battery system should be investigated, to cover for the peaks of wind power production. Finally, the selection of the type of electrolyser technology is important for the whole operation of the coupled system. The most dominant electrolyser technologies include the alkaline and the Proton Exchange Membrane (PEM) electrolysers [9].

1.3 Installation and O&M of floating wind farms

The lifetime of a floating wind farm can be divided into five distinct phases [23]: development and consenting, production and acquisition, installation and commissioning, operation, and decommissioning phase. This work focuses on the installation and O&M phase, which will therefore be described in more detail.

The main factors determining the installation and O&M costs of offshore floating wind farms are the distance from shore/port, the weather conditions and the types of required vessels, together with the limiting conditions for the different vessels and offshore activities [24]:

- If there is no port with the required infrastructure in proximity to the wind farm site, it should be considered to upgrade the nearest port to be able to perform installation and maintenance tasks. These likely high investment costs at the early stages of the project need to be compared to the alternatives, which include high risk and associated costs due to more restrictive weather windows and higher vessel costs, which derive from the selection of a port further away from the site [24, 25].

- In situ measurements can provide reliable metocean data, essential for the planning of the offshore activities. Therefore, it is suggested to undertake in situ measurements, when the final location of interest is selected [25]. In addition to measurements, useful wind, currents and waves data in a range of 120 km from shore can be obtained by the usage of high frequency radars [26].
- Special attention should be given to the operational significant wave height for the vessels, as well as the wind speed limit for various activities, such as onshore/offshore lifts [25]. In addition, wave period could be a limiting factor for offshore activities. Short wave periods, in the order of 8-12 sec, could affect the operation of tug boats and Anchor Handling Vessels (AHVs) [15]. Moreover, as vessels' charter amounts to a significant part of the installation and maintenance cost of floating wind farms, the development of low-cost and not over-specified vessels is of utmost importance [6, 15]. On top of that, the optimal use of locally available vessels and port facilities can further reduce the installation and O&M costs [25]. In addition, depending on the demand and the size of the wind farm, it might be profitable for the wind farm operator to purchase their own O&M vessels, to offset the risk related to the volatility of the daily rates of vessels [4].
- In order to perform the required installation and maintenance tasks, the deployment of skilled personnel is required, to work on floating structures. This increases the safety concerns about the whole operation, and makes necessary the mobilisation of CTVs or W2W vessels for maintenance activities [6]. It is suggested to avoid wave periods between 4.5-7 sec, as this can cause sea-sickness in the personnel working on the floating sub-structure [27]. Another issue with floating wind, is the safe transfer of equipment to the wind turbine, like transformers or generators, a procedure which gets more complicated when performed between a vessel and a floating structure. In general, mitigating risks makes an offshore wind farm a more attractive investment opportunity, thus strengthening the development of the industry [6]. Therefore, it is of paramount importance to increase the weather windows of all offshore operations as well as to enhance the health and safety of the personnel [6, 25].

More details related to the procedures of installation and O&M, are presented in subsections 1.3.1 and 1.3.2 respectively.

1.3.1 Installation of floating wind farms

The total installation cost of the floating wind farm comprises the installation of the wind turbines, the floaters, the electric system, the mooring and the anchoring system and the start-up cost. After the installation of the wind farm, the next step is its commissioning [25]. These installation costs are one of the most vital aspects of the life-cycle of an offshore floating wind farm [28].

Generally, the installation of floating wind farms requires the deployment of a higher number, but cheaper and more easily available vessels, compared to the bottom-fixed structures [25], thus resulting in lower installation cost. This can be attributed to a variety of reasons [6]. First, the mooring lines and the anchors are easier to be installed compared to heavy monopile or jacket foundations with strict positioning requirements. Moreover, floating wind turbines can be assembled onshore or in sheltered waters, thus being less susceptible to the weather conditions, compared to bottom-fixed solutions. The installation of the latter is dependent on the harsher weather conditions at site, although jack-up vessels can provide some support in case of adverse weather [29]. Nevertheless, the towing of floating structures also faces strict weather limits, that can considerably delay the whole installation procedure.

Furthermore, the environmental impact of the installation of floating wind turbines is lower compared to the bottom-fixed ones. This is largely related to the mooring and anchoring system's lower seabed penetration and disruption of marine ecosystems compared to the bottom-fixed case [6, 25, 30]. In an effort to reduce the environmental impact of floating wind turbines, the use of more efficient vessels and the reduction of the overall number of trips should be pursued [31].

For the installation of floating wind farms, onshore cranes are necessary for quayside lifting activities. In addition, a wide range of vessels can be used, each one of which is involved in specific activities. The main vessels that are expected to take part in the installation campaign and their respective tasks are reported hereafter:

- **Anchor Handling Vessel (AHV)**: installation of mooring and anchoring system, towing and support in the installation of floating units at wind farm site
- **Cable Laying Vessel (CLV)**: installation of export cable and inter-array cables, connection of the floating units with the inter-array cables
- **Tug boat**: towing of barges, sub-structures and complete floating units, support in upending, ballasting, installation processes, pre-commissioning, commissioning
- **Crane barge**: offshore lift and installation of components
- **Heavy Lift Vessel (HLV)**: offshore lift, even of an entire wind turbine, and mating with sub-structures
- **Barge**: transiting components, ballasting of spar buoys

The installation procedure of floating wind turbines varies depending on the selected sub-structure. However, when performed offsite, either at quayside or at sheltered waters, it can be divided in distinctive steps, all together determining a complicated procedure [6]:

1. At site, the mooring and anchoring system is already installed with the use of AHVs. According to [32], the use of AHV is cheaper compared to the use of barges and tug boats for the installation of mooring and anchoring systems.
2. The electrical cables are pre-installed at site with the aid of a CLV as well as a rock-dumping vessel for the scour protection [20]. For the installation of the offshore sub-station, a HLV and a tug and/or a barge vessel are required [20].
3. Float-out of the sub-structure from the port is performed. This can be achieved with either the use of a crane (if the mass is low enough), slipways, or by flooding a dry dock, in case the fabrication of the sub-structure takes place in a dry dock.
4. The wind turbine is installed onto the sub-structure at quayside using cranes, if the water depth of the port allows for this procedure. Spar buoys, due to their high draft, have to follow a different procedure, as explained in the following step.
5. The assembly of the sub-structure with the wind turbine is towed to the site with AHVs, tug boats and/or barges depending on the floating sub-structure type, as shown in Figure 1.2. Spar buoys, due to their high draft, are wet-towed to sheltered areas to be upended and ballasted. Then, the wind turbine is assembled on the spar buoy. Finally, they are towed to site in the same way as for other foundation types.
6. Mooring lines are connected to the foundation to secure stability of the whole system, under limiting sea conditions (Significant Wave Height (H_s) < 1.5 m). Extra attention should be given at this step, as mistakes could lead to future damages and increased maintenance costs for the mooring system.
7. After the connection of the floater with the mooring lines, its ballast is adjusted to ensure stable and safe operating conditions [24].
8. Mooring lines are tensioned to the predefined levels.

9. Electrical cables are connected to the wind turbines.
10. Final commissioning of the whole system is undertaken.

Figure 1.2: Tow of a complete wind turbine on a semi-submersible sub-structure [33].

In case the assembly of the wind turbine on the sub-structure is carried out at site, for the transportation of the offshore wind farm components, two different strategies can be applied, namely feeding and transiting [4]. **Feeding** is the strategy where the specialised installation vessel is fed by other vessels with the required components. The former operates constantly at site, while the latter transit between the port and the wind farm site. On the other hand, **transiting** is the strategy where the installation vessel completes both the installation and transportation of components. This leads to the deployment of fewer vessels at the expense of a more time-consuming procedure. Depending on the weather windows and the distance to port, one strategy might prove to be more economically viable than the other. In addition, by increasing the number of installation lifts, the total offshore installation time might increase, but at the same time the necessary requirements of the cranes and the vessels are reduced and the limiting weather conditions can be lifted [4].

Finally, the mooring system installation can be divided into pre-set or concurrent installation. In the former case, the anchors and the mooring lines are installed at site, before the installation of the floating sub-structures takes place, thus limiting the interaction with the rest of the installation. During concurrent installation, on the other hand, the anchor and mooring system is installed at the same time with the floating structures, thus reducing the number of required transports [4]. Moreover, a possibility to reduce the installation costs of the mooring system would be to connect several mooring lines to the same anchor, and thus reduce the required number of anchors in the wind farm [4].

1.3.2 O&M of floating wind farms

O&M costs account for around 20-30% of the total life-time costs of floating offshore wind farms [4, 20, 27, 34]. These costs are further divided into fixed and variable costs. Fixed costs include sea-bed rental, insurance, grid access fees, administrative costs and service contracts for planned maintenance [20, 35]. Variable costs include unplanned maintenance activities, replacement parts and materials [35].

Similar to onshore wind farms, during the operation of floating wind farms, maintenance activities are necessary to ensure their smooth operation. Maintenance procedures include the exchange of parts, the removal of damaged parts, the installation of new parts, reconfiguration of settings, software updates as well as lubrication or cleaning processes [4]. Three different O&M strategies are widely used [17]: (i) calendar based preventive, (ii) condition based preventive and planned corrective, and (iii) unplanned corrective maintenance. In order to reduce maintenance costs, unplanned corrective maintenance of failed components could be combined with preventive maintenance procedures performed on other components. This strategy, is defined as opportunistic maintenance [36].

In an effort to reduce the need for unplanned corrective maintenance activities, inspection of all the components of the wind farm needs to be performed throughout the lifetime of the project. The inspections may occur in predefined intervals, depending on the examined component. According to [27], DNV suggests that periodic inspection shall be performed once at most every five years. For critical items of the sub-structure, the recommended interval for inspection is at least once per year. Critical areas which require more detailed and frequent inspections include the fairlead region, the splash zone, the connectors and the rope terminations as well as the seabed touchdown area [27]. Moreover, for underwater inspections, the use of Remotely Operated Vehicles (ROVs) is suggested [25], as diver operations should be avoided whenever possible due to safety reasons. Diver operations could be required, however, for a detailed visual inspection.

Moreover, preventive maintenance, with the aid of a continuous monitoring system, could prove vital for the whole cost of the wind farm by reducing the unexpected offshore maintenance activities and thus revenue loss. In general, customised solutions for floating wind applications, might lead to higher cost reductions of floating wind, than just trying to implement ideas of bottom-fixed systems [6]. In addition, according to [25], developments in the robotic fields could prove useful for inspection and maintenance purposes.

The main cause of downtime is due to failures of the wind turbines, while the elements of the floating and electrical infrastructure, i.e., mooring and anchoring system, floating platform, dynamic cables and export cable, are not expected to contribute substantially to the downtime of the system [23]. However, the replacement of mooring and anchoring systems is accompanied by the highest expenditures.

Depending on the category of the issue, different maintenance activities might be required. Towards this direction, the maintenance activities of a floating wind farm can be split into three categories: minor repair, major repair and major replacement. According to [37], the latter category refers to the replacement of a component which requires a jack up vessel, in the case of bottom-fixed wind turbines, or a HLV, in the case of floating wind turbines. These components include the generator, the gearbox, the main bearings, the transformer and the blades. A major repair refers to components which do not require the use of such vessels, but their repair is costly and time-consuming, such is the case of the converter. Finally, minor repair refers to fast repairs of small components, including but not limited to fixing an anemometer or other sensors.

Generally, O&M operations are characterised by stricter weather restrictions opposed to the installation ones, as maintenance operations are expected to be performed with vessels of lower specifications compared to the installation of the wind farm [19]. Therefore, special attention should be paid to the metocean conditions at site to select the most appropriate vessels and strategy for the O&M activities [25]. Vessel daily rates and the cost of repairs and/or replacements are expected to be the main driver of the O&M costs, followed by labour and fuel costs at a much lower share [23].

The main vessels that are expected to take part in the O&M campaigns and their respective tasks are reported hereafter:

- **Crew Transfer Vessel (CTV)**: transfer of technicians from port to site to perform offshore repairs, support in re-commissioning
- **Walk-to-Work vessel (W2W)**: transfer of technicians at site to perform offshore repairs, allowing higher accessibility than CTVs through the use of a gangway system, support in re-commissioning
- **Heavy Lift Vessel (HLV)**: onsite (or at sheltered location) major replacement of components
- **Tug boat**: towing of complete floating units, support in major replacement of components, (de)ballasting, disconnection/re-connection activities and re-commissioning
- **Anchor Handling Vessel (AHV)**: towing of complete floating units, support in major replacement of components and disconnection/re-connection activities

One of the main advantages of floating wind turbines is their ability to be towed offsite for their required maintenance, as this can lead to safer operations and reduced use of expensive vessels, thus leading to substantial cost reduction [6, 15, 38]. According to [25], semi-submersible floating units can be towed back to port for quayside maintenance activities by relatively cheap, but possibly weather limited, vessels. For spar buoys, an expensive HLV is necessary, regardless if the operation is performed onsite or offsite. However, offsite repair strategies impose various challenges. While the wind turbine is offsite, electrical continuity within the array is required [6]. Moreover, towing operation is a difficult procedure. The inherently high mass of substructures and their unstable operation when towed, require a low towing speed and strict weather limits [6]. These limitations need to be overcome when commercial floating wind farms will be commissioned.

The selection of onsite or offsite maintenance strategy mainly depends on the onsite weather conditions, distance from available ports and the degree to which port weather conditions are milder than the ones onsite [15]. In general, onshore operations are preferable compared to the offshore ones, due to lower risk and shorter execution time, as the weather conditions are more restrictive in the latter case [28].

The connection of the mooring lines with the foundations is accomplished with the deployment of a ROV. This is an operation that requires highly skilled personnel and sufficient time. Simplifying connection and disconnection of the electrical cables and mooring lines in higher sea states could substantially reduce O&M costs of offsite maintenance strategies [6, 15, 25].

In the case of small repairs where the lifting equipment available at site is adequate to perform the maintenance operations, a CTV or a W2W vessel could be deployed. The former vessel is characterised by a low daily rate at the expense of limiting sea capabilities, whereas the latter is able to operate at higher sea states but with higher daily rate and mobilisation cost. It should be noted, that the use of CTVs may be limited for far offshore wind farms [39]. Nevertheless, as further progress in the maritime industry is expected, an analysis of such a vessel is deemed relevant in order to examine the potential of using a cheaper but more weather limited vessel for minor and major repairs of a floating wind farm. It is also suggested in the literature that repair costs of a floating wind farm could be reduced with the deployment of a mother vessel, which can act as an offshore base for the personnel and service vessels [4].

According to [15], it is unlikely that the HLV availability will drive the selection between offsite and onsite repair strategy. However, as in the future, larger far-offshore wind farms are expected to be developed, the demand for specialised vessels will also increase, and thus a growth in the supply of these vessels is expected. In any case, the (de)mobilisation costs and the daily rates of vessels are highly volatile and dependent on the market demand and supply at the time of interest.

If the number of wind turbines to be repaired in a single campaign increases, it becomes more difficult to find an adequate weather window to perform all the required tasks [15]. Therefore, the operations might be delayed and subsequently the downtime of the farm increased. On the other hand, by conducting a larger campaign, the fixed costs of the vessels, mainly mobilisation costs, can be divided among the number of turbines and thus reduce the overall cost, especially when the deployment of expensive vessels is required.

1.4 Research questions

The first step of the implementation of every technological breakthrough is to fully understand its characteristics and optimise its design and performance. While this is an important starting point for all technologies, and thus for floating wind, research should also focus on the optimisation of the installation and O&M procedures of a floating wind farm [6]. This is necessary to reduce the costs associated with these procedures and thus the overall LCOE of the project. Reducing floating wind's LCOE is highly important, as currently the cost of electricity production of floating wind farms is higher than the average electricity price.

According to [23], installation, commissioning and O&M account for 30% of the overall cost of offshore installations. However, the installation and O&M costs are highly dependent on the different strategies selected. Various installation strategies have been proposed in the literature for different floating sub-structures, including semi-submersibles, spar buoys and TLPs. Furthermore, depending on the type of the sub-structure, the distance from shore and the weather conditions of the location of interest, onsite or offsite repair works could be more or less convenient. However, since floating wind farms have not reached commercial stage yet, there is not yet consensus on their optimal installation and operation [25].

This thesis aims to shed light on the optimal strategies for the installation and operation phase of far-offshore floating wind farms. This goal can be formulated as the following main research question:

Which are the optimum strategies for the installation and O&M of far-offshore floating wind farms from a techno-economic point of view?

The first step to achieving this goal, is to identify the different installation and O&M strategies for floating wind turbines, installed on spar buoys and semi-submersibles, that have been proposed in the literature. Then, an efficient deterministic installation and O&M cost model will be developed. This model will be used to compare different installation and O&M strategies and identify which solution offers the highest LCOE reduction potential. The selection of a low-fidelity, deterministic cost model is made, since it can provide results in short time, which is essential due to the fact that this model will be included in an optimisation framework for floating wind farms. The scope of the model is thus not to obtain the exact estimation of the installation and O&M cost for a given wind farm, but rather to incorporate the main drivers determining the overall cost of each installation or maintenance strategy, allowing to identify which set of conditions make one strategy more convenient than the others.

The necessary steps towards the main research question, can be re-defined as the following research sub-questions:

1. *Which are the current installation strategies of the different floating sub-structures?*
2. *Which are the current O&M strategies of the different floating sub-structures?*
3. *Which are the main drivers determining installation and O&M costs?*
4. *Which are the main drivers determining installation and O&M duration?*
5. *Which installation and O&M strategies can lead to the highest LCOE reduction of a far-offshore floating wind farm?*

2 | Methodology

The aim of this Chapter is to present the different installation and O&M strategies of floating wind farms considered in this thesis. This answers the first two research sub-questions. In section 2.1, the four different installation strategies examined in this thesis are presented. In section 2.2, the four different O&M strategies addressed in this thesis are offered. In section 2.3, main assumptions, resulting from an extensive literature review, are presented. Finally, in section 2.4, the working principle of the code is introduced.

2.1 Implemented installation strategies

As aforementioned, different installation strategies can be applied depending on the type of the sub-structure used. For the scope of this thesis, two different installation strategies are examined for semi-submersibles and spar buoys. The examined strategies are:

1. Semi-submersible installation with wind turbine assembly at quayside
2. Semi-submersible installation with wind turbine assembly at wind farm site
3. Spar buoy installation with wind turbine - spar buoy mating in one lift with HLV
4. Spar buoy installation with wind turbine assembly on spar buoy in multiple lifts with crane barge

The aim of this section is to provide the sequence of these strategies and relevant assumptions concerning the duration of each installation activity and vessels' weather limitations. It should be noted, at this point, that the scope of this thesis is restricted to the evaluation of different installation and O&M strategies of floating units. Therefore, the installation and maintenance of the anchoring and mooring system, the electrical balance of plant and the hydrogen components is not treated because it is assumed to be the same for all the strategies investigated. Thus, this does not have any effect on determining which strategy is the most cost-effective. The structure of this section follows; semi-submersible installation with wind turbine assembly at quayside is presented in subsection 2.1.1, while semi-submersible installation with wind turbine assembly at wind farm site is offered in subsection 2.1.2. In addition, spar buoy installation with HLV is described in subsection 2.1.3, while spar buoy installation with crane barge is presented in subsection 2.1.4.

2.1.1 Semi-submersible installation with wind turbine assembly at quayside

In the first strategy under analysis, semi-submersibles are assumed as the floating sub-structure selected for the wind farm, and the assembly of the turbine on the floater is expected to take place at quayside. Figure 2.1 depicts the sequence of the required activities for the installation of the floating units. A further explanation of these activities follows:

- **Float-out semi-submersible**: The semi-submersibles are assumed to be manufactured in a shipyard, which is different from the port used as base for installation. Therefore, the floating sub-structures have to be towed to a port closer to the wind farm site, where the turbines' main components are stored. There, the wind turbine is assembled on the sub-structure. The

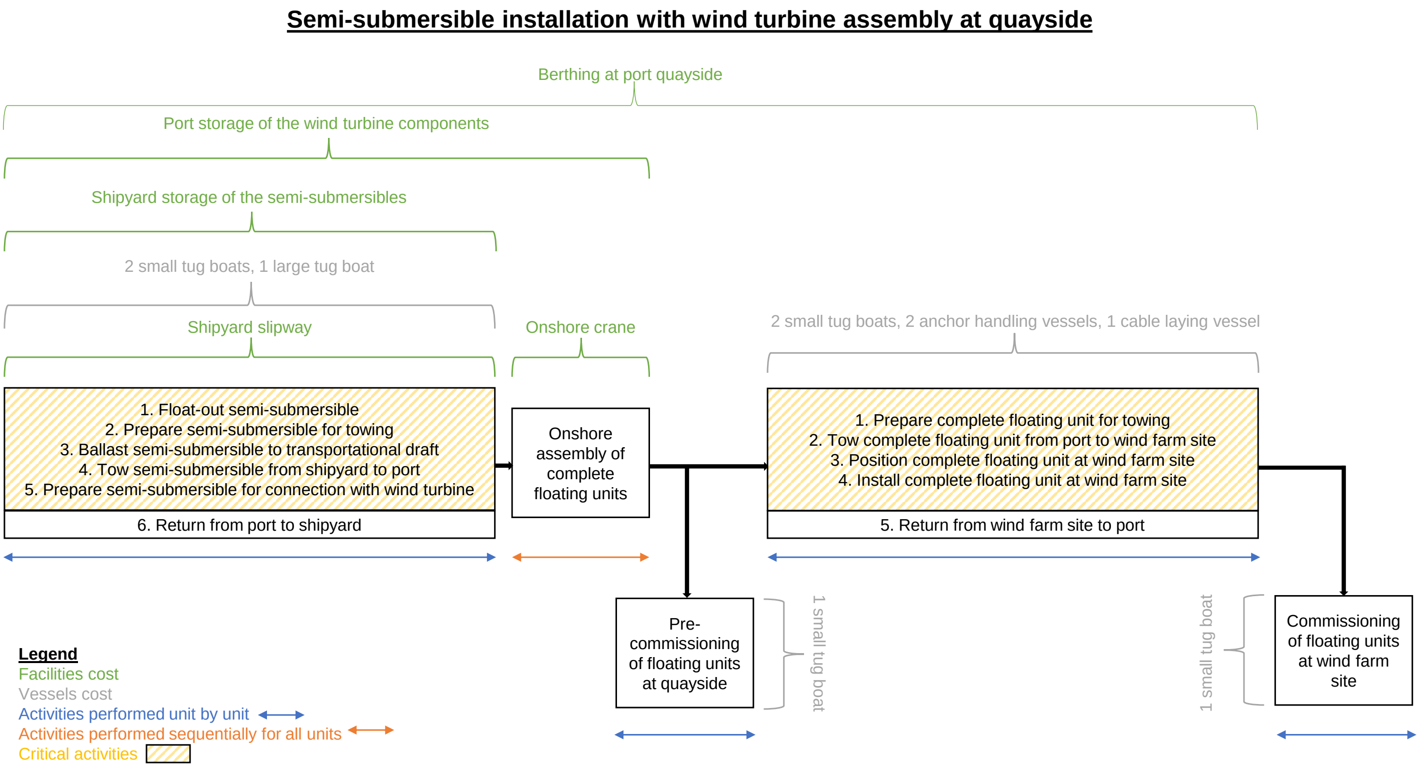


Figure 2.1: Sequence diagram of the semi-submersible installation with wind turbine assembly at quayside.

first step towards this direction, is the float-out of the semi-submersibles, so that they can be towed to port. It is assumed that the required float-out is performed with the use of a slipway.

- **Prepare semi-submersible for towing**: The next step is the connection of the semi-submersible with tug boats in order to be towed to port. The towing process is assumed to be undertaken with the aid of two small tug boats and one large tug boat.
- **Ballast semi-submersible to transportational draft**: After this connection, the semi-submersible is ballasted to its towing draft via dynamic ballasting.
- **Tow semi-submersible from shipyard to port**: Then, the semi-submersible is towed to the port where the wind turbine will be installed on the floater.
- **Prepare semi-submersible for connection with wind turbine**: Additional buoyancy units are added to the sub-structure to enter into the port, which are then removed once the semi-submersible is in position at the quayside.
- **Return from port to shipyard**: The tug boats return to shipyard so that the procedure is repeated for the next semi-submersible unit.
- **Onshore assembly of complete floating units**: When all semi-submersibles have been transited to the port, the assembly of the wind turbines on top of the semi-submersibles is performed at quayside. This procedure is expected to be carried out in six lifts: two tower segments, nacelle and hub assembly, and three blades. The lift of these components is performed with onshore cranes at quayside. This step is finished when all wind turbines are installed on the semi-submersibles.
- **Pre-commissioning of floating units at quayside**: The next step of the wind turbine - semi-submersible assembly is the pre-commissioning of all floating units. For this activity a small tug boat is mobilised. This activity is assumed to be parallel to the critical path

of the installation sequence. Whenever a wind turbine is assembled on a floater, its pre-commissioning can take place.

- **Prepare complete floating unit for towing**: After the assembly of the wind turbines and their pre-commissioning, the floating assemblies are ready to be towed to the site. The floating units are connected with two AHVs and two small tug boats to be towed to the wind farm site. Buoyancy units are installed on the semi-submersibles to exit the port, and removed once they are outside the port.
- **Tow complete floating unit from port to wind farm site**: Then, the floating unit is towed to the wind farm site.
- **Position complete floating unit at wind farm site**: Upon arrival at the designated location, the floating unit is ballasted to reach its operational draft.
- **Install complete floating unit at wind farm site**: The installation of the floating unit at its specified location is performed, with the aid of a CLV to perform the electrical connection of the wind turbine.
- **Return from wind farm site to port**: The tug boats and the AHVs return to port so that the procedure is repeated for the next floating unit.
- **Commissioning of floating units at wind farm site**: The final step of the installation procedure is the commissioning of the wind farm. For this activity a small tug boat is mobilised. This activity is assumed to be parallel to the critical path of the installation sequence. Whenever a wind turbine is installed, its commissioning can take place.

During the installation campaign, some activities need to be performed in a row, without the vessels standing idle due to unfavourable weather conditions. Such activities comprise a critical sequence, whose required weather window includes all the activities within the sequence. In this case, the first critical sequence starts with the float-out of the semi-submersible from shipyard and ends with its positioning at port quayside. The second critical sequence begins with the preparation of the complete floating unit for towing at port and finishes with its installation at wind farm site.

Throughout the installation campaign, the various components of the floating units have to be stored at the shipyard or at the port. The duration of the shipyard storage of the floaters is set equal to the required time to tow all floaters from shipyard to port. The duration of the port storage of the wind turbine components is set equal to the required time to tow all floaters from shipyard to port plus the time for their assembly with the semi-submersibles. Finally, the complete floating units have to be stored at the quayside. This berthing duration is assumed to start at the first time step of the installation procedure and finish with the installation of all wind turbines at the wind farm site.

All the required activities, as well as the vessels' operations, are characterised by their respective theoretical duration and weather limits. Since offshore floating wind is still at a novel stage, there is no clear overview on the duration and weather constraints of the different installation activities. An extensive literature study was carried out to identify suitable net time and operational limits for different installation activities, to be used in the installation model. These data for semi-submersible installation with wind turbine assembly at quayside are reported in Table 2.1 [4, 15, 23, 25, 28, 40, 41].

Table 2.1: Duration and weather limits for the activities involved in the semi-submersible installation with wind turbine assembly at quayside (for a single floating unit).

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Float-out	3.0	-	-
Prepare floater for towing	2.0	4.0	-
Ballast floater to transportational draft	4.0	4.0	-
Prepare floater for wind turbine assembly	12.0	4.0	-
Assembly of a single component	3.0	4.0	12.0
Pre-commissioning	24.0	-	-
Prepare floating unit for towing	12.0	4.0	-
Position at site	12.0	2.5	-
Installation at site	15.0	1.5	-
Commissioning	12.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Tow floater	3.33	2.0	18.0
Tow floating unit	2.33	2.0	18.0
Free transit	6.11	3.2	30.0

2.1.2 Semi-submersible installation with wind turbine assembly at wind farm site

In the second strategy under analysis, semi-submersibles are assumed as the floating substructure selected for the wind farm, and the assembly of the turbine on the floater is expected to take place at wind farm site. This follows a feeding strategy, as the wind turbine components are transited to site by a different vessel than the crane vessel which performs the final assembly. Figure 2.2 depicts the sequence of the required activities for the installation of the floating units. A further explanation of these activities follows:

- **Float-out semi-submersible**: The semi-submersibles are assumed to be manufactured in a shipyard, which is different from the port used as base for installation. The floating substructures have to be towed to the wind farm site to be installed. The first step towards this direction, is the float-out of the semi-submersibles, so that they can be towed to the wind farm site. It is assumed that the required float-out is performed with the use of a slipway.
- **Prepare semi-submersible for towing**: The next step is the connection of the semi-submersible with the towing vessels. The towing process is assumed to be undertaken with the aid of one AHV, one small tug boat and one large tug boat.
- **Ballast semi-submersible to transportational draft**: After this connection, the semi-submersible is ballasted to its towing draft via dynamic ballasting.

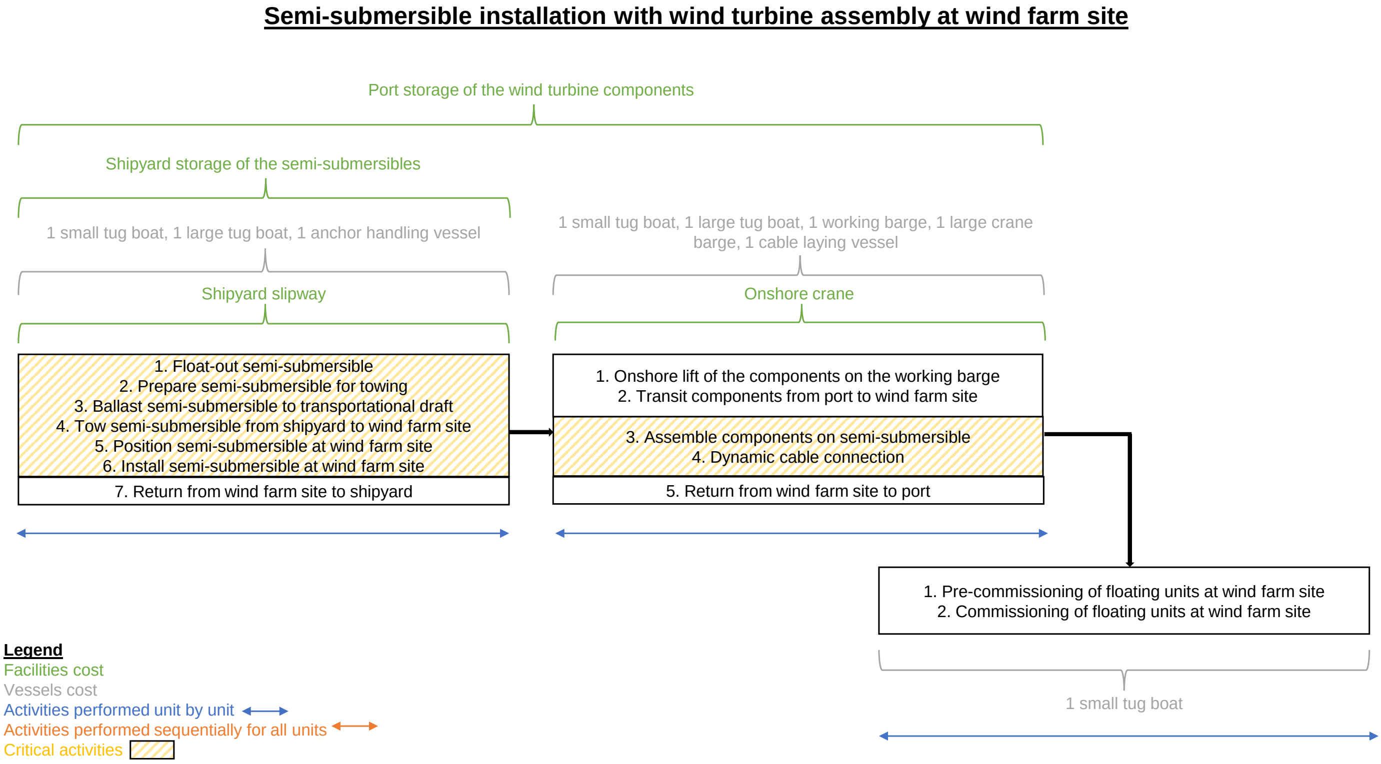


Figure 2.2: Sequence diagram of the semi-submersible installation with wind turbine assembly at wind farm site.

- **Tow semi-submersible from shipyard to wind farm site**: Then, the semi-submersible is towed to the wind farm site to be connected with the mooring lines.
- **Position semi-submersible at wind farm site**: Upon arrival at the designated location, the floater is ballasted down.
- **Install semi-submersible at wind farm site**: The installation of the floater is performed at the wind farm site.
- **Return from wind farm site to shipyard**: The AHV and the two tug boats return to shipyard so that the procedure is repeated for the next semi-submersible unit.
- **Onshore lift of the components on the working barge**: After all floaters have been installed at the wind farm site, the components of the wind turbine are loaded on a barge to be towed to site. Six lifts are necessary to lift the components of the wind turbine onto the working barge: two lifts for the tower sections, one lift for the nacelle and hub, and three lifts for the blades. Each component is loaded on the working barge with the aid of onshore cranes.
- **Transit components from port to wind farm site**: The loaded working barge is towed to the wind farm site with the aid of one small and one large tug boat.
- **Assemble components on semi-submersible**: At the wind farm site, a large crane barge is deployed to assemble all wind turbine components on top of the semi-submersible floater. This crane barge remains at the wind farm site during the whole installation sequence.
- **Dynamic cable connection**: A CLV is used to perform the electrical connection of the wind turbine.
- **Return from wind farm site to port**: The tug boats and the working barge return to port so that the procedure is repeated for the next floating unit.

- **Pre-commissioning of floating units at wind farm site**: The turbine-assemblies are pre-commissioned. For this activity a small tug boat is mobilised. This activity is assumed to be parallel to the critical path of the installation sequence. Whenever a wind turbine is installed, its pre-commissioning can take place.
- **Commissioning of floating units at wind farm site**: The final step of the installation procedure is the commissioning of the wind farm. For this activity a small tug boat is used. Commissioning follows pre-commissioning as a parallel activity to the critical path.

For this strategy, the first critical sequence starts with the float-out of the semi-submersible from shipyard and ends with its installation at wind farm site. The second critical sequence begins with the assembly of the wind turbine components on top of the semi-submersibles at wind farm site and finishes with the dynamic cable connection.

Throughout the installation campaign, the various components of the floating units have to be stored at the shipyard or the port. The duration of the shipyard storage of the floaters is set equal to the required time to install all the floaters at the wind farm site. The time required to store the wind turbine components at port is set equal to the required time to install all floaters at the wind farm site plus the time to assemble all wind turbines on the semi-submersibles.

Net duration required for each activity and vessels limits were obtained from the available literature on the subject [4, 15, 23, 25, 28, 40, 41] and are presented in Table 2.2.

Table 2.2: Duration and weather limits for the activities involved in the semi-submersible installation with wind turbine assembly at wind farm site (for a single floating unit).

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Float-out	3.0	-	-
Prepare floater for towing	2.0	4.0	-
Ballast floater to transportational draft	4.0	4.0	-
Position at site	12.0	2.5	-
Installation at site	6.0	1.5	-
Onshore lift of a single component	3.0	4.0	12.0
Offshore assembly of a single component	4.5	1.5	12.0
Cable connection	9.0	1.5	-
Pre-commissioning	24.0	-	-
Commissioning	12.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Tow floater	3.33	2.0	18.0
Tow working barge	2.33	2.0	18.0
Free transit	6.11	3.2	30.0

2.1.3 Spar buoy installation with HLV

In the third case, spar buoys are selected as support structure for the wind farm. The assembly of the spar buoy and the wind turbine occurs in sheltered waters, by means of a HLV capable of installing the whole turbine on the spar in one single lift. Figure 2.3 depicts the sequence of the required activities for the installation of the floating units. A further explanation of these activities follows:

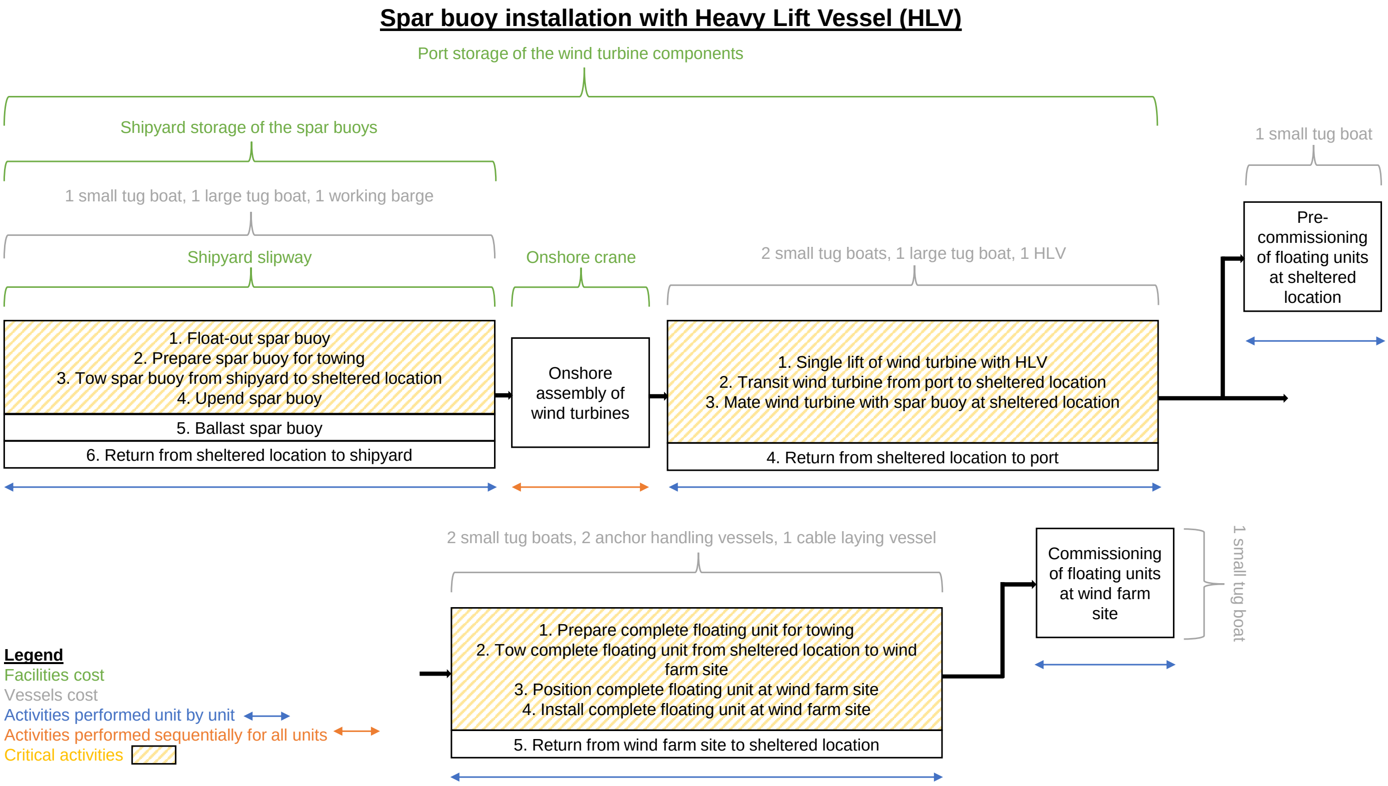


Figure 2.3: Sequence diagram of the spar buoy installation with HLV.

- **Float-out spar buoy**: The spar buoys are assumed to be manufactured in a shipyard, which is different from the port used as base for installation. The floating sub-structures have to be towed to a sheltered location, near port, where the wind turbine is assembled on the floater. A sheltered location with deep waters is necessary, as due to the high draft of spar buoys, it is not possible to install the wind turbine on the sub-structure at port. The first step is the float-out of the spar buoys, so that they can be towed to the sheltered location. It is assumed that the required float-out is performed with the use of a slipway.
- **Prepare spar buoy for towing**: The next step is the connection of the spar buoy with tug boats in order to be horizontally towed to the sheltered location. The towing process is assumed to be undertaken with the aid of one small tug boat and one large tug boat.
- **Tow spar buoy from shipyard to sheltered location**: Then, the spar buoy is towed to the sheltered location to be upended and ballasted.
- **Upend spar buoy**: When the spar buoy reaches the sheltered location, it is upended and ballasted as preparation of the wind turbine installation. The upending is accomplished with the aid of a working barge. After the completion of the upending, the spar buoy is temporarily secured to a support.
- **Ballast spar buoy**: After the completion of the upending, the ballast of the spar buoy is performed at the sheltered location.

- **Return from sheltered location to shipyard**: The tug boats return to shipyard so that the procedure is repeated for the next spar buoy unit.
- **Onshore assembly of wind turbines**: When all spar buoys have been transited to the sheltered location, the wind turbines are assembled at the quayside. The lift of the wind turbine components is performed with onshore cranes of the port. This step is concluded when all wind turbines are assembled.
- **Single lift of wind turbine with HLV**: The following step is the mating of the wind turbines with the spar buoys. The entire wind turbine is lifted by a HLV.
- **Transit wind turbine from port to sheltered location**: The HLV transits to the sheltered location.
- **Mate wind turbine with spar buoy at sheltered location**: The mating of the wind turbine with the spar buoy is performed. Two small tug boats and a large tug boat aid this process by stabilising the spar buoy.
- **Return from sheltered location to port**: The HLV returns to port so that the procedure is repeated for the next floating unit.
- **Pre-commissioning of floating units at sheltered location**: The next step of the wind turbine - spar buoy assembly is the pre-commissioning of all floating units at the sheltered location. For this activity a small tug boat is mobilised. This activity is assumed to be parallel to the critical path of the installation sequence. Whenever a floating unit is assembled, its pre-commissioning can take place.
- **Prepare complete floating unit for towing**: When all wind turbines are assembled and pre-commissioned, the next step is their installation at the wind farm site. Therefore, the floating assembly is connected with two AHVs and two small tug boats to be towed to the wind farm site.
- **Tow complete floating unit from sheltered location to wind farm site**: Then, the floating unit is towed to the wind farm site.
- **Position complete floating unit at wind farm site**: Upon arrival at the designated location, the floating unit is ballasted to reach its operational draft.
- **Install complete floating unit at wind farm site**: The installation of the floating unit at the wind farm site is performed, with the aid of a CLV to perform the electrical connection of the wind turbine.
- **Return from wind farm site to sheltered location**: The tug boats and the AHVs return to the sheltered location so that the procedure is repeated for the next floating unit.
- **Commissioning of floating units at wind farm site**: The final step of the installation procedure is the commissioning of the wind farm. For this activity a small tug boat is mobilised. This activity is assumed to be parallel to the critical path of the installation sequence. Whenever a floating unit is installed, its final commissioning can take place.

In this strategy, the first critical sequence starts with the float-out of the spar buoy from the shipyard and ends with its upending at the sheltered location. The second critical sequence begins with the single lift of the wind turbine with the HLV and ends with its mating on top of the spar buoy at the sheltered location. Finally, the third critical sequence starts with the preparation of the complete floating unit for towing from the sheltered location to the wind farm site and ends with its installation at site.

Throughout the installation campaign, the various components of the floating units have to be stored at the shipyard or the port. The duration of the shipyard storage of the floaters is set equal to the required time to tow all spar buoys from the shipyard to the sheltered location. The duration of the port storage of the wind turbine components is set equal to the time required to tow the spar buoys from the shipyard to the sheltered location plus the time to assemble all wind turbines at the port quayside and mate them with the spar buoys at the sheltered location.

Net duration required for each activity and vessels limits were obtained from the available literature on the subject [4, 15, 23, 25, 28, 40, 41] and are presented in Table 2.3.

Table 2.3: Duration and weather limits for the activities involved in the spar buoy installation with HLV (for a single floating unit).

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Float-out	3.0	-	-
Prepare floater for towing	2.0	4.0	-
Upend	9.0	3.0	-
Ballast	13.5	4.0	-
Onshore lift of a single component	3.0	-	12.0
Single lift of a wind turbine	4.0	4.0	12.0
Mating	6.0	2.5	12.0
Pre-commissioning	24.0	-	-
Prepare floating unit for towing	12.0	4.0	-
Position at site	9.0	2.5	-
Installation at site	18.0	1.5	-
Commissioning	12.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Tow floater (tug boat)	2.36	2.0	18.0
Tow floating unit (tug boat)	1.47	2.0	18.0
Free transit (tug boat)	6.11	3.2	30.0
Transit wind turbine (HLV)	3.08	2.1	11.0
Free transit (HLV)	6.22	10.0	25.0

2.1.4 Spar buoy installation with crane barge

The final implemented strategy refers to the assembly of wind turbines with spar buoys with the aid of a medium sized crane barge. The lifting capacity of such a crane barge should be in the order of 850 tons, so that it can lift the nacelle-hub assembly. Figure 2.4 depicts the sequence of the required activities for the installation of the floating units. This strategy is similar to the installation procedure with the HLV presented in subsection 2.1.3. Their main difference lies in the critical sequence of assembling the wind turbine on the spar buoy at the sheltered location. While in the previous case the wind turbines are fully assembled at the port quayside and the mating with the spar buoy is performed by the HLV, in this strategy the following activities are performed:

- **Onshore lift of a wind turbine component on the crane barge**: One wind turbine

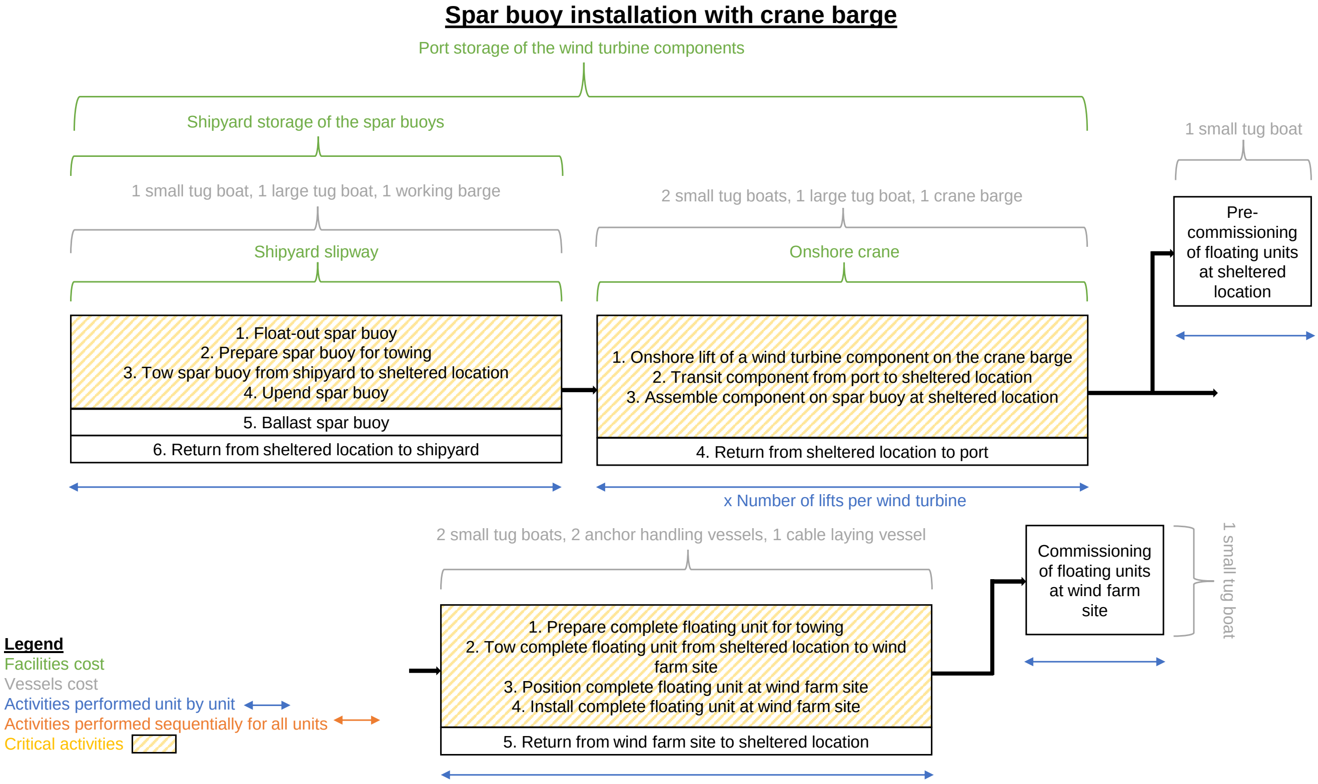


Figure 2.4: Sequence diagram of the spar buoy installation with crane barge.

component is loaded on the crane barge, to be transported to the sheltered location and installed on the spar buoy. This lift is performed with the aid of onshore cranes of the port.

- **Transit component from port to sheltered location**: The crane barge transits to the sheltered location.
- **Assemble component on spar buoy at sheltered location**: Finally, the wind turbine component is installed on the spar buoy with the aid of the crane barge. In addition, two small tug boats and one large tug boat aid with the stabilisation of the spar buoy.

This critical sequence needs to be repeated for each wind turbine six times, equal to the number of lifts necessary to assemble the wind turbines. Net duration required for each activity and vessels limits were obtained from the available literature on the subject [4, 15, 23, 25, 28, 40, 41] and are presented in Table 2.4.

As aforementioned in all implemented installation strategies, pre-commissioning and commissioning activities are treated to be parallel to the critical path of the installation campaign. During the simulations, it is assumed that these activities have shorter execution period than the parallel critical sequences and thus only one repetition of these activities is added for the calculation of the total installation duration. As presented in the installation results in Chapter 3, this assumption holds for most implemented strategies, with the exception of semi-submersible installation with wind turbine assembly at quayside and spar buoy installation with HLV in summer months, when the respective critical sequences have relatively shorter execution duration. Therefore, the actual installation duration and cost would be a bit higher, although negligible, as these activities are performed with the aid of a small tug boat, which is characterised by a low daily rate.

Table 2.4: Duration and weather limits for the activities involved in the spar buoy installation with crane barge (for a single floating unit).

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Float-out	3.0	-	-
Prepare floater for towing	2.0	4.0	-
Upend	9.0	3.0	-
Ballast	13.5	4.0	-
Onshore lift of a single component	3.0	4.0	12.0
Offshore assembly of a single component	4.5	2.5	12.0
Pre-commissioning	24.0	-	-
Prepare floating unit for towing	12.0	4.0	-
Position at site	9.0	2.5	-
Installation at site	18.0	1.5	-
Commissioning	12.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Tow floater (tug boat)	2.36	2.0	18.0
Tow floating unit (tug boat)	1.47	2.0	18.0
Free transit (tug boat)	6.11	3.2	30.0
Transit wind turbine component (crane barge)	1.44	2.5	15.0
Free transit (crane barge)	3.60	3.0	20.0

2.2 Implemented O&M strategies

The aim of this section is to present the different O&M strategies of floating wind farms, thus answering the second research sub-question. As aforementioned, the maintenance campaigns of a floating wind farm can be sub-divided into minor repairs, major repairs and major replacements of components. In order to simulate the maintenance activities, it is essential to be familiar with the failure rate of each category as well as its respective component cost. The failure rates of each category, based on [42], and their respective component cost for a 15-MW wind turbine, based on [37], are listed in Table 2.5.

Since this thesis is based on a wind farm consisting of 30 wind turbines with a lifetime of 25 years, it is assumed that every year approximately 3 wind turbines undergo a major replacement. Therefore, a 3-turbine campaign is assumed to be performed once per year for the whole wind farm. Furthermore, since major replacement activities are not usually performed during the autumn-winter months, a waiting-for-good-season lead-time is added during the simulations which have a starting period during autumn and winter. This lead-time pushes the start of each

Table 2.5: Failure rate and cost per repair category.

Repair Category	Failure rate (failure/(turbine*year))	Cost of repair (€)
Minor repair	5.675	2,600
Major repair	1.023	61,000
Major replacement	0.111	1,141,300

strategy at the 21st of the following March.

As aforementioned, different maintenance strategies can be applied depending on the type of repair needed and the type of the sub-structure. For the scope of this thesis, two different vessels are examined for minor/major repairs and two different approaches for major replacements. To be more precise, the examined strategies are:

1. Onsite repair with a crew transfer vessel or a walk-to-work vessel
2. Onsite major replacement
3. Semi-submersible offsite major replacement
4. Spar buoy offsite major replacement

The onsite strategies are assumed to be identical for both types of sub-structures, while a differentiation is made for the offsite replacement strategy. This is dictated by the different towing requirements of each sub-structure and their unique drafts, which in the case of a spar buoy renders a replacement at quayside impossible. It should be noted that for all repair and replacement maintenance campaigns, it is assumed that the vessels are chartered on a case-by-case scenario, as opposed to being owned by the wind farm operator.

The aim of this section is to provide the sequence of these strategies and their required input data. The structure of this section follows; onsite repair with a CTV or a W2W vessel is presented in subsection 2.2.1. In addition, onsite major replacement is described in subsection 2.2.2, while semi-submersible and spar buoy offsite major replacement strategies are presented in subsections 2.2.3. and 2.2.4, respectively.

2.2.1 Onsite repair

For minor/major repairs, no replacement of large components is needed, and all the operations can be performed with the lifting equipment available at site. These maintenance campaigns are examined with the use of either a CTV or a W2W vessel, so as to compare a cheaper vessel with limited working capabilities, against a more expensive option which can withstand harsh weather conditions. Figure 2.5 depicts the sequence of the required activities for the aforementioned strategy. A further explanation of these activities follows:

- **Transit from port to wind farm site**: A CTV or a W2W is mobilised and then transits to the wind farm site to perform the required minor/major repair.
- **Position at wind farm site**: The next step is the positioning of the vessel at site so that the technicians can board the floating unit.
- **Onsite repair**: After positioning, technicians board the wind turbine and the onsite repair is performed.
- **Return from wind farm site to port**: When the repair is finished, the CTV or the W2W returns to port to be de-mobilised.

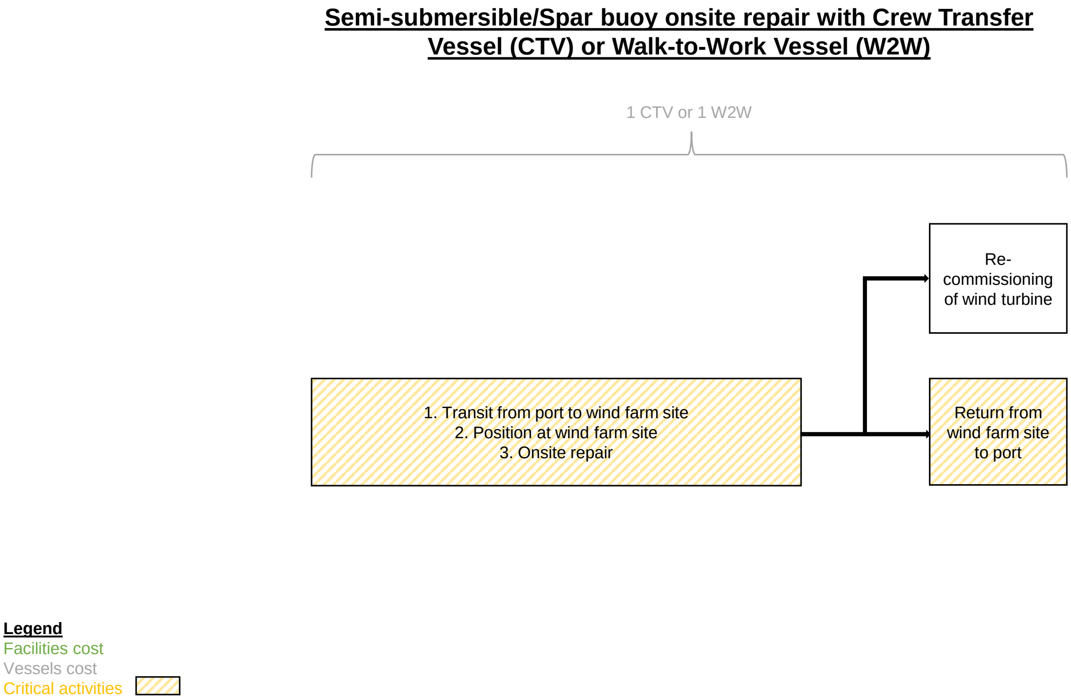


Figure 2.5: Sequence diagram of the onsite repair strategy with a CTV or a W2W vessel.

- **Re-commissioning of wind turbine**: Then, the wind turbine is re-commissioned and it is set back into operation. This activity is assumed to be parallel to the return to port.

The whole onsite repair strategy is treated as a critical sequence, due to the limiting sea capabilities of these vessels. As aforementioned, this critical sequence does not include the re-commissioning of the wind turbine. It is worth mentioning that the onsite repair strategy with the use of a W2W vessel was examined also with the transits not being a part of the critical sequence, since a W2W can withstand harsher weather conditions. Nevertheless, the duration and cost results were similar with the former case, thus this approach is omitted from the report.

All the required activities, as well as the vessels operations, are characterised by their respective theoretical duration and weather limits. The duration and weather constraints of these activities are based on sources available in the literature [4, 15, 17, 23, 25, 28]. The input data for all activities for the onsite repair with the use of a CTV are presented in Table 2.6 and with the use of a W2W in Table 2.7. It is clear that the W2W vessel can operate in harsher weather conditions compared to a CTV, as the wave height limit of the former vessel is estimated to be 3.0 m, compared to the 1.5 m limit of CTV.

Table 2.6: Duration and weather limits for the activities involved in the onsite repair with the use of a CTV.

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Position at site	1.5	1.5	-
Onsite repair (minor)	7.0	1.5	12.0
Onsite repair (major)	19.0	1.5	12.0
Re-commissioning	12.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
CTV Transit	10.28	1.5	20.0

Table 2.7: Duration and weather limits for the activities involved in the onsite repair with the use of a W2W vessel.

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Position at site	1.5	2.5	-
Onsite repair (minor)	7.0	1.5	12.0
Onsite repair (major)	19.0	1.5	12.0
Re-commissioning	12.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
W2W Transit	6.17	3.0	20.0

2.2.2 Onsite major replacement

The next examined maintenance strategy belongs in the category of major components replacement. Therefore, the distinction between the different strategies originates from their onsite or offsite execution. At first, the onsite maintenance strategy is analysed, which comprises the same activities and vessels for both the semi-submersible and spar buoy floating types. Figure 2.6 depicts the sequence of the required activities for the replacement of the components of the floating units. A further explanation of these activities follows:

- **Rigging installation and loading components**: For the onsite major replacement, a HLV and a CTV are to be used. Sufficient time is needed for rigging installation and loading the components to be used as replacement offshore.
- **Transit from port to wind farm site**: The vessels transit to site to perform the required maintenance of the wind turbines.
- **Position at wind farm site**: Upon reaching the wind farm site, extra time is needed for the HLV to position at the first wind turbine of the maintenance campaign.
- **Vessel - wind turbine coupling**: Before the onsite replacement, it is essential that the

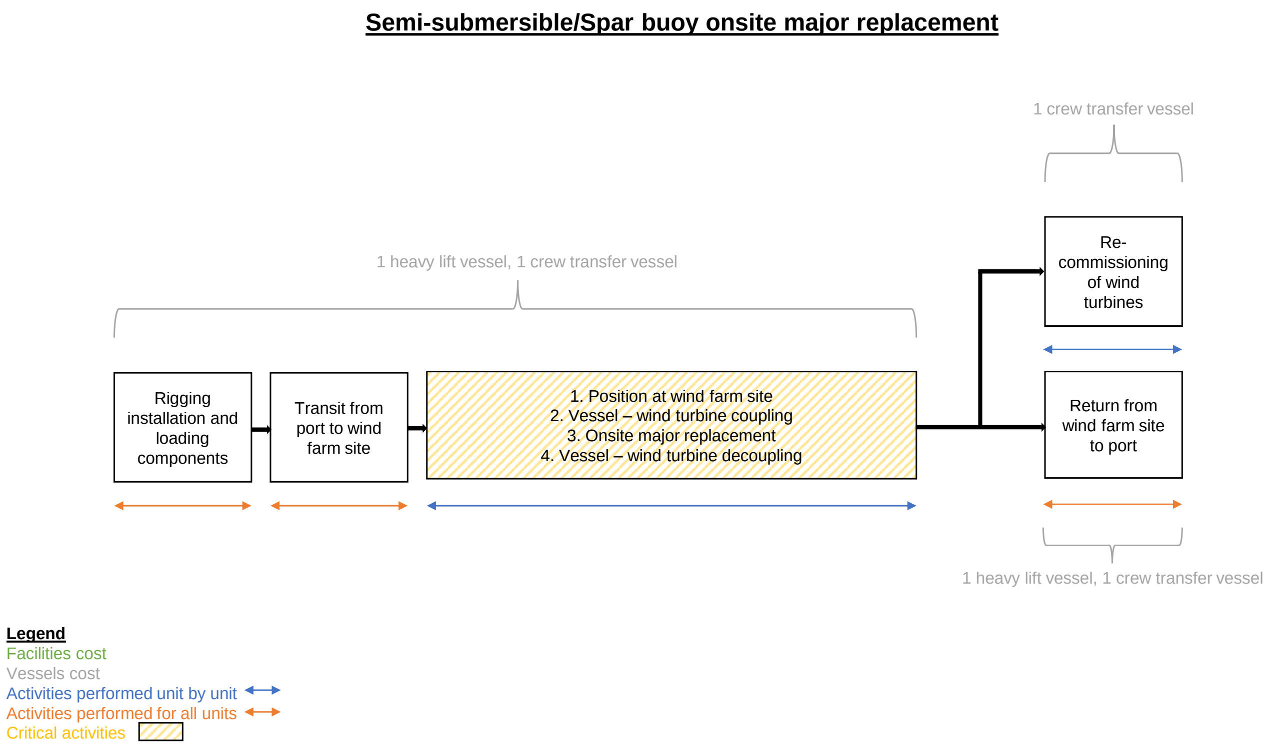


Figure 2.6: Sequence diagram of the onsite major replacement.

coupling of the HLV and the floating unit is performed, so that the float-to-float operations become feasible.

- **Onsite major replacement**: Then, the replacement of the faulty component takes place.
- **Vessel - wind turbine decoupling**: When the replacement is complete, the HLV is decoupled from the wind turbine, in order to transit to the next wind turbine.
- **Re-commissioning of wind turbines**: When the decoupling of the vessel with the wind turbine is complete, the re-commissioning takes place. The CTV is assumed to be available during re-commissioning, in case transfer of technicians is needed. This activity is assumed to be parallel to the critical path of the maintenance sequence.
- **Return from wind farm site to port**: When all components have been replaced, the two vessels return back to port to be demobilised.

In this strategy, the critical sequence starts with the HLV positioning at site and ends with the vessel - wind turbine decoupling. It should be noted that the end of this replacement strategy is defined by the maximum duration between the re-commissioning of the last wind turbine and the return of the vessels to port. All the required activities, as well as the vessels operations, are characterised by their respective theoretical duration and weather limits, which are based on the available literature [4, 15, 17, 23, 25, 28] and presented in Table 2.8.

Table 2.8: Duration and weather limits for the activities involved in the onsite major replacement (for a single floating unit).

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Rigging installation and loading components	15.0	4.0	-
Position at site	3.0	2.5	-
Vessel - wind turbine coupling	4.0	2.5	-
Onsite replacement	48.0	1.5	12.0
Vessel - wind turbine decoupling	4.0	2.5	-
Re-commissioning	12.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
HLV transit	6.22	10.0	25.0

2.2.3 Semi-submersible offsite major replacement

The next implemented strategy refers to the offsite major replacement of a component of a wind turbine installed on a semi-submersible. Figure 2.7 depicts the sequence of the required activities for the semi-submersible offsite major replacement. A further explanation of these activities follows:

- **Transit from port to wind farm site**: The first step of the offsite strategy is the transit of the vessels to the wind farm site. Two AHVs and two small tug boats are to be used to tow back to port the wind turbines.
- **Vessel - wind turbine coupling**: Then, the next step is positioning at site and coupling with the wind turbine to be towed.
- **Dynamic cable disconnection**: Before the towing is possible, the disconnection of the dynamic cable of the wind turbine is performed.
- **Mooring lines disconnection**: Then, the mooring lines are disconnected, so that the floating unit can be towed.
- **Deballast semi-submersible to transportational draft**: To allow for the towing to port, the semi-submersible is deballasted to its transportational draft.
- **Tow complete floating unit from wind farm site to port**: Finally, the floating unit is towed back to port, where the major replacement will take place.
- **Position complete floating unit at quayside**: Upon arrival at the quayside, extra time is needed for the floating unit to be moored next to the quayside and acquire its necessary ballast so that maintenance operations can be undertaken. When this activity is complete, the vessels transit back to the wind farm site so that they can tow the rest of the wind turbines involved in the maintenance campaign.
- **Offsite major replacement at quayside**: When all wind turbines are towed back to the port, an onshore crane is used to perform the replacement of the major component. During this time, the vessels wait at port in order to tow the wind turbines back to the wind farm site, after their replacement is completed.

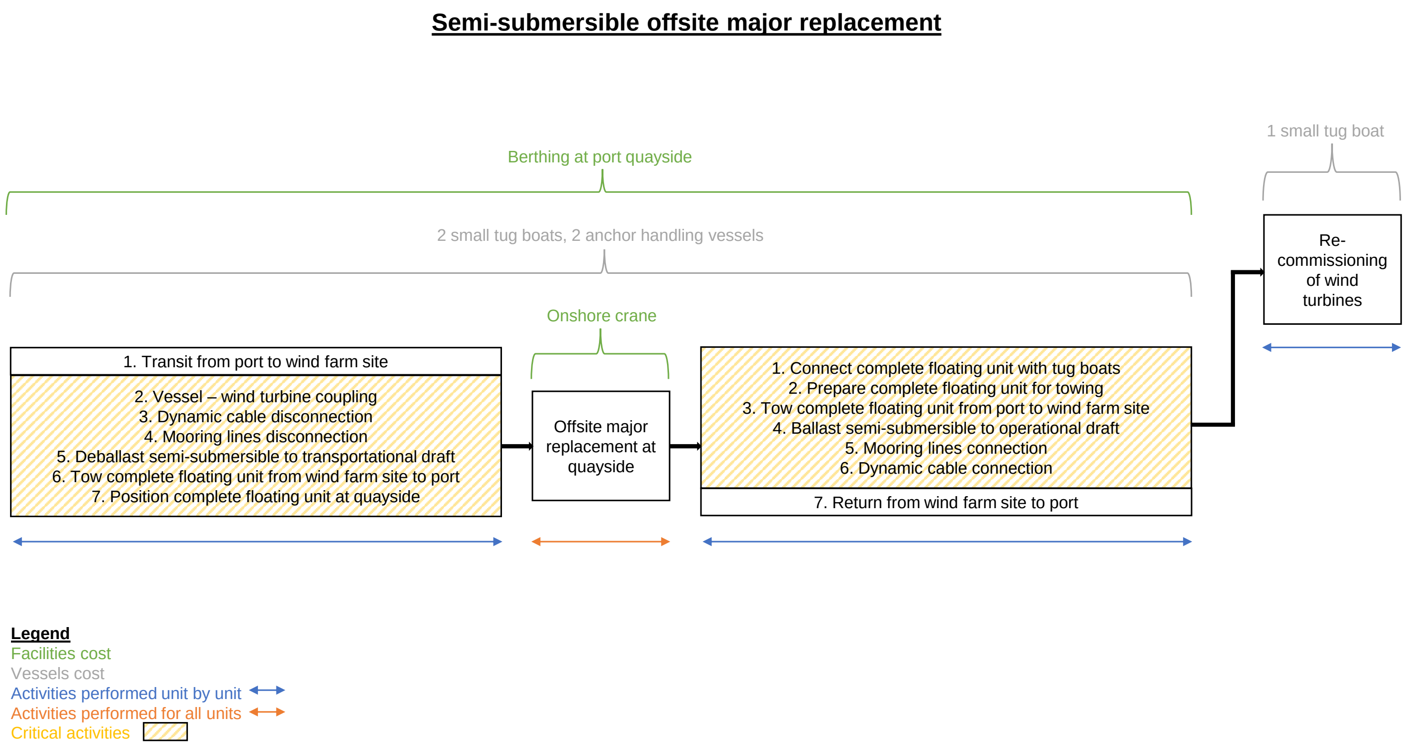


Figure 2.7: Sequence diagram of the semi-submersible offsite major replacement.

- **Connect complete floating unit with tug boats**: After the replacement, the wind turbines are partially re-commissioned and connected with the vessels in order to be towed back to the wind farm site.
- **Prepare complete floating unit for towing**: Then, the floating unit is deballasted again to acquire its transportational draft and it is prepared to leave the O&M port.
- **Tow complete floating unit from port to wind farm site**: Afterwards, the floating unit is towed back to site.
- **Ballast semi-submersible to operational draft**: Upon arrival at the designated location, the floating unit is ballasted to reach its operational draft.
- **Mooring lines connection**: Then, the mooring lines are connected back to the semi-submersible.
- **Dynamic cable connection**: Finally, the dynamic cable is re-connected to the wind turbine so that the electricity production can resume.
- **Return from wind farm site to port**: After the dynamic cable connection, the vessels return back to port to perform the same sequence for the next wind turbine.
- **Re-commissioning of wind turbines**: When cable connection is finalised, the wind turbine is re-commissioned. One small tug boat is assumed to be available during re-commissioning, in case transfer of technicians is needed. This activity is assumed to be parallel to the critical path of the maintenance sequence.

In this strategy, the first critical sequence starts with the vessel - wind turbine coupling at site and finishes with the positioning of the floating unit at quayside. Then, the second critical sequence begins with the connection of the complete floating unit with tug boats to be towed back to wind farm site and ends with the dynamic cable connection.

The complete floating units have to be stored at the quayside. The requirement for quayside space is assumed to have the same duration as the total maintenance campaign. This is a reasonable approach as it is expected that the wind farm operator will rent working space, quayside space and facilities at the port used as O&M base for the whole lifetime of the wind farm. It should be noted that the end of this replacement strategy is defined by the maximum duration of the re-commissioning of the last wind turbine and the return to port of the vessels. All the required activities, as well as the vessels operations, are characterised by their respective theoretical duration and weather limits, which are based on available literature [4, 15, 17, 23, 25, 28] and presented in Table 2.9.

Table 2.9: Duration and weather limits for the activities involved in the semi-submersible offsite major replacement (for a single floating unit).

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Vessel - wind turbine coupling	4.0	2.5	-
Cable disconnection	4.0	1.5	-
Mooring lines disconnection	6.0	1.5	-
Deballast semi-submersible to transportational draft	6.0	2.5	-
Position at quayside	18.0	4.0	-
Replacement at quayside	47.0	4.0	12.0
Connect floating unit	6.0	4.0	-
Prepare floating unit for towing	9.0	4.0	-
Ballast semi-submersible to operational draft	12.0	2.5	-
Mooring lines connection	6.0	1.5	-
Cable connection	9.0	1.5	-
Re-commissioning	9.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Tow floating unit	2.33	2.0	18.0
Free transit	6.11	3.2	30.0

2.2.4 Spar buoy offsite major replacement

The final implemented strategy refers to the offsite major replacement of a component of a wind turbine for a spar buoy floating unit. Due to its high draft, a spar buoy cannot be towed back to port. Therefore, similarly to its installation procedure, a spar buoy needs to be towed to a sheltered location, where the main component replacement takes place with the use of a

HLV. Figure 2.8 depicts the sequence of the required activities for the spar buoy offsite major replacement. A further explanation of these activities follows:

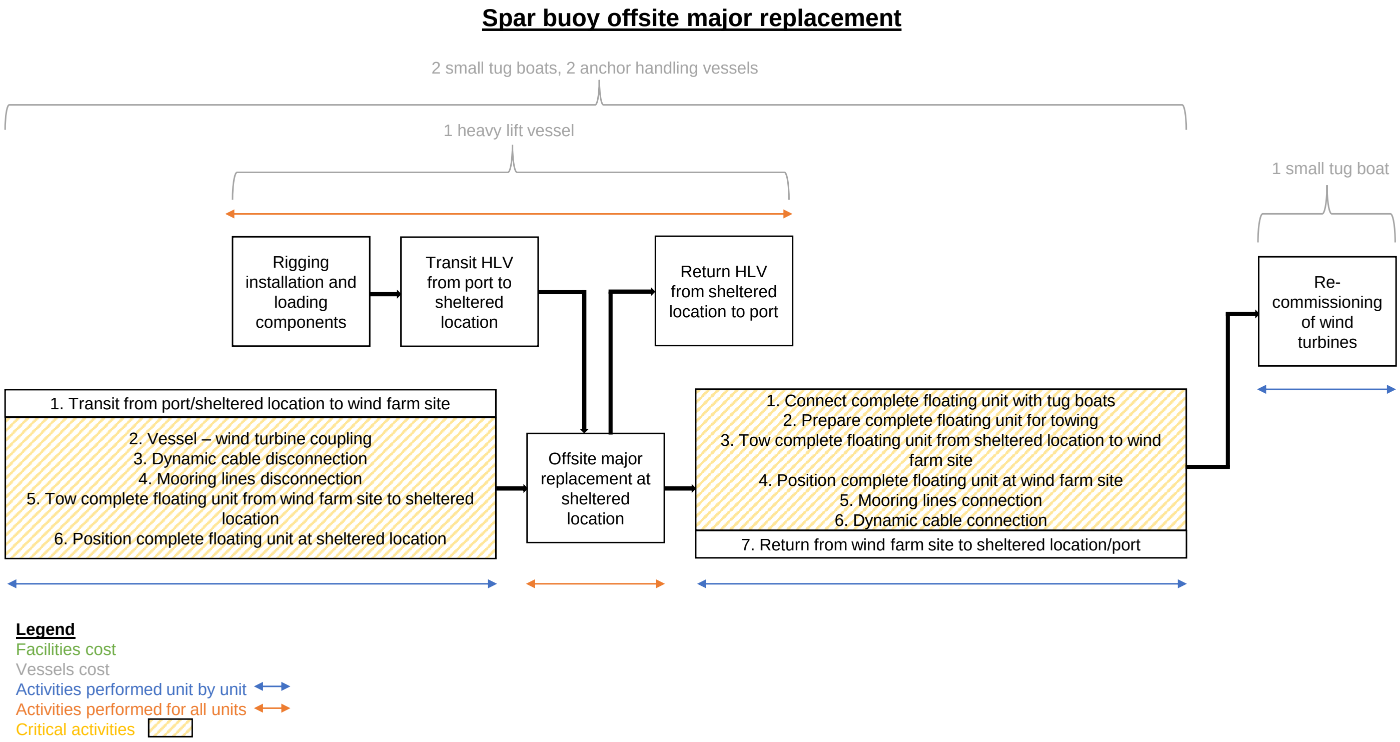


Figure 2.8: Sequence diagram of the spar buoy offsite major replacement.

- **Transit from port/sheltered location to wind farm site**: The first step of the offsite strategy is the transit of the vessels to the wind farm site. Two AHVs and two small tug boats are mobilised to tow back to the sheltered location the floating assemblies.
- **Vessel - wind turbine coupling**: Then, the vessels are positioned at site and coupled with the wind turbine to be towed.
- **Dynamic cable disconnection**: Before the towing is possible, the disconnection of the dynamic cable of the wind turbine is performed.
- **Mooring lines disconnection**: Moreover, the mooring lines are disconnected, so that the floating unit can be towed.
- **Tow complete floating unit from wind farm site to sheltered location**: Finally, the floating unit is towed back to the sheltered location, where the major replacement will take place.
- **Position complete floating unit at sheltered location**: Upon arrival at the sheltered location, extra time is needed for the floating unit to be positioned so that maintenance operations can be undertaken. When this activity is complete, the vessels transit back to wind farm site so that they can tow the rest of the wind turbines of the maintenance campaign.
- **Rigging installation and loading components**: Sufficient time is needed for rigging installation and loading the components to be used as replacement at the sheltered location.
- **Transit HLV from port to sheltered location**: A HLV is mobilised and transits to the sheltered location to perform the replacement of the major components of all wind turbines.
- **Offsite major replacement at sheltered location**: When all wind turbines are towed back to the sheltered location, a HLV is used to perform the replacement of the major

components. During this time, the vessels wait at the sheltered location in order to tow the wind turbines back to the wind farm site, after their replacement is completed.

- **Return HLV from sheltered location to port**: When all major replacements are performed, the HLV returns back to port to be demobilised. This activity, as well as the rigging installation and loading of components and the HLV transit to sheltered location, do not belong to the critical path of the maintenance campaign, albeit they are performed in parallel.
- **Connect complete floating unit with tug boats**: After the replacement, the wind turbines are partially re-commissioned and connected with the vessels in order to be towed back to the wind farm site.
- **Prepare complete floating unit for towing**: Then, the floating unit is prepared to leave the sheltered location.
- **Tow complete floating unit from sheltered location to wind farm site**: Afterwards, the floating unit is towed back to site.
- **Position complete floating unit at wind farm site**: Upon arrival at the wind farm site, the floating unit is positioned at its designated location.
- **Mooring lines connection**: Then, the mooring lines are connected back to the spar buoy.
- **Dynamic cable connection**: Finally, the dynamic cable is re-connected to the wind turbine so that the electricity production can resume.
- **Return from wind farm site to sheltered location/port**: When the dynamic cable connection is complete, the vessels transit back to sheltered location so that they can tow the rest of the wind turbines of the maintenance campaign.
- **Re-commissioning of wind turbines**: When the cable connection is finalised, the re-commissioning of the wind turbine is performed. One small tug boat is assumed to be available during re-commissioning, in case transfer of technicians is needed. This activity is assumed to be parallel to the critical path of the maintenance sequence.

In this strategy, the first critical sequence starts with the vessel - wind turbine coupling and ends with the positioning of the complete floating units at the sheltered location. Then, the second critical sequence begins with the connection of the floating units with tug boats to be towed back to the wind farm site and ends with their dynamic cable connection.

It should be noted that the end of this replacement strategy is defined by the maximum duration of the re-commissioning of the last wind turbine and the return of the vessels to port. All the required activities, as well as the vessels operations, are characterised by their respective theoretical duration and weather limits, which are based on literature [4, 15, 17, 23, 25, 28] and presented in Table 2.10.

Table 2.10: Duration and weather limits for the activities involved in the spar buoy offsite major replacement (for a single floating unit).

Activity	**Duration (h)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Vessel - wind turbine coupling	4.0	2.5	-
Cable disconnection	4.0	1.5	-
Mooring lines disconnection	9.0	1.5	-
Position at sheltered location	18.0	4.0	-
Rigging installation and loading components	15.0	4.0	-
Replacement at sheltered location	48.0	2.5	12.0
Connect floating unit	6.0	4.0	-
Prepare floating unit for towing	9.0	4.0	-
Position at site	9.0	2.5	-
Mooring lines connection	9.0	1.5	-
Cable connection	9.0	1.5	-
Re-commissioning	9.0	-	-
Activity	**Speed (m/s)**	**Significant wave height limit (H_s) (m)**	**Wind speed limit (U_{100}) (m/s)**
Tow floating unit (tug boat)	1.47	2.0	18.0
Free transit (tug boat)	6.11	3.2	30.0
HLV transit	6.22	10.0	25.0

2.3 Wind farm and daily rates assumptions

In this section, the reference wind farm used for this thesis is introduced, as well as assumptions related to the daily rates of vessels and port facilities and other incurred costs. In subsection 2.3.1, the specifications of the selected wind turbine and floaters are listed. In subsection 2.3.2, the location of the wind farm site, the port and the shipyard is presented. In subsection 2.3.3 the daily rates and the mobilisation costs of different vessels as well as required facilities and personnel costs are offered. Moreover, the calculation of the required shipyard and port storage as well as the lost revenue during downtime are presented.

2.3.1 Specifications of wind farm components

The main specifications of the IEA 15-MW reference wind turbine are listed in Table 2.11. It should be noted that the tower height should be adapted to match the desired hub height depending on the height of the interface between the tower base and the floating sub-structure

[4]. Furthermore, the assumption of a nacelle diameter of 9.0 m and a nacelle length of 7.0 m is made. This assumption is not critical to the outcome of the thesis, as it is only relevant for the calculation of the port storage cost.

Table 2.11: Main specifications of the IEA 15-MW offshore reference wind turbine [13].

Parameter	**Value**	**Parameter**	**Value**
Power rating (MW)	15	Hub height (m)	150
Cut-in wind speed (m/s)	3.00	Blade mass (ton)	65.25
Rated wind speed (m/s)	10.59	Nacelle mass (ton)	630.89
Cut-out wind speed (m/s)	25.00	Hub mass (ton)	190.00
Rotor diameter (m)	240	RNA mass (ton)	1016.64
Blade length (m)	117	Tower mass (ton)	860.00
Maximum blade chord (m)	5.77		

For the scope of this thesis, two different sub-structures are examined, due to their high potential: semi-submersibles and spar buoys. The WindCrete (spar buoy) and ActiveFloat (semi-submersible) [14] concrete sub-structures designed to support the 15-MW IEA reference wind turbine are used for this study. Technical specifications for both the designs are reported in Table 2.12.

Table 2.12: Main specifications of the selected sub-structures to be mated with the IEA 15-MW reference wind turbine [14].

Semi-submersible		**Spar buoy**	
Parameter	**Value**	**Parameter**	**Value**
Length (m)	76.0	Length (m)	155.0
Breadth (m)	83.9	Diameter (m)	18.6
Floater mass including ballast (tons)	34,387	Floater mass including ballast (ton)	39,805
Tower base diameter (m)	10.00	Tower base diameter (m)	13.20
Tower diameter at 40% height (m)	8.60	Tower diameter at 40% height (m)	10.35

2.3.2 Wind farm location

The exact location of the wind farm site is not of utmost importance for the scope of this thesis, since the aim is to find some general conclusions over the optimum installation and O&M strategies of floating wind farms, which are not related to a specific site. However, one location should be decided upon, representative of far-offshore weather conditions. For this reason, the selection of a far-offshore location was made inside the Exclusive Economic Zone (EEZ) of the Netherlands, approximately 200 km from shore. The coordinates of this location are 55.0°N 4.15°E. It is assumed that the water depth at the far-offshore site is sufficient to allow for the installation of a spar buoy. The 30-year reanalysis weather time series acquired from LAUTEC database [43] for this location are used for all the activities that are performed at the wind farm site.

In addition, near shore weather time series are needed for all the activities that are performed at port or shipyard or at sheltered location. For this reason, a node from the LAUTEC database [43] located in the proximity of the Northern shore of the Netherlands - coordinates 52.45°N 4.45°E - was selected as representative of the near-shore wind climate. While the port, shipyard and sheltered location are assumed not to be adjacent during the simulation, the weather conditions of each one of them is based on the 30-year weather time series acquired from [43] for the near-shore location specified. Similarly, as in the case of the wind farm site, the water depth at the sheltered location is assumed to be greater than the draft of the spar buoy. Finally, for activities performed between the wind farm site and onshore/near-shore locations, such as the towing of a complete floating unit from the port to the wind farm site, the average of the offshore and near-shore weather data are used. It should be noted that, during the simulations, significant wave height and wind speed at 100 m height are examined as limiting conditions for installation and maintenance activities, while wave period is neglected.

The simulations are based on 25-year weather time series obtained for the wind farm site and near-shore location. The selection of 25 over 30 years is made, in order to allow the simulations beginning at the end of the 25th year to be concluded without running out of available time steps. The installation and O&M sequences are assumed to begin every hour of these 25 years, and the average results of all these simulations are used as the representative values of the respective strategies. A 24-hour long work day has been assumed for all operations. Furthermore, for the installation campaigns, the simulations are performed for three different periods, namely: Spring-Summer period (21st March - 20th September), Autumn-Winter period (21st September - 20th March) and the whole year. This division is made, since it is a common practice that offshore operations do not occur during the winter period, due to adverse weather conditions. Therefore, it is interesting to examine whether it is more economically viable to perform all installation activities during the spring-summer period and halt all operations during the autumn-winter one, or if it is more efficient to perform the installation sequence throughout the whole year.

A base case scenario is assumed for all time periods, the characteristics of which are presented in Table 2.13. In addition, the weather limits of each activity and vessel operation, which are elaborated in sections 2.1 and 2.2, are assumed to be constant during the base case scenario. Moreover, a sensitivity analysis is performed on the parameters that highly influence the total cost and duration of the installation and O&M strategies: distance from shore/port and operational limits for the different activities. For these parameters, the effect of a decrease up to 50% and of an increase up to 50% of their nominal values is examined, with intervals of 5%. As a result, each simulation is run 42 times in order to gain a better insight into the dependence of installation and O&M costs and duration upon distance from shore/port and vessels operational limits.

It is worth mentioning that the same weather data are used throughout the sensitivity analyses. Despite the changing distance from shore, it is assumed that the selected weather data are representative of far-offshore locations, either the wind farm is based 100 or 300 km from shore. Furthermore, it is assumed that the same vessel equipment is mobilised and used, even when the distance from shore increases further than the base case distance of 200 km.

Table 2.13: Base case scenario characteristics.

Parameter	**Value**
Number of wind turbines (-)	30
Distance shipyard - port (km)	200
Distance port - wind farm site (km)	200
Distance shipyard - wind farm site (km)	200
Distance shipyard - sheltered location (km)	200
Distance port - sheltered location (km)	20
Distance sheltered location - wind farm site (km)	180

2.3.3 Cost assumptions

Other key inputs for the installation and O&M strategies are the vessel daily rates and their mobilisation costs, as well as other costs associated with port and shipyard activities. Vessels costs are highly volatile as they are heavily dependent on market supply and demand. In the context of this research, the cost estimation was carried out based on the existing literature [4, 6, 8, 15, 18, 20, 23, 25, 27, 28, 31, 38], which is reported in Table 2.14. The mobilisation costs are assumed to be equal to 3.5 daily rates.

Table 2.14: Vessel rates and mobilisation costs.

Vessel	**Daily rate (€/day)**	**Mobilisation cost (€)**
CTV	2,050	7,175
W2W	35,000	122,500
Small tug boat	4,500	15,750
Large tug boat	28,350	99,225
AHV	43,150	151,025
CLV	61,550	215,425
Working barge	33,400	116,900
HLV	467,950	1,637,825
Large sized crane barge (used at 2.1.2)	128,500	449,750
Medium sized crane barge (used at 2.1.4)	56,100	196,350

In addition to the vessel costs, the total installation and maintenance costs comprise also facilities costs, including the use of slipways and onshore cranes as well as the port/shipyard storage space and the quayside space requirements. The latter is applicable only for the semi-submersible installation at quayside and offsite major replacement. Similarly to the vessels, the exact values of these costs are highly volatile. In the context of this thesis, port and shipyard costs are based on the existing literature, and are presented in Table 2.15.

Table 2.15: Facilities costs of the installation and maintenance campaigns.

Type of cost	**Value**	**Sources**
Slipway hourly rate (€/h)	850.0	[4]
Crane hourly rate (€/h)	850.0	[8, 20, 28]
Storage daily rate (€/(day*m^2)	0.2	[44]
Berthing daily rate (€/(day*unit)	300.0	[45]

During the installation procedure, both the floaters and the wind turbine components need to be stored at the shipyard and port facilities, respectively. The area of the required shipyard storage for the case of semi-submersibles is given by equation 2.3.1, while for the case of spar buoys by equation 2.3.2:

$$S_{shipyard} = 1.1 * N_{WTG} * L_{semi} * B_{semi} \tag{2.3.1}$$

$$S_{shipyard} = 1.1 * N_{WTG} * L_{spar} * D_{spar} \tag{2.3.2}$$

where $S_{shipyard}$ is the required shipyard storage surface, N_{WTG} is the number of wind turbines, L is the length of the floaters, B_{semi} is the breadth of the semi-submersible and D_{spar} is the diameter of the spar buoy. A coefficient of 1.1 is used to ensure enough space for internal movements.

The area of the required port storage for all installation strategies is given by equation 2.3.3:

$$S_{port} = 1.1 * N_{WTG} * (\frac{\pi}{4} * (D^2_{lower} + D^2_{upper}) + 3 * L_{blade} * L_{chord} + D_{nacelle} * L_{nacelle}) \tag{2.3.3}$$

where S_{port} is the required port storage surface, N_{WTG} is the number of wind turbines, D_{lower} is the base diameter of the lower section of the tower of the wind turbine, D_{upper} is the base diameter of the upper section of the tower of the wind turbine, L_{blade} is the length of one blade, L_{chord} is the maximum chord of one blade, $D_{nacelle}$ is the nacelle diameter and $L_{nacelle}$ is the nacelle length. A coefficient of 1.1 is used to ensure enough space for internal movements.

Moreover, during the cost calculation of the maintenance strategies, the number of required technicians is introduced. Depending on the type of the required maintenance, different number of technicians are used. According to [42], for a minor repair a team of two technicians is needed, while for a major repair a team of three. In addition, a team of eight technicians is required for a major replacement. Since the length of the working day is set to be equal to 24 hours, two shifts of teams are used per day for all strategies. Finally, the daily rate of a single technician is set to be 200 €/day [17].

During the maintenance procedure, the lost revenue due to the downtime of the wind turbines is calculated as an additional cost. This is an important factor for the selection of the optimal O&M strategy, as strategies with longer duration result in higher lost revenue due to the increased downtime. Therefore, a trade-off can be identified between a fast maintenance strategy with the use of expensive vessels and a slower one with the use of cheaper vessels. As a base case scenario, a fixed electricity price of 100 €/MWh is assumed. For the calculation of the energy output of a single wind turbine, equation 2.3.4 is used:

$$P_{WTG} = \begin{cases} 0, & \text{if } U_{hub} < U_{cut-in} \\ \frac{1}{2} * \rho_{air} * c_p * U_{hub}^3 * \frac{\pi}{4} * D_{WTG}^2, & \text{if } U_{hub} < U_{rated} \\ P_{rated}, & \text{if } U_{hub} < U_{cut-out} \\ 0, & U_{hub} > U_{cut-out} \end{cases} \tag{2.3.4}$$

where P_{WTG} is the power output of a wind turbine, ρ_{air} is the air density equal to 1.225 kg/m^3 and c_p is the optimal power coefficient of the reference wind turbine equal to 0.456. The remaining specifications of the reference wind turbine can be found at Table 2.11. For the estimation of the energy losses, the time series of wind data (height of 100 m) have been extrapolated to hub height (height of 150 m) with power law, using an offshore power law exponent equal to 0.11.

2.4 Code implementation

In Figure 2.9, the implementation of a critical sequence in the installation code is shown for a better understanding of how these activities are simulated. A similar approach is used for the maintenance campaigns. The critical sequence consisting of connection of turbine for towing, towing to wind farm site, positioning at site and offshore installation is depicted, as this is applied in all installation strategies apart from the semi-submersible installation with wind turbine assembly at wind farm site. In the given flowchart, a counter for each activity is used in order to determine its completion. If this counter becomes greater or equal than the theoretical duration of this activity, then the activity is considered to be completed and then the calculation of the counter of the next activity begins. If one of the weather limits of the activities of the critical sequence is not satisfied, then all counters are set to zero and the whole process should start from the beginning with the next time step. In this case, a total counter for each critical sequence is incremented to account for the delay due to waiting on weather. This procedure is iterated until all separate activities can be performed with no interruption due to weather conditions. A similar procedure is followed for non-critical activities.

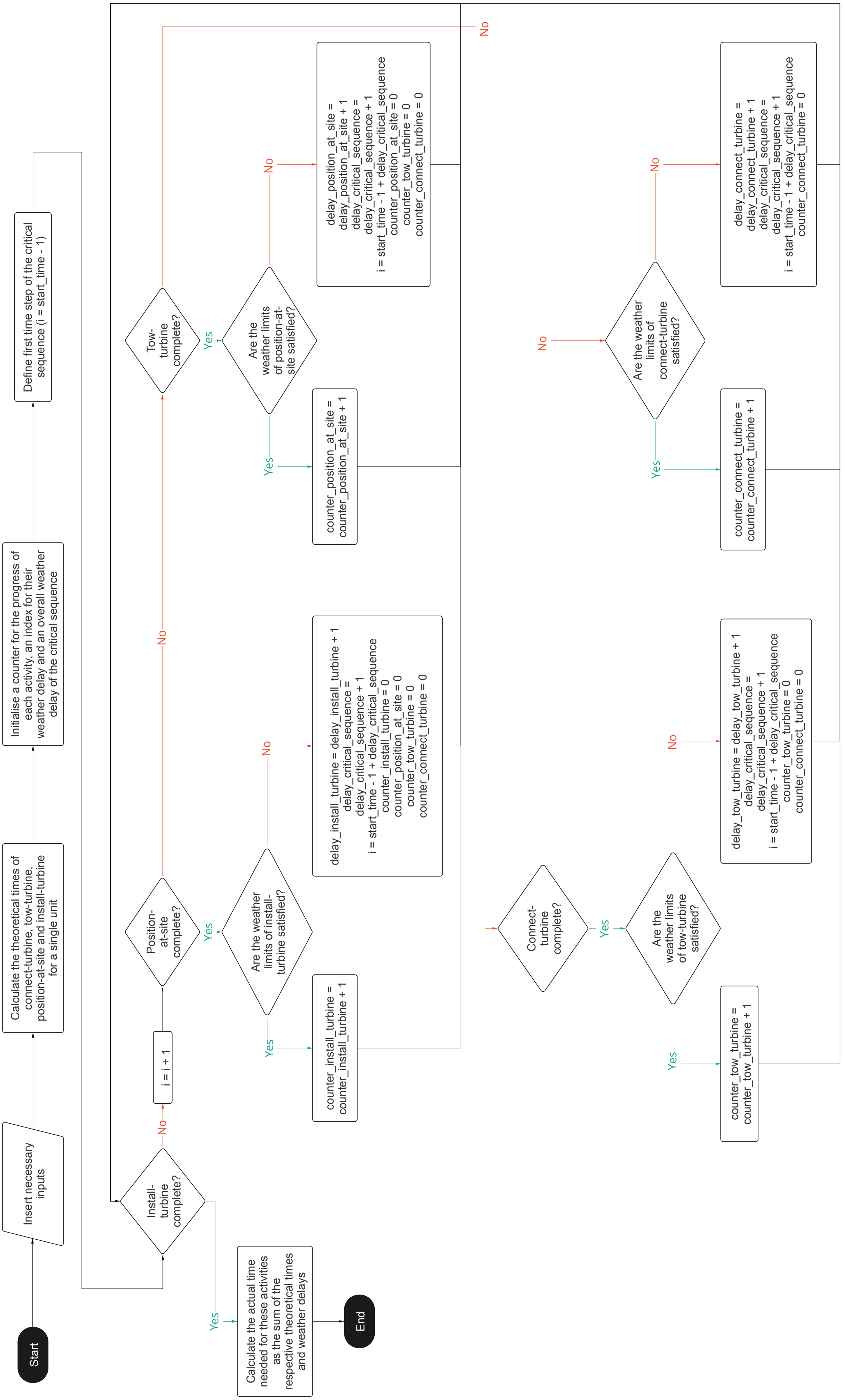


Figure 2.9: Flowchart of one critical sequence in the installation code.

3 | Installation Results

In this Chapter, the main results of the simulation of the different installation strategies are presented. In section 3.1, the installation base case scenario results are presented for all strategies. In addition, in section 3.2, the weather delays of various activities as well as cost and duration histograms of all strategies are presented. Finally, in section 3.3, the results of the sensitivity analysis are detailed.

3.1 Installation base case comparison

The comparison of the different strategies is first undertaken for the base case scenario. In Figure 3.1, the total facilities and vessels cost per MW of the different installation strategies for all examined time periods are presented. The facilities costs include the cost of slipway, onshore cranes, port and shipyard storage as well as berthing, when applicable. The costs of the vessels include both their mobilisation costs and their cumulative daily rates over the hiring period.

The operational costs of the vessels represent the largest percentage of the total installation costs of the floating wind farm. Moreover, during the spring-summer period, the costs are substantially lower than for the autumn-winter case. This is due to the adverse weather conditions in the bad season, resulting in increased weather delay for all operations and therefore longer duration of the whole installation sequence. This increased duration is accompanied by higher cumulative daily vessel rates as well as longer hiring time of shipyard and port facilities. Thus, a total increase of both the facilities and vessels costs can be observed. It is evident that performing all the installation activities during the spring-summer months could result in lower installation costs compared to the yearly operation. However, in case the installation of all the units in the wind farm was to exceed the allocated time frame, operations would continue the following year. Then, vessels' mobilisation and demobilisation costs might have to be repaid and hiring port/shipyard facilities might need to be extended for the next year, but with a smaller required storage area. Therefore, the difference between limiting the operations to the good season or extending them to the whole year will decrease to some extent.

This conclusion can be drawn for all the examined installation strategies. However, it is important to compare the installation costs of the implemented strategies for the same time periods. From Figure 3.1, it is evident that the semi-submersible installation with wind turbine assembly at quayside is the least expensive option for all time periods, with a total installation cost of 69.9 k€/MW for the spring-summer period and 108.8 k€/MW for the yearly one. The spar buoy installation with HLV follows, with a total installation cost of 107.0 k€/MW for the spring-summer period and 163.1 k€/MW for the yearly one. This proves the big advantage of floating wind turbines; their ability to perform operations offsite. The spar buoy installation with crane barge and the semi-submersible installation with wind turbine assembly at wind farm site are less cost-effective, ranking respectively third and fourth in terms of cost-convenience. The assembly of wind turbines with semi-submersible floaters at wind farm site results in high installation costs, as the whole procedure is highly susceptible to the far-offshore weather conditions. While a total cost increase of 56% is observed between the spring-summer and the yearly operation of the semi-submersible installation with wind turbine assembly at quayside, a total cost increase of 78% is observed in the semi-submersible installation with wind turbine assembly at wind farm site.

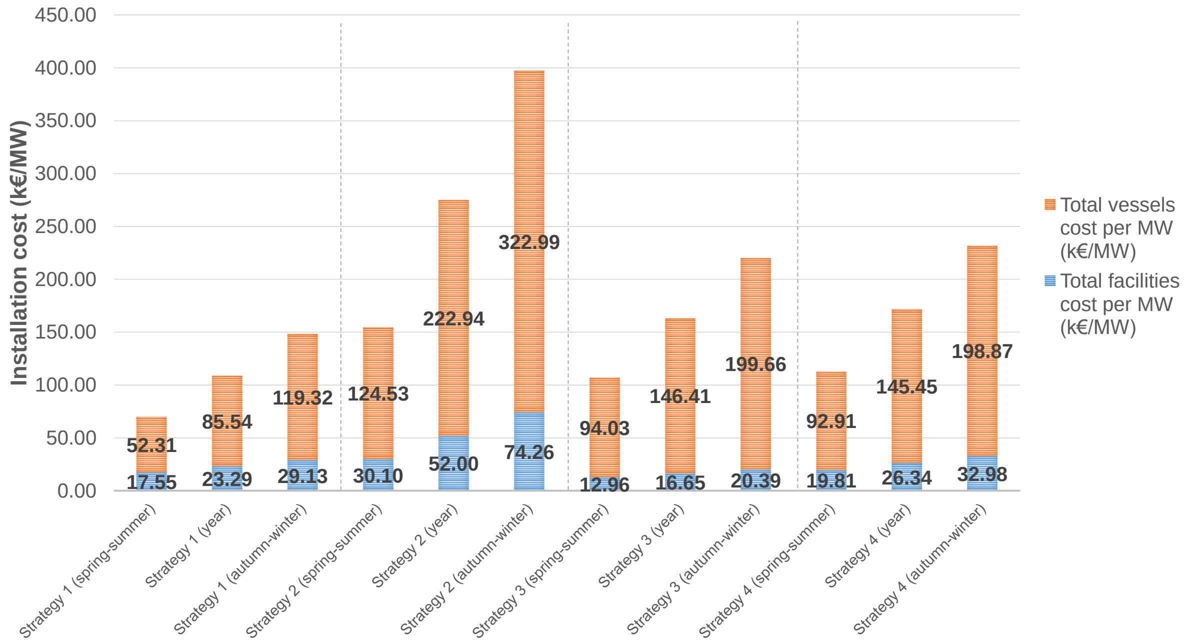


Figure 3.1: Total facilities and vessels cost per MW for the base case scenario of the examined installation strategies. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation wind wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.

The conclusions which can be drawn by the comparison of the different spar buoy installation strategies are not so evident, as the ones derived from the semi-submersible ones. From Figure 3.1, it is clear that the vessel costs for both strategies are almost identical during all the examined time periods, with a yearly increase, compared to the spring-summer one, of 52% for both cases. Therefore, using a cheaper crane barge does not provide a significant cost advantage, as the crane barge has to be deployed for longer periods. Due to this higher duration of the installation sequence, the cost of shipyard and port facilities for the spar buoy installation with crane barge are higher than the installation with the deployment of the HLV, as the storage duration of wind turbine components is increased. Nevertheless, as the prices of the vessels are quite volatile, one or the other strategy might prove to be more economically promising for wind farm developers.

Similar conclusion can be drawn from Figure 3.2, where the installation duration per floating unit is examined for all strategies. It is clear that due to more favourable weather conditions, installation during the spring-summer months results in lower installation time. However, the yearly duration increase is in the order of 43-47% for all strategies, except for semi-submersible installation with wind turbine assembly at site, where it is in the order of 66%. Furthermore, as previously explained, the spar buoy installation with crane barge results in higher duration than the spar buoy installation with HLV, due to the increased number of trips required for the assembly of the wind turbines and the spar buoys at the sheltered location. Moreover, despite its high dependence on far-offshore weather conditions, the duration of the semi-submersible installation with wind turbine assembly at wind farm site is comparable to spar buoy installation strategies, as it involves a reduced number of required activities. Overall, the semi-submersible installation with quayside assembly of wind turbines and floaters, seems to be the most promising strategy for the floating wind farm, also as far as the expected duration of the installation sequence is concerned.

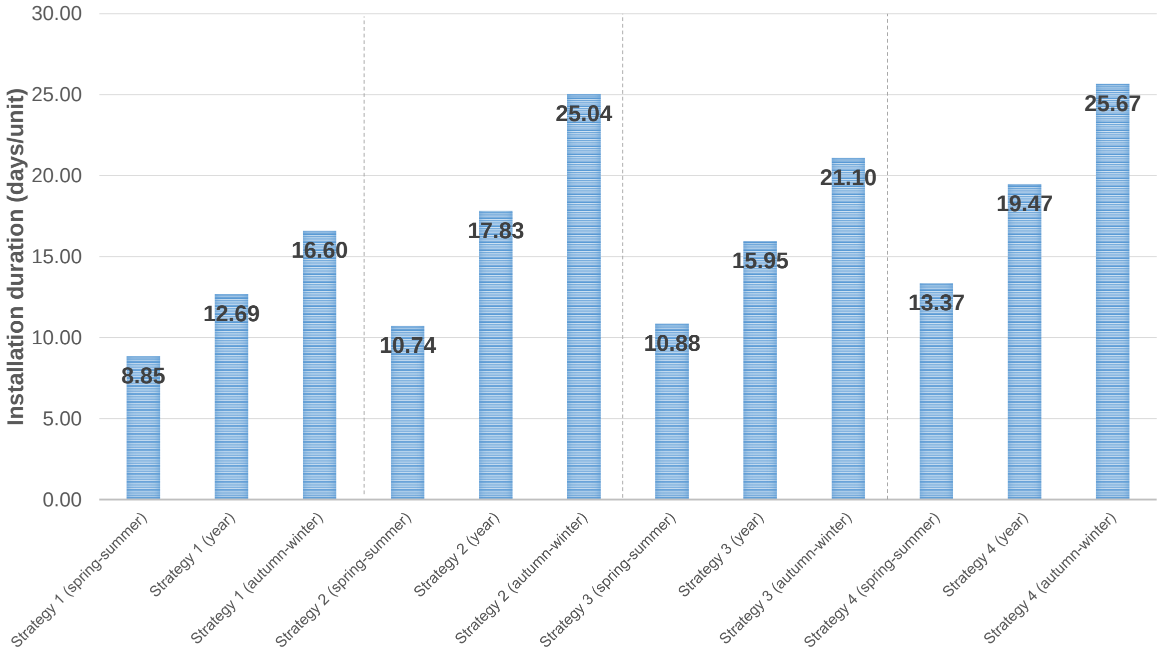


Figure 3.2: Installation duration per floating unit for the base case scenario of the examined installation strategies. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation with wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.

3.2 Seasonal evaluation of installation strategies for the base case scenario

A relevant item when dealing with floating wind farms' installation is the seasonal evaluation of all installation strategies in order to get better insight into the best period to execute the installation sequence. In this section, the waiting on weather and the weather delay of all installation strategies are addressed for all examined time periods, for the base case scenario. It should be noted that, in this thesis, waiting on weather refers to the absolute increase of the duration of each activity due to the implemented weather limits, while the weather delay is defined as the percentage increase of the theoretical duration of one activity, given by equation 3.2.1:

$$WeatherDelay = \frac{AverageDuration - TheoreticalDuration}{TheoreticalDuration} * 100\% \qquad (3.2.1)$$

where Average Duration is the average duration of each activity after the 25-year simulations and Theoretical Duration is the net duration of each activity, if there were no weather limits. It should be noted, however, that since this weather delay is based on the theoretical duration of each activity, some activities with small net duration might be characterised by very high weather delay, even if their actual waiting on weather is not very significant.

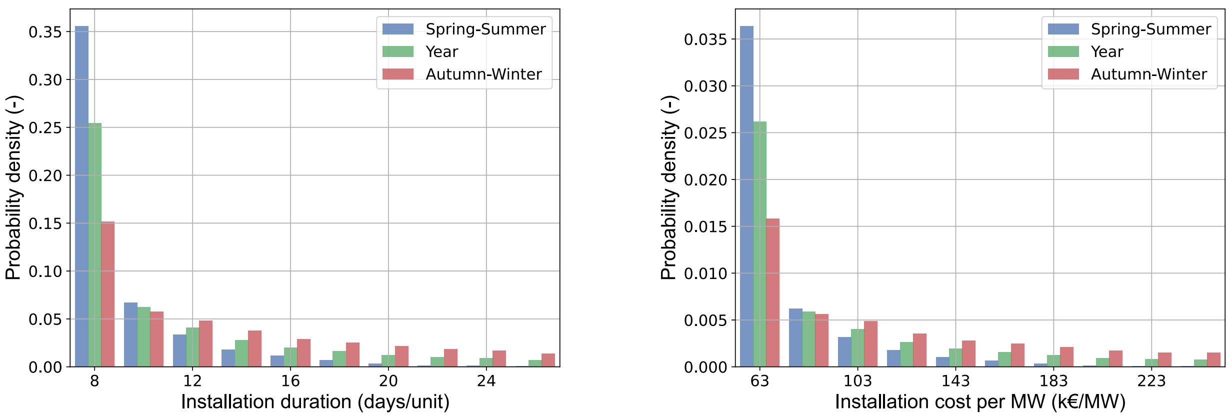
As observed in Figures 3.4, 3.6, 3.8 and 3.10, the waiting on weather and weather delays during the autumn-winter months are much higher than the ones during the spring-summer period for all installation strategies, as the weather conditions are much more severe and limiting for offshore activities. Furthermore, the density histograms of the installation duration per floating unit and the total installation cost per MW of all installation strategies, are presented in Figures

3.3, 3.5, 3.7 and 3.9. As expected, the installation cost and duration are lower during the spring-summer period compared to the yearly and the autumn-winter ones. The left-side bins of the spring-summer case are characterised by higher probability density, while the right-side bins of the autumn-winter period are characterised by higher probability density than the spring summer case. It should be noted that only a selected number of bins is presented in Figures 3.3, 3.5, 3.7 and 3.9, as a small number of simulations results in higher cost and duration. However, these extreme results are omitted to focus on the interesting portion of the figures. Thus, the area of the histograms is lower than 1.

The structure of this section follows; in subsection 3.2.1, the seasonal evaluation of semi-submersible installation with wind turbine assembly at quayside is introduced, and the evaluation of the semi-submersible installation with wind turbine assembly at wind farm site is presented in subsection 3.2.2. Then, the seasonal evaluations of the spar buoy installation with HLV and with crane barge are reported in subsections 3.2.3 and 3.2.4, respectively.

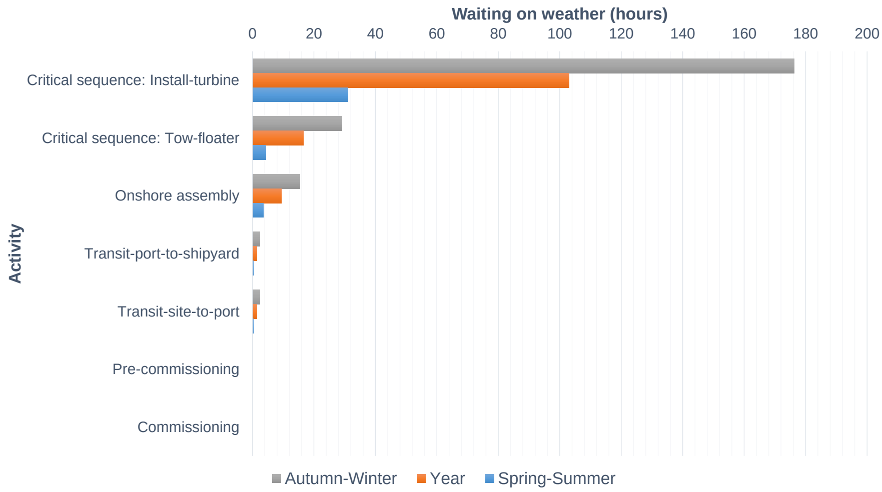
3.2.1 Seasonal evaluation of semi-submersible installation with wind turbine assembly at quayside

As it can be observed in Figure 3.4a, for the case of the semi-submersible installation with wind turbine assembly at quayside, the critical activities of installation of the wind turbines at site and towing of the floaters are the ones resulting in the highest waiting on weather for all time periods (up to 103 h and 17 h, respectively, during yearly simulation). This is mainly due to the restrictive weather limits of far-offshore activities and the long weather windows required for the towing operations. Onshore assembly is the next activity with the highest share of the total waiting on weather. This depends on the fact that the assembly of the wind turbine onshore is highly susceptible to wind conditions at hub height, thus resulting in considerable weather delays. As previously explained, in Figure 3.4b, it is evident that onshore assembly is characterised by higher weather delay compared to the critical sequence of towing of the floaters, a conclusion which can be explained by the shorter net duration of the former activity compared to the latter.

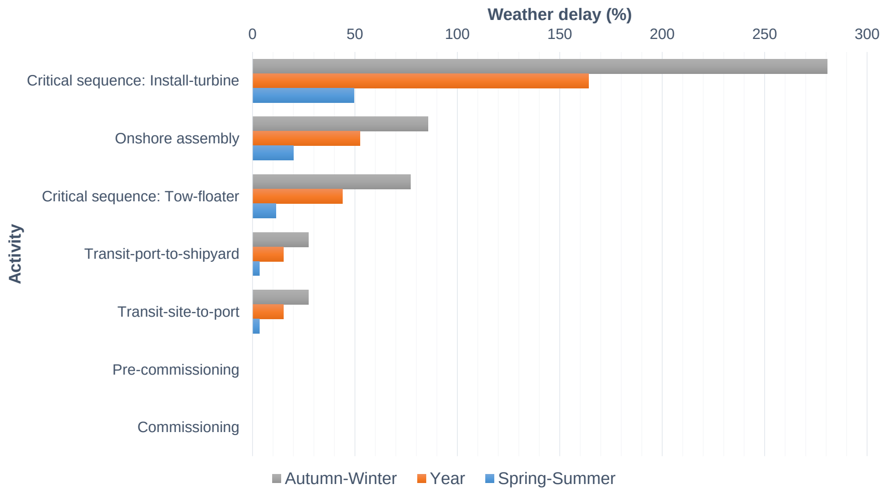


(a) Duration histogram (b) Cost histogram

Figure 3.3: Histograms of installation duration per floating unit and total installation cost per MW of the semi-submersible installation with wind turbine assembly at quayside for the three examined time periods.



(a) Waiting on weather

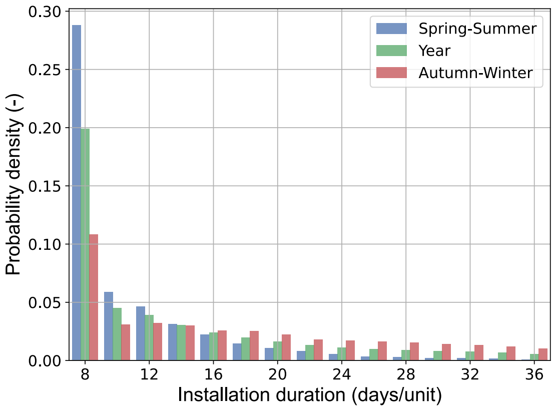


(b) Weather delay

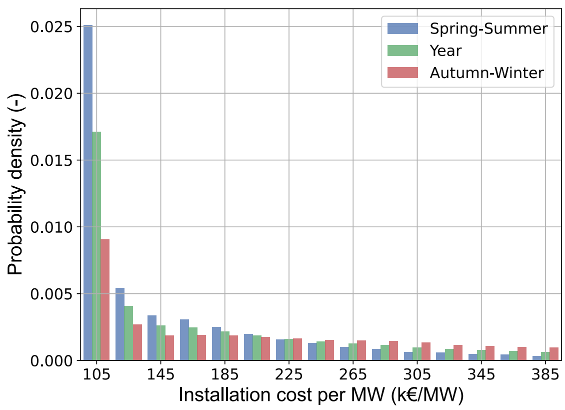
Figure 3.4: Waiting on weather and weather delay of installation activities of the semi-submersible installation with wind turbine assembly at quayside for the three examined time periods.

3.2.2 Seasonal evaluation of semi-submersible installation with wind turbine assembly at wind farm site

As it can be observed in Figure 3.6a, for the case of the semi-submersible installation with wind turbine assembly at wind farm site, the critical sequence of offshore wind turbine installation and the critical sequence of installing the floaters at site are the ones with the highest waiting on weather for all time periods (up to 153 h and 64 h, respectively, for the yearly installation case). This is mainly due to the restrictive weather windows and high duration of the offshore assembly and the towing operations. The transit of the turbine components is the next activity with the highest share of the total waiting on weather. This is due to the requirements for a long weather window in harsh weather conditions. In Figure 3.6, it is clear that the same order of activities for both waiting on weather and weather delay is observed.

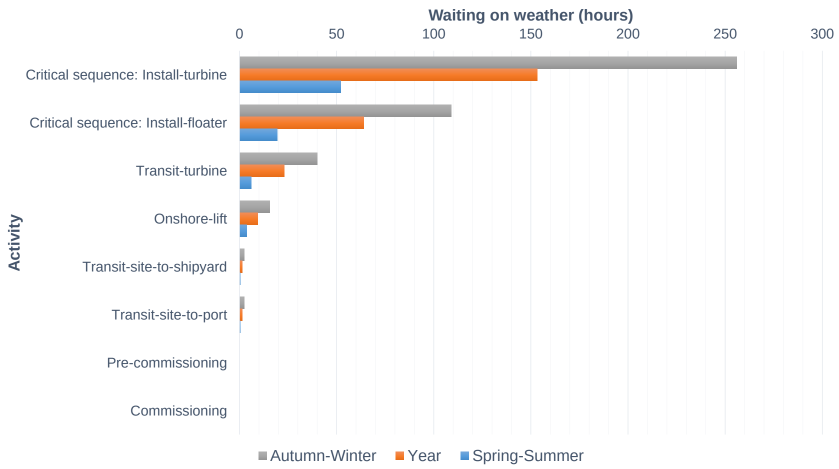


(a) Duration histogram

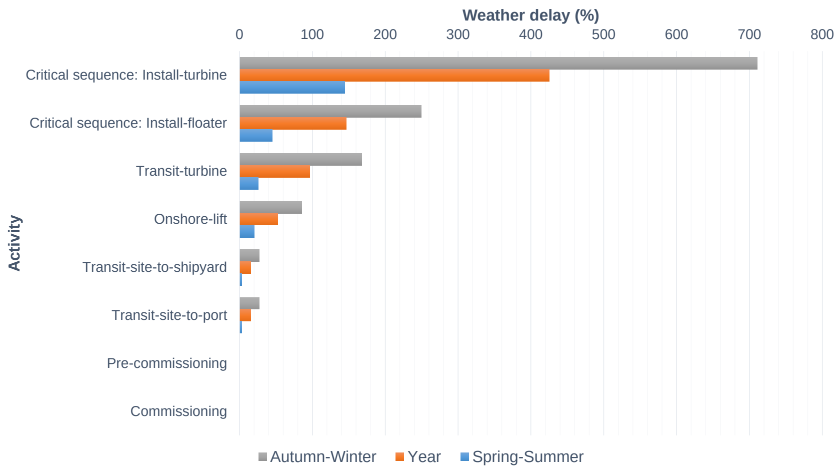


(b) Cost histogram

Figure 3.5: Histograms of installation duration per floating unit and total installation cost per MW of the semi-submersible installation with wind turbine assembly at wind farm site for the three examined time periods.



(a) Waiting on weather



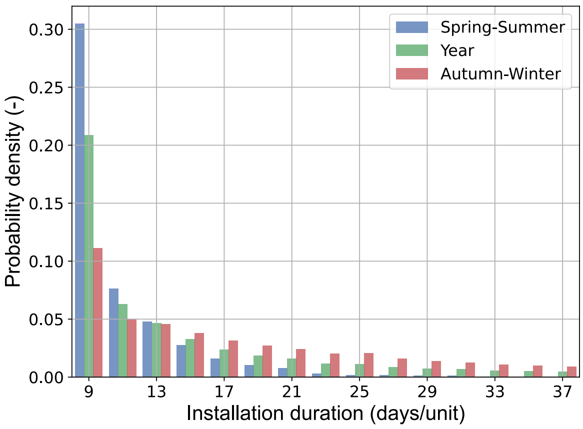
(b) Weather delay

Figure 3.6: Waiting on weather and weather delay of installation activities of the semi-submersible installation with with turbine assembly at wind farm site for the three examined time periods.

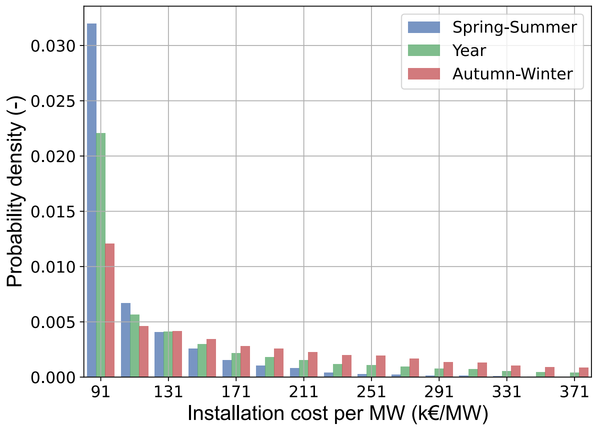
3.2.3 Seasonal evaluation of spar buoy installation with HLV

As it can be observed in Figure 3.8a, for the case of the spar buoy installation with HLV, the critical activities of installation of the wind turbines at site and towing of the floaters are the ones with the highest waiting on weather for all time periods (up to 128 h and 24 h, respectively, during yearly simulation). This is again related to the restrictive offshore weather limits and long weather-window requirements of the towing operations. The critical sequence of mating the wind turbine with the spar buoy is the next activity with the highest share of the total waiting on weather. This can be explained, as this critical sequence is characterised by relative high duration and restrictive significant wave height and wind speed limits. As it can be observed in Figure 3.8b, the critical sequence of mating the wind turbines with the spar buoys has higher weather delay compared to the critical sequence involving the towing of the floaters, a conclusion which can be explained by the shorter duration of the former critical sequence compared to the latter.

Furthermore, as it is shown in Figure 3.7, the probability density of the left-side bins of this strategy, is lower compared to the semi-submersible installation with wind turbine assembly at quayside (see Figure 3.3), but higher than the semi-submersible installation with wind turbine assembly at wind farm site (see Figure 3.5), thus supporting the conclusions presented in section 3.1, that spar buoy installation with HLV is more weather dependent than the semi-submersible installation with wind turbine assembly at quayside, but less weather dependent than the semi-submersible installation with wind turbine assembly at wind farm site.

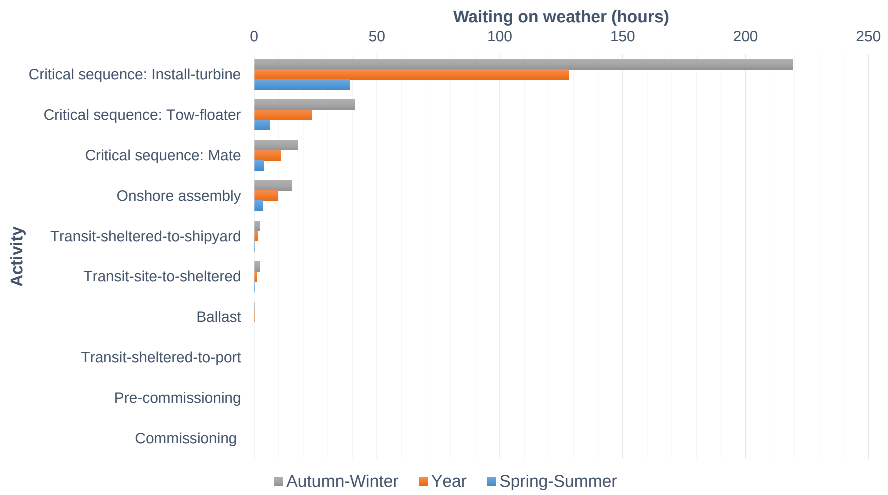


(a) Duration histogram

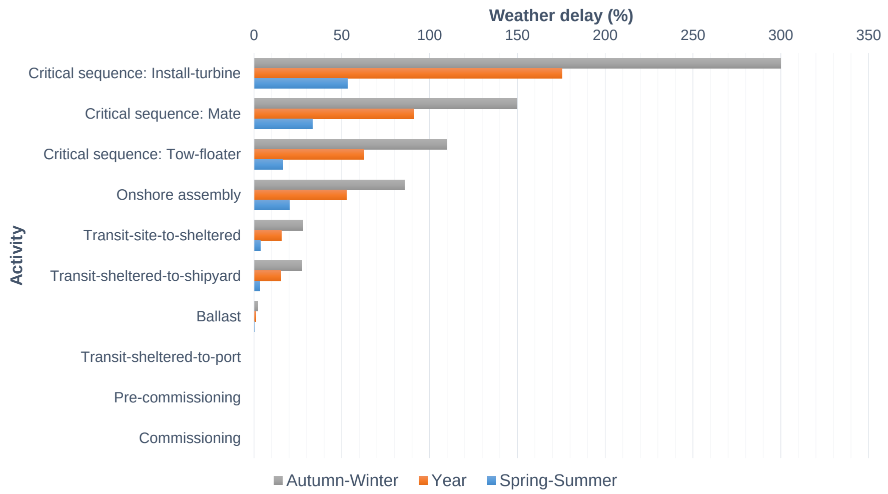


(b) Cost histogram

Figure 3.7: Histograms of installation duration per floating unit and total installation cost per MW of the spar buoy installation with HLV for the three examined time periods.



(a) Waiting on weather

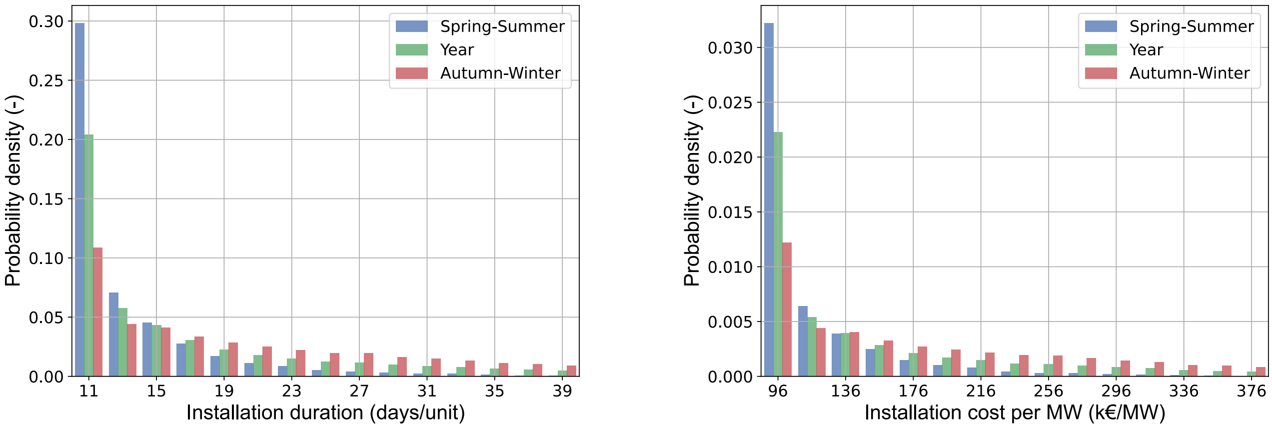


(b) Weather delay

Figure 3.8: Waiting on weather and weather delay of installation activities of the spar buoy installation with HLV for the three examined time periods.

3.2.4 Seasonal evaluation of spar buoy installation with crane barge

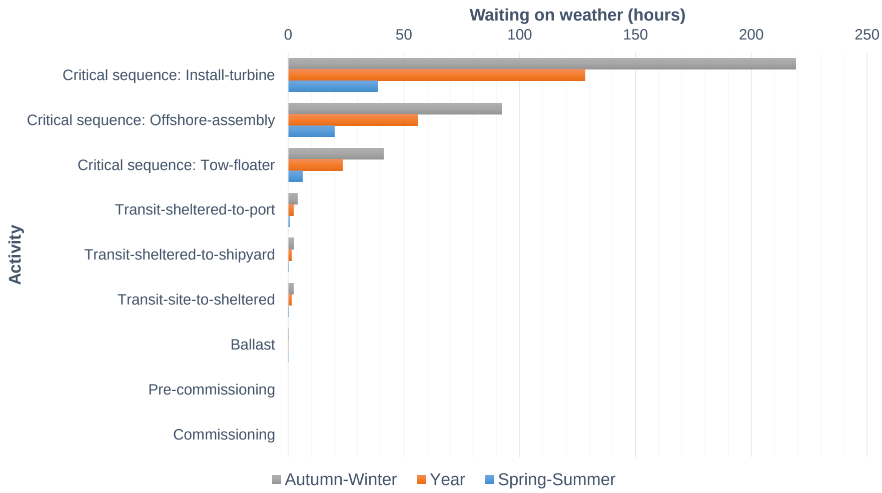
As it can be observed in Figure 3.10a, for the case of spar buoy installation with crane barge, the critical activities of installation of the wind turbines at site and offshore assembly at the sheltered location are the ones with the highest waiting on weather for all time periods (up to 128 h and 56 h, respectively, during yearly simulation). This is mainly due to the restrictive weather limits of offshore operations. The critical sequence of towing floaters is the next activity with the highest share of the total waiting on weather, again due to the restrictive weather limits and long weather window requirements. As it is shown in Figure 3.10b, in this installation strategy, the order of the activities is the same both for their waiting on weather and their weather delay.



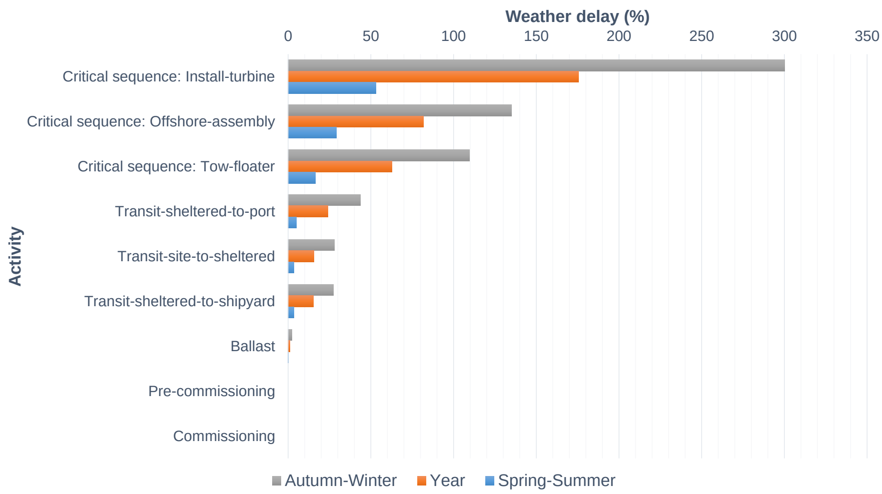
(a) Duration histogram

(b) Cost histogram

Figure 3.9: Histograms of the installation duration per floating unit and total installation cost per MW of the spar buoy installation with crane barge for the three examined time periods.



(a) Waiting on weather



(b) Weather delay

Figure 3.10: Waiting on weather and weather delay of installation activities of the spar buoy installation with crane barge for the three examined time periods.

3.3 Sensitivity analysis of installation strategies

As aforementioned, the distance from shore/port, the weather conditions and the operational limits for the installation activities, are the most vital parameters that affect the total installation cost and duration of floating wind farms. For this reason, a sensitivity analysis is performed on these parameters, as introduced in subsection 2.3.2. The results of this analysis, are presented in three subsections; subsection 3.3.1 refers to the spring-summer period, subsection 3.3.2 refers to the yearly period, and subsection 3.3.3 refers to the autumn-winter period.

For every examined time period, the following general conclusions hold. As it can be observed in the following subsections, it is clear that a nearly linear relation exists between the total installation cost and the distance from shore/port for all time periods. Moreover, it is evident, that semi-submersible installation with wind turbine assembly at quayside is, in any case, the least expensive option to pursue, while the semi-submersible installation with wind turbine assembly at wind farm site is the most expensive one. In addition, as the distances increase, the cost difference between spar buoy installation with HLV and crane barge increases, as a result of the multiple number of trips that the crane barge needs to perform.

Moreover, it can be concluded that in all the cases under consideration, there is no linear relation between the total installation cost and the operational weather limits. When stricter weather limits are applied, higher costs are observed; when weather limits are reduced down to 50% of the base case scenario ones, the installation cost per MW increases exponentially for all implemented installation strategies in all time periods. This is predominantly true for the semi-submersible installation with wind turbine assembly at site, which highlights the high dependence on weather limits of this strategy, whereas semi-submersible installation with wind turbine assembly at quayside is less affected by the weather conditions and thus weather limits, proven by the lowest cost increase. As a result, the cost difference between the different strategies is increased when stringent weather limits are applied. Furthermore, when the weather limits are relaxed compared to the nominal ones, the cost difference is much smaller, as the cost curve becomes nearly horizontal and close to its net theoretical value. Also in this case, semi-submersible installation with wind turbine assembly at site has the highest cost decrease, when weather limits are relaxed by 50%, proving its high dependence on far-offshore weather conditions. In any case, the ranking of the installation strategies remains the same for all the cases considered in this sensitivity analysis.

Furthermore, a linear relation between the installation duration per floating unit and distance is observed, similar to the installation cost per MW. For all the examined distances and time periods, the semi-submersible installation with wind turbine assembly at quayside is the fastest one, while the order of the rest of the strategies highly depends on the examined time period and distance from shore/port. The differences between the implemented strategies, however, are not constant. It can be observed that the spar buoy installation with crane barge becomes the slowest strategy, when the distances increase in all time periods, as the crane barge needs to perform multiple trips between the port and the sheltered location, thus resulting in a higher total duration.

Finally, similarly to the installation cost, it is evident that there is no linear relation between the installation duration and the weather limits. The installation strategies which are more dependent on weather limits are characterised by the highest duration increase, and as a result, semi-submersible installation with wind turbine assembly at site is the slowest strategy when the strictest weather limits are applied, despite its low net theoretical duration. When the weather limits are relaxed, the duration differences between implemented strategies become slim, as the actual durations approach their theoretical values.

3.3.1 Sensitivity analysis for the spring-summer period

At first, the installation cost results of all implemented strategies are presented; in Figure 3.11a with respect to changing distance, and in Figure 3.11b in respect of changing weather limits.

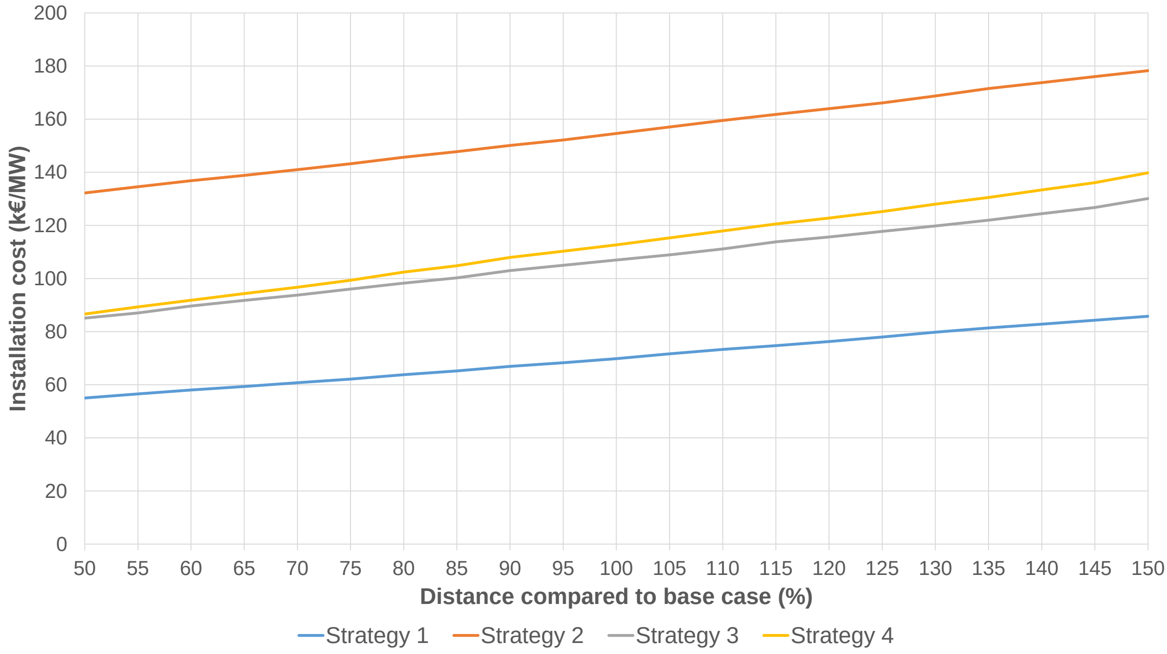
As it can be observed in Figure 3.11a, an installation cost increase of 15-24% occurs with an increase of 50% of the distance, while a general decrease of 15-23% is observed with a decrease of 50% compared to the nominal case. The maximum variation is observed for the spar buoy installation with crane barge, due to the multiple number of required trips. The minimum difference is observed for the semi-submersible installation with wind turbine assembly at site, as its installation cost is mainly driven by far-offshore weather conditions rather than distance from shore/port.

Furthermore, as it can be observed from Figure 3.11b, when the operational weather limits are equal to 50% of the base case scenario, an installation cost increase of 649% is observed in the strategy with semi-submersible installation with wind turbine assembly at site, while in the case of the semi-submersible installation with wind turbine assembly at quayside, this increase is limited to 255%. Similarly, the spar buoy installation with HLV is characterised by an installation cost increase of 321%, while spar buoy installation with crane barge by an installation cost increase of 336%. When weather limits are relaxed by 50% compared to the nominal case, semi-submersible installation with wind turbine assembly at site has the highest installation cost decrease equal to 30%, while the rest of the installation strategies are characterised by a decrease in the order of 19-20%.

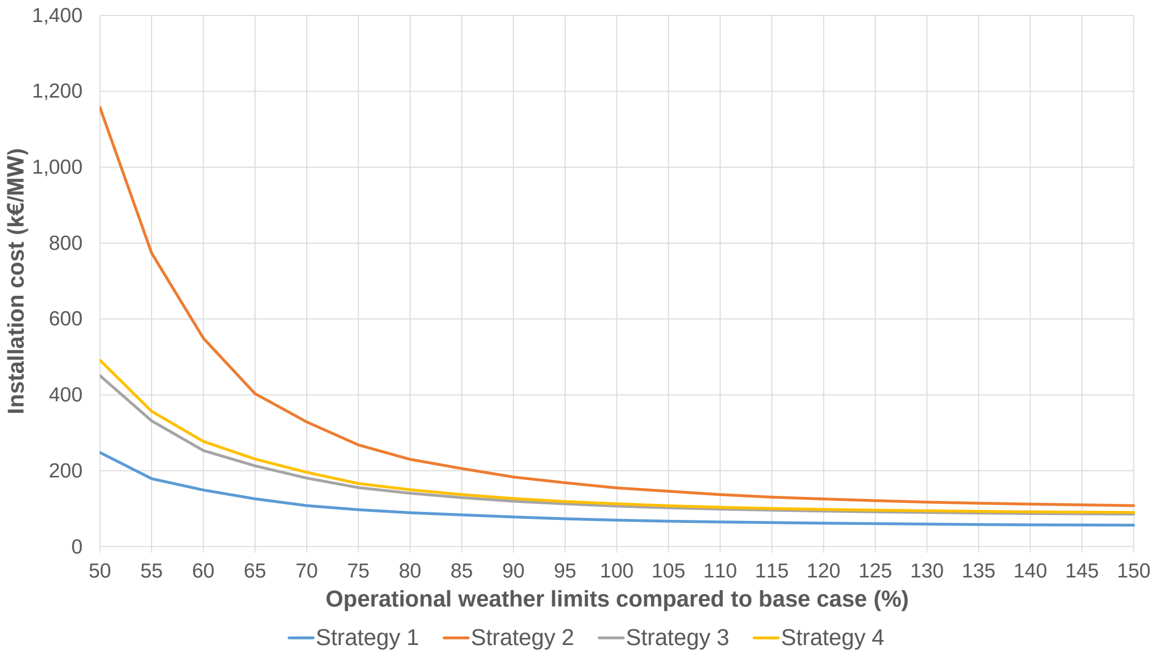
Moreover, the installation duration results of all implemented strategies are presented; in Figure 3.12a with respect to changing distance, and in Figure 3.12b in respect of changing weather limits.

From Figure, 3.12a, it is clear that for all the examined distances, the semi-submersible installation with wind turbine assembly at quayside is the fastest strategy, while spar buoy installation with crane barge is the slowest one. Semi-submersible installation with wind turbine assembly at site becomes faster than the spar buoy installation with HLV, approximately when the distance from shore/port is equal to 90% of the nominal one. The differences between the implemented strategies, however, are not constant. In fact, a 50% decrease of distance compared to the nominal one results in a duration decrease of 17% for the semi-submersible installation with wind turbine assembly at quayside and of 14% for the semi-submersible installation with wind turbine assembly at site, whereas the spar buoy installations with HLV and crane barge are characterised by a decrease of 19% and 21%, respectively. Similarly, a 50% increase of distance compared to the nominal one, results in an increase of the same order of magnitude for all strategies, respectively. Therefore, it is evident that the spar buoy installation strategies are more dependent on the distance from shore/port compared to the semi-submersible ones.

Finally, from Figure 3.12b, it can be observed that when a weather-limit decrease of 50% is applied, the duration of semi-submersible installation with wind turbine assembly at quayside is increased by 208%, the duration of semi-submersible installation with wind turbine assembly at site is increased by 512%, the duration of spar buoy installation with HLV is increased by 267% and the duration of spar buoy installation with crane barge is increased by 297%. Therefore, the same strategies that perform better in terms of cost while decreasing the operational weather limits, also perform better in terms of installation time. Moreover, the strategies that show a higher increase in installation duration with stricter weather limits, also show the higher decrease when weather limits are relaxed, with a general decrease of 15-25% for all implemented strategies. In particular, semi-submersible installation with wind turbine assembly at wind farm site shows such a strong dependence on weather conditions, that from being the slowest installation strategy with strict weather limits, it becomes the second fastest one when the weather limits are relaxed.

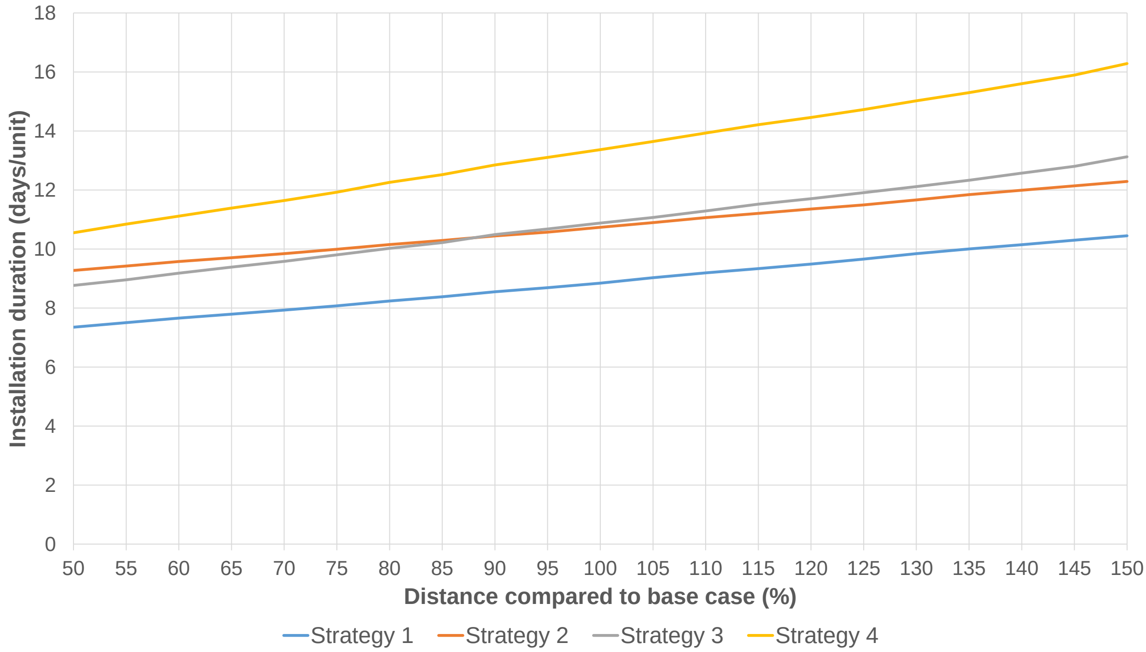


(a) Total installation cost per MW as a function of distance

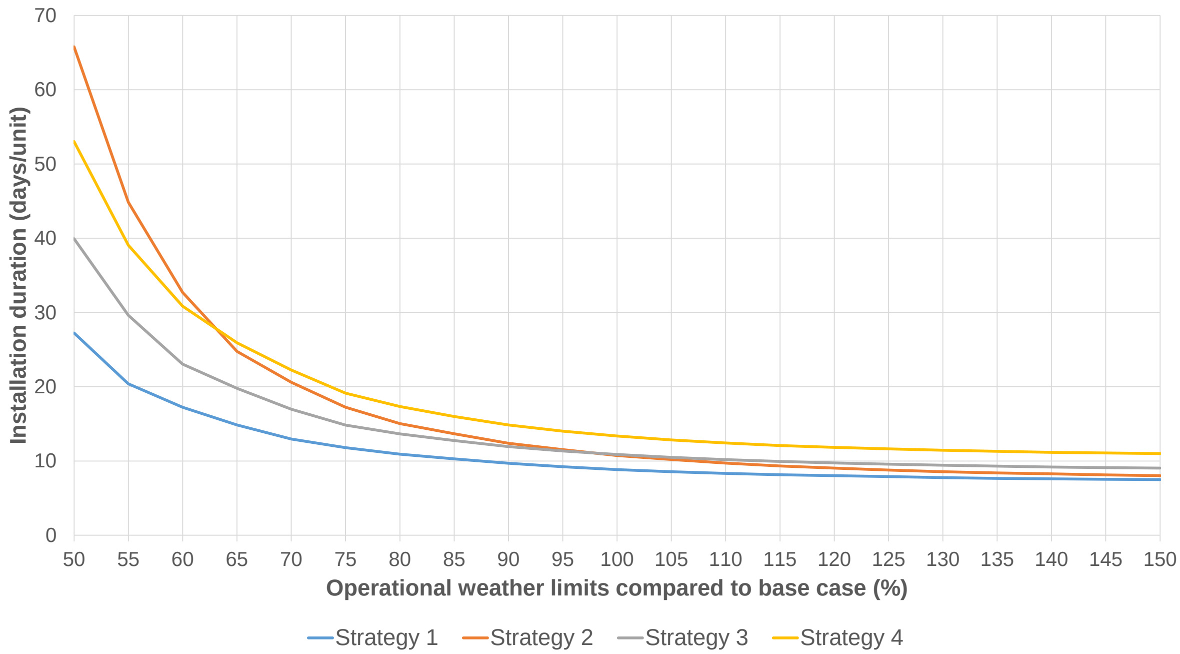


(b) Total installation cost per MW as a function of operational weather limits

Figure 3.11: Sensitivity analysis of the installation cost per MW of the different examined installation strategies for the spring-summer period. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation with wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.



(a) Installation duration per floating unit as a function of distance



(b) Installation duration per floating unit as a function of operational weather limits

Figure 3.12: Sensitivity analysis of the installation duration per floating unit of the different examined installation strategies for the spring-summer period. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation with wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.

3.3.2 Sensitivity analysis for the yearly period

The second period to be presented is the yearly one. At first, the installation cost results of all implemented strategies are presented; in Figure 3.13a with respect to changing distance, and in Figure 3.13b in respect of changing weather limits.

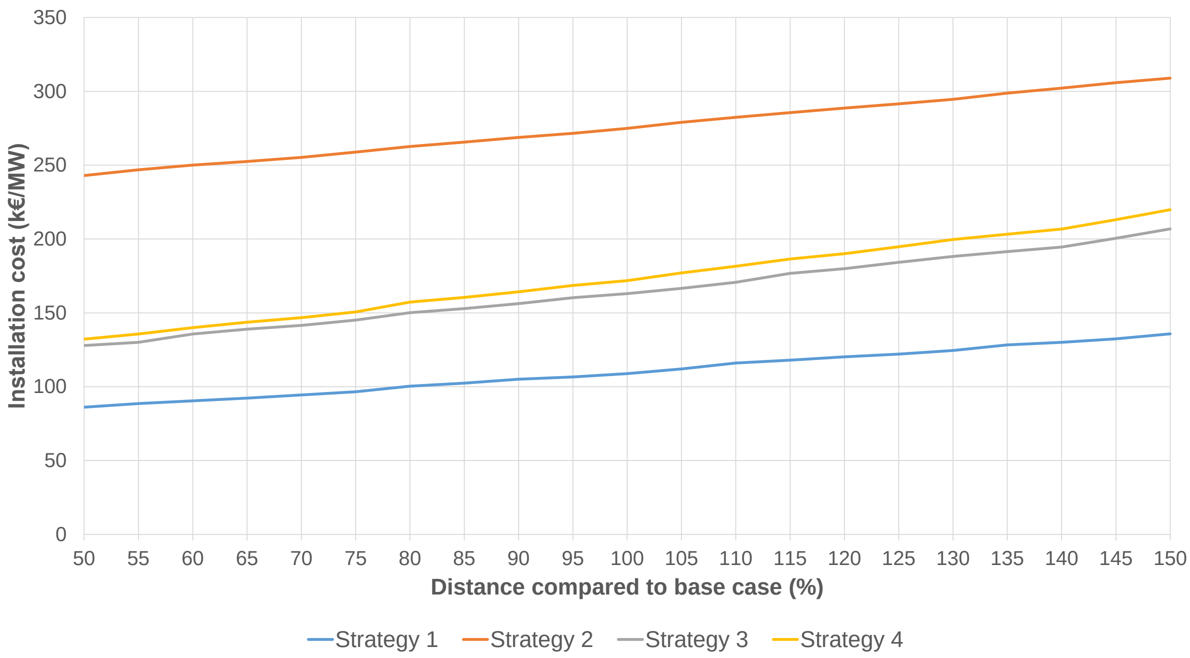
As it can be observed in Figure 3.13a, an installation cost increase of 12-28% occurs with an increase of 50% of the distance, while a general decrease of 12-23% is observed with a decrease of 50% compared to the nominal case. Similarly to the spring-summer period, the maximum variation is observed for the spar buoy installation with crane barge, while the minimum difference is observed for the semi-submersible installation with wind turbine assembly at site.

Furthermore, as it can be observed in Figure 3.13b, when weather limits are equal to 50% of the base case scenario, an installation cost increase of 639% is observed for the semi-submersible installation with wind turbine assembly at site, while in the case of the semi-submersible installation with wind turbine assembly at quayside, this increase is limited to 382%. Similarly, the spar buoy installation with HLV is characterised by an installation cost increase of 412%, while spar buoy installation with crane barge by an increase of 432%. When weather limits are relaxed by 50% compared to the nominal case, semi-submersible installation with wind turbine assembly at site has the highest installation cost decrease equal to 49%, while the rest of the installation strategies are characterised by a cost decrease of 39%.

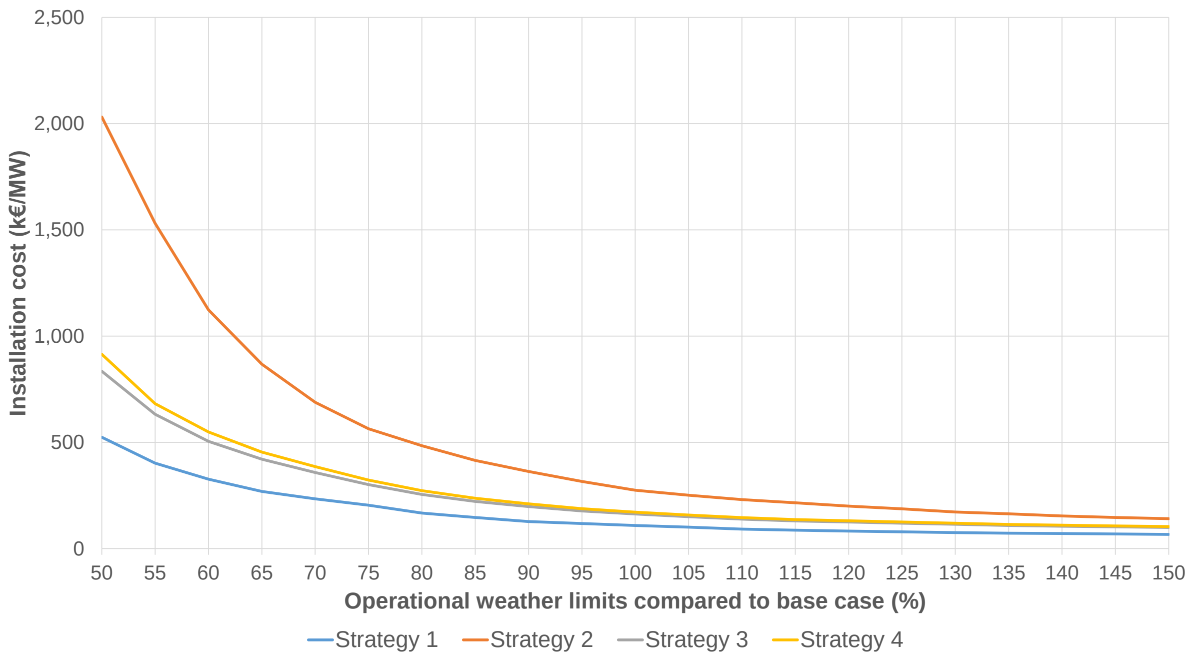
Moreover, the installation duration results of all implemented strategies are presented; in Figure 3.14a with respect to changing distance, and in Figure 3.14b in respect of changing weather limits.

From Figure, 3.14a, it is clear that for all the examined distances, the semi-submersible installation with wind turbine assembly at quayside is the fastest one. Spar buoy installation with crane barge becomes the slowest strategy for distances greater than approximately 65% of the nominal case, while semi-submersible installation with wind turbine assembly at site becomes as fast as the spar buoy installation with HLV only when the distance from shore/port becomes equal to 150% of the nominal case. The differences between the implemented strategies, however, are not constant. A 50% decrease of distance compared to the nominal one, results in an installation duration decrease of 18% for the semi-submersible installation with wind turbine assembly at quayside and of 12% for the semi-submersible installation with wind turbine assembly at site, whereas the spar buoy installations with HLV and crane barge are characterised by a decrease of 21% and 22%, respectively. Similarly, a 50% increase of distance compared to the nominal one, results in an installation duration increase of 21% for the semi-submersible installation with wind turbine assembly at quayside and of 13% for the semi-submersible installation with wind turbine assembly at site, whereas the spar buoy installations with HLV and crane barge are characterised by an increase of 27% and 26%, respectively.

Finally, from Figure 3.14b, it can be concluded that when a weather-limit decrease of 50% is applied, the duration of the semi-submersible installation with wind turbine assembly at quayside is increased by 330%, the duration of the semi-submersible installation with wind turbine assembly at site by 559%, the duration of the spar buoy installation with HLV by 367% and the duration of the spar buoy installation with crane barge by 400%. Moreover, the strategies that show a higher increase in installation duration with stricter weather limits, also show the higher decrease when weather limits are relaxed, with a general decrease of 33-44% for all implemented strategies. Again, the semi-submersible installation with wind turbine assembly at wind farm site shows such a strong dependence on weather conditions, that from being the slowest installation strategy with strict weather limits, it becomes the second fastest strategy when the operational weather limits are relaxed.

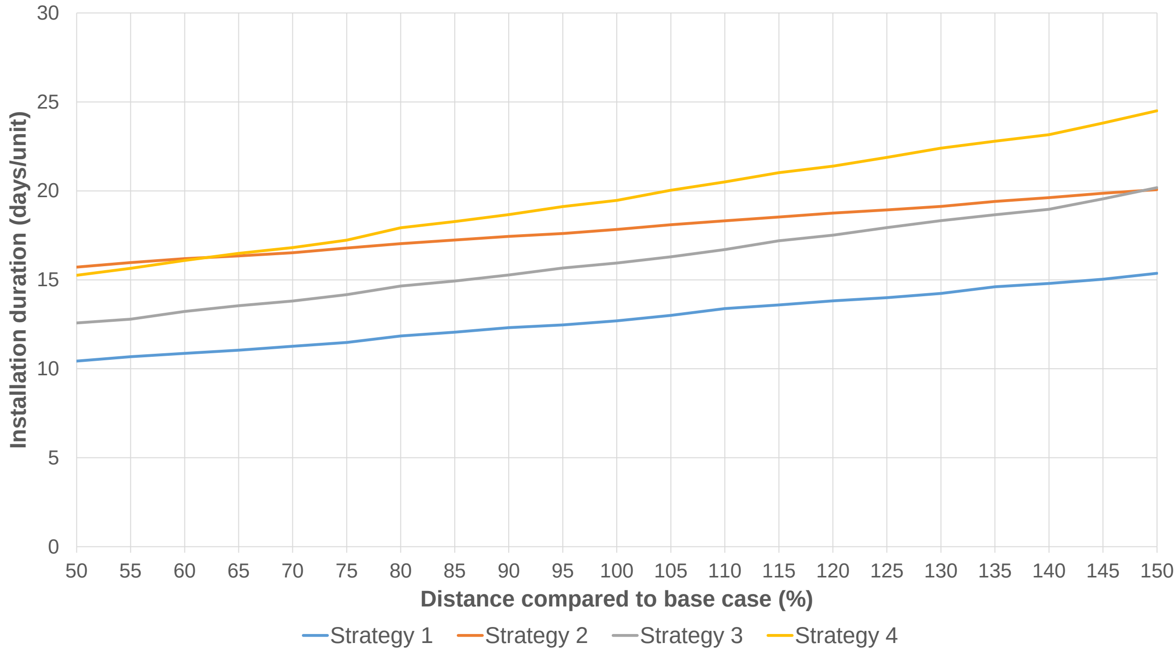


(a) Total installation cost per MW as a function of distance

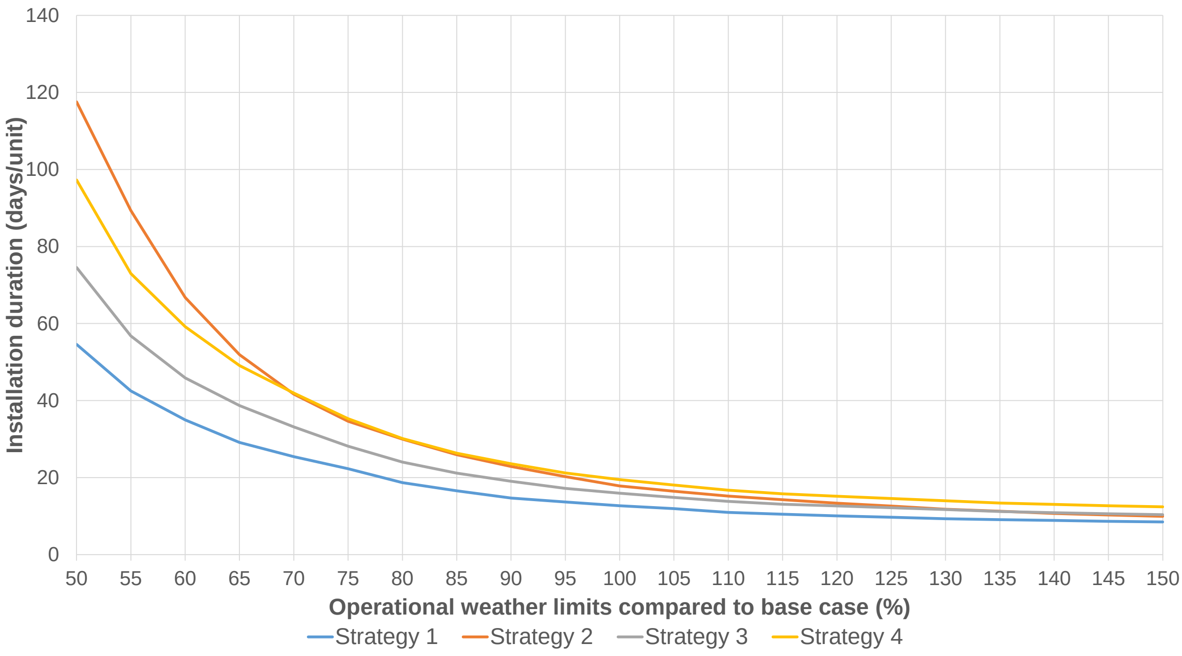


(b) Total installation cost per MW as a function of operational weather limits

Figure 3.13: Sensitivity analysis of the installation cost per MW of the different examined installation strategies for the yearly period. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation with wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.



(a) Installation duration per floating unit as a function of distance



(b) Installation duration per floating unit as a function of operational weather limits

Figure 3.14: Sensitivity analysis of the installation duration per floating unit of the different examined installation strategies for the yearly period. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation with wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.

3.3.3 Sensitivity analysis for the autumn-winter period

The last case taken into consideration is the autumn-winter period. At first, the installation cost results of all implemented strategies are presented; in Figure 3.15a with respect to changing distance, and in Figure 3.15b in respect of changing weather limits.

As it can be observed in Figure 3.15a, an installation cost increase of 11-30% occurs with an increase of 50% of the distance, while a general decrease of 11-23% is observed with a decrease of 50% compared to the nominal case. Similarly to the other two time periods, the maximum variation is observed for the spar buoy installation with crane barge, while the minimum difference is observed for the semi-submersible installation with wind turbine assembly at site.

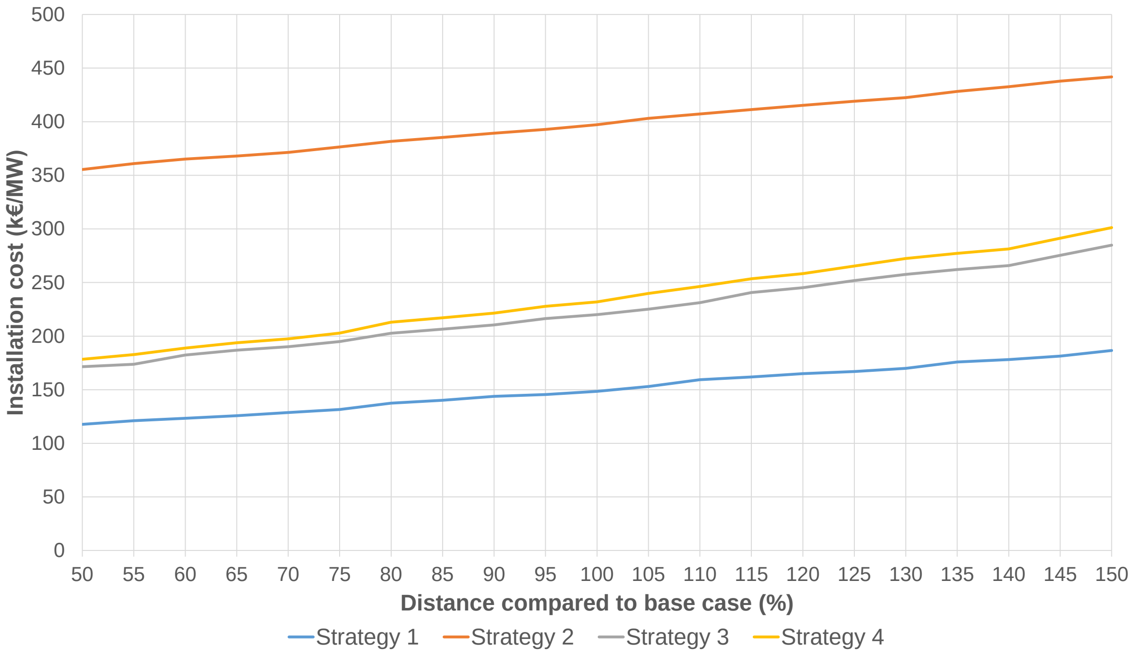
Furthermore, as it can be observed in Figure 3.15b, when weather limits are equal to 50% of the base case scenario, an installation cost increase of 635% is observed in the strategy of semi-submersible installation with wind turbine assembly at site, while in the case of the semi-submersible installation with wind turbine assembly at quayside, this increase is limited to 442%. Similarly, the spar buoy installation with HLV is characterised by an installation cost increase of 457%, while spar buoy installation with crane barge by an increase of 480%. When weather limits are relaxed by 50% compared to the nominal case, semi-submersible installation with wind turbine assembly at site has the highest installation cost decrease equal to 56%, while the rest of the installation strategies are characterised by a decrease in the order of 48-49%.

Moreover, the installation duration results of all implemented strategies are presented; in Figure 3.16a with respect to changing distance, and in Figure 3.16b in respect of changing weather limits.

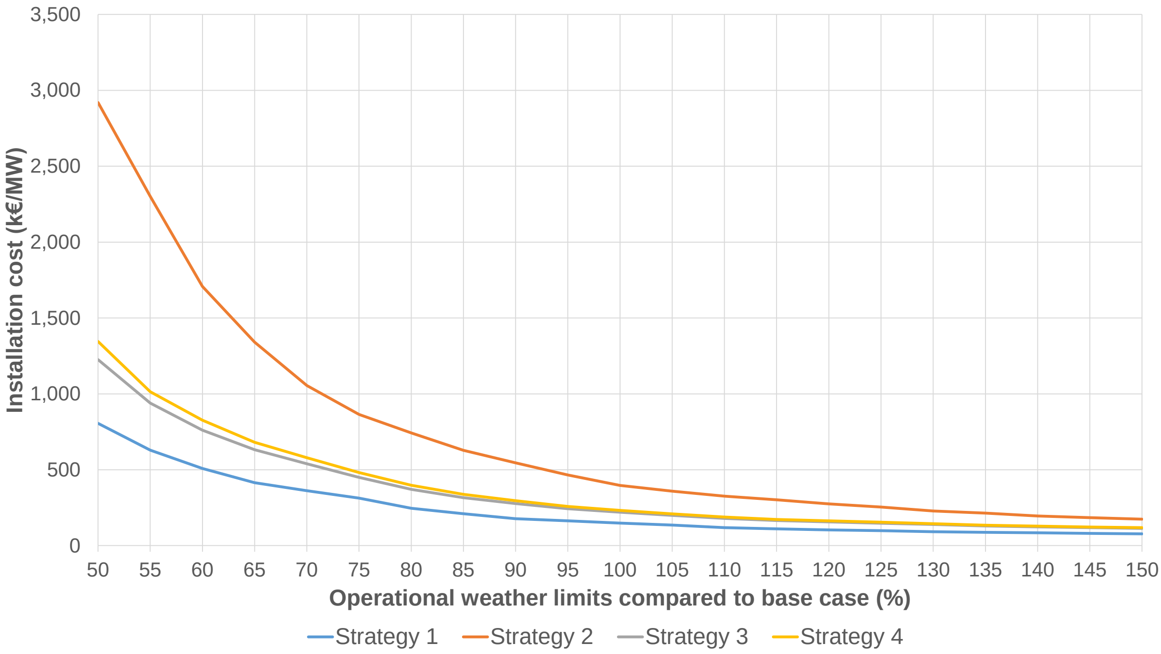
From Figure, 3.16a, it is clear that for all the examined distances, the semi-submersible installation with wind turbine assembly at quayside is the fastest one followed by the spar buoy installation with HLV. When the distances are equal to 90% of their nominal value, the semi-submersible installation with wind turbine assembly at site becomes faster than the spar buoy installation with crane barge. The differences between the implemented strategies, however, are not constant. A 50% decrease of distance compared to the nominal one, results in an installation duration decrease of 18% for the semi-submersible installation with wind turbine assembly at quayside and of 11% for the semi-submersible installation with wind turbine assembly at site, whereas the spar buoy installations with HLV and crane barge are both characterised by a decrease of 22%. Similarly, a 50% increase of distance compared to the nominal one, results in an installation duration increase of 23% for the semi-submersible installation with wind turbine assembly at quayside and of 12% for the semi-submersible installation with wind turbine assembly at site, whereas the spar buoy installations with HLV and crane barge are characterised by an increase of 30% and 28%, respectively.

Finally, from Figure 3.16b, it can be concluded that when a weather-limit decrease of 50% is applied, the duration of the semi-submersible installation with wind turbine assembly at quayside is increased by 396%, the duration of semi-submersible installation with wind turbine assembly at site by 580%, the duration of spar buoy installation with HLV by 420% and the duration of spar buoy installation with crane barge by 454%. Moreover, the strategies that show a higher increase in installation duration with stricter weather limits, also show the higher decrease when weather limits are relaxed, with a general decrease of 43-52% for all implemented strategies.

Overall, similar cost trends between the implemented strategies are evident during all time periods and throughout both the sensitivity analyses. Semi-submersible installation with wind turbine assembly at quayside is always the cheapest installation strategy followed by spar buoy installation with HLV, spar buoy installation with crane barge and semi-submersible installation with wind turbine assembly at site. The ranking of the installation strategies with respect to their duration depends on the distance the vessels have to cover and the operational weather



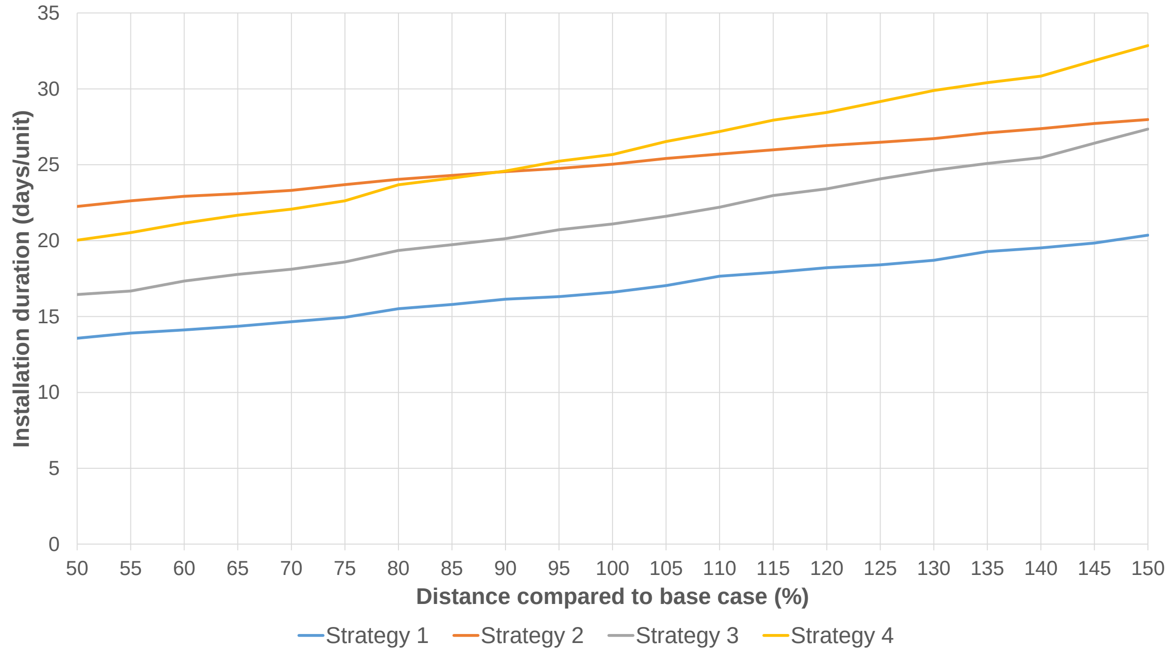
(a) Total installation cost per MW as a function of distance



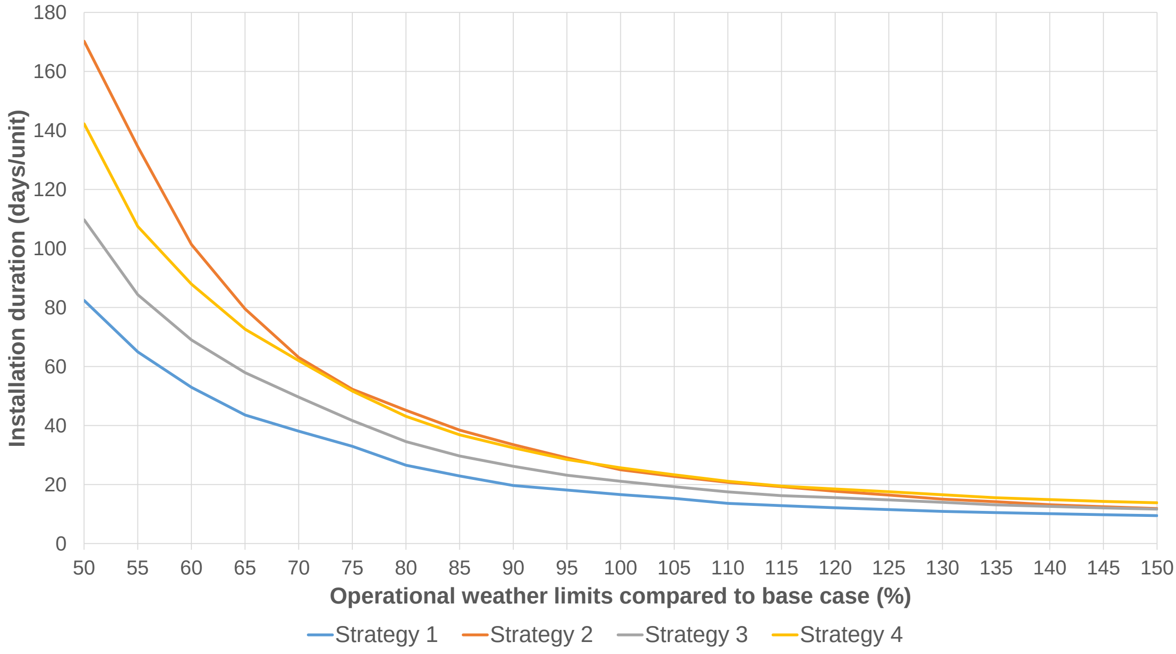
(b) Total installation cost per MW as a function of operational weather limits

Figure 3.15: Sensitivity analysis of the installation cost per MW of the different examined installation strategies for the autumn-winter period. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation with wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.

conditions, with the exception of the semi-submersible installation with wind turbine assembly at quayside, which is always the fastest strategy.



(a) Installation duration per floating unit as a function of distance



(b) Installation duration per floating unit as a function of operational weather limits

Figure 3.16: Sensitivity analysis of the installation duration per floating unit of the different examined installation strategies for the autumn-winter period. Strategy 1 refers to semi-submersible installation with wind turbine assembly at quayside, Strategy 2 to semi-submersible installation with wind turbine assembly at wind farm site, Strategy 3 to spar buoy installation with HLV and Strategy 4 to spar buoy installation with crane barge.

4 | O&M Results

The aim of this Chapter is to present the main results of the simulation of the different O&M strategies. In section 4.1, the O&M base case scenario results are presented for all strategies. In addition, in section 4.2, the weather delays of various activities as well as cost and duration histograms of all strategies are presented. Finally, in section 4.3, the results of the sensitivity analysis are detailed.

4.1 O&M base case comparison

The comparison of the different strategies is first undertaken for the base case scenario. In Figures 4.1 and 4.2, the total vessels cost, lost revenue and additional costs of the different repair and replacement strategies are presented, respectively. The costs of the vessels include both their mobilisation costs and their cumulative daily rates. Lost revenue is calculated based on the lost energy output of the wind turbines during their downtime, as explained in equation 2.3.4. Additional costs include the facilities cost, the personnel cost and the cost of new components. In all cases, the additional costs are dominated by the cost of the new components.

As it can be observed in Figure 4.1, the minor and major repairs with a CTV are cheaper than the ones performed with the aid of a W2W vessel, predominantly due to their much lower daily rate. The higher sea-keeping capabilities of the W2W vessels lead to a lower weather delay than when adopting CTVs. However, the resulting lower lost revenue is not enough to outweigh the higher cost of the W2W vessels. Therefore, the use of a CTV for a minor/major repair seems to be more economically viable compared to the use of a W2W vessel. However, as aforementioned, currently CTVs are not able to transit to far-offshore locations. This may change with further progress in the maritime industry.

In Figure 4.2, it is clear that for the semi-submersible floating units, the offsite 3-wind turbine major replacement campaign is by far the most economically viable option, proving once more the advantage of towing semi-submersible floating units at quayside for installation and maintenance activities. Despite its increased lost revenue compared to the onsite replacement strategy, its overall cost is much lower since there is no need of an expensive HLV. For the spar buoy, the HLV is required both in the onsite and offsite major replacement strategies. However, the offsite replacement strategy is less susceptible to adverse far-offshore weather conditions, leading to lower vessel costs, which are counterbalanced by a longer downtime leading to higher personnel costs and production losses. As the cost difference is small, the selection of the optimum spar buoy replacement strategy is highly dependent on the volatility of the vessel daily rates and electricity prices.

Overall, onsite repair with the use of a CTV is the most cost-effective strategy with a total minor repair cost of 120.0 k€, and a total major repair cost of 242.8 k€. In the case of a W2W vessel, these costs are equal to 322.1 k€, and 525.5 k€, respectively. In addition, semi-submersible offsite major replacement campaign of 3 wind turbines is by far the most cost-effective strategy with a total cost of 10.8 m€, followed by spar buoy offsite replacement strategy with a total cost of 18.6 m€, and onsite replacement strategy with a total cost of 18.9 m€.

As previously explained, from Figure 4.3, it is clear that the duration of onsite repairs is lower when using a W2W vessel, due to its higher sea capabilities. However, this saving in time is

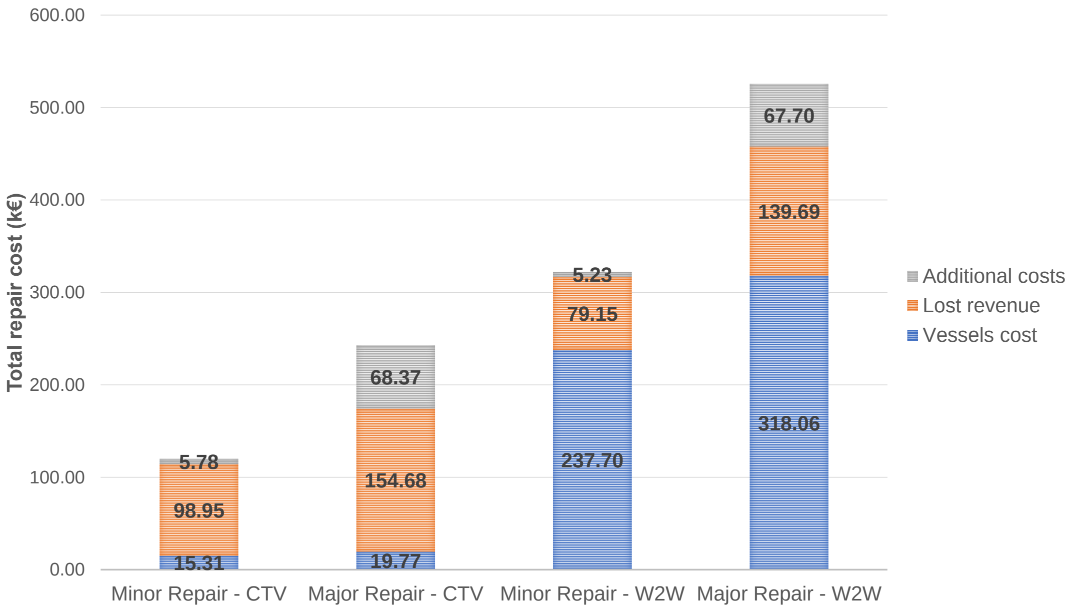


Figure 4.1: Total vessels cost, lost revenue and additional costs for the base case scenario of the examined repair strategies.

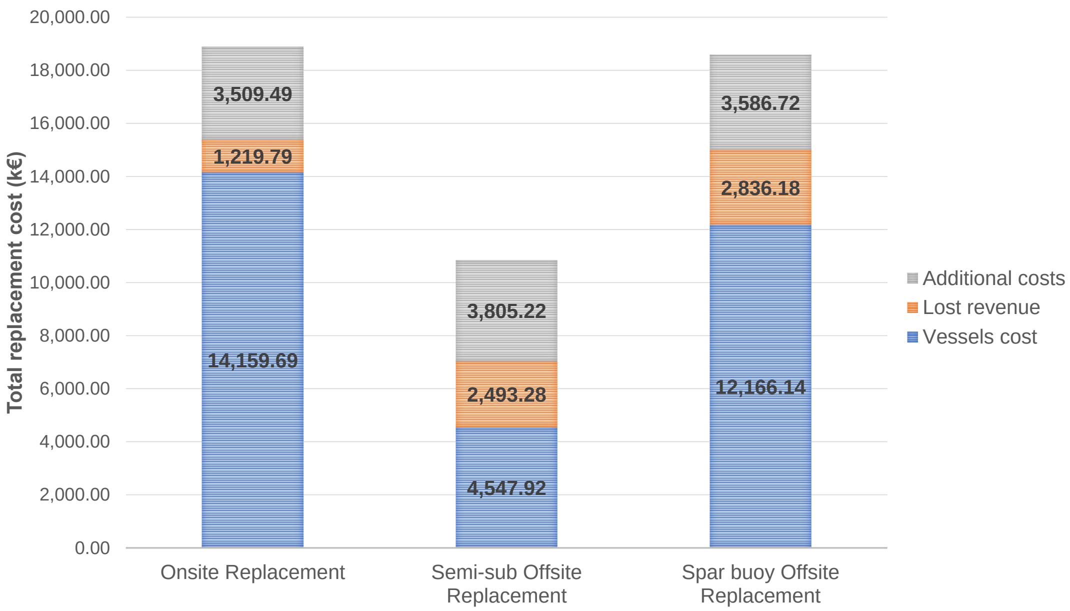


Figure 4.2: Total vessels cost, lost revenue and additional costs for the base case scenario of the examined replacement strategies.

not enough to make it the most economically viable strategy for a single repair. However, in far-offshore floating wind farms with large capacity, it is expected that repair campaigns might include numerous wind turbines, possibly making W2W vessels necessary, due to the ability to operate in adverse weather conditions and to provide accommodation to technicians for longer repair campaigns.

Furthermore, from Figure 4.4, it is evident that onsite replacement strategy of semi-submersible and spar buoy floating units is considerably faster that their offsite alternatives. This can be explained as towing is not necessary between the wind farm site and the port/sheltered location. However, as seen in Figure 4.2, despite its much shorter duration, onsite replacement

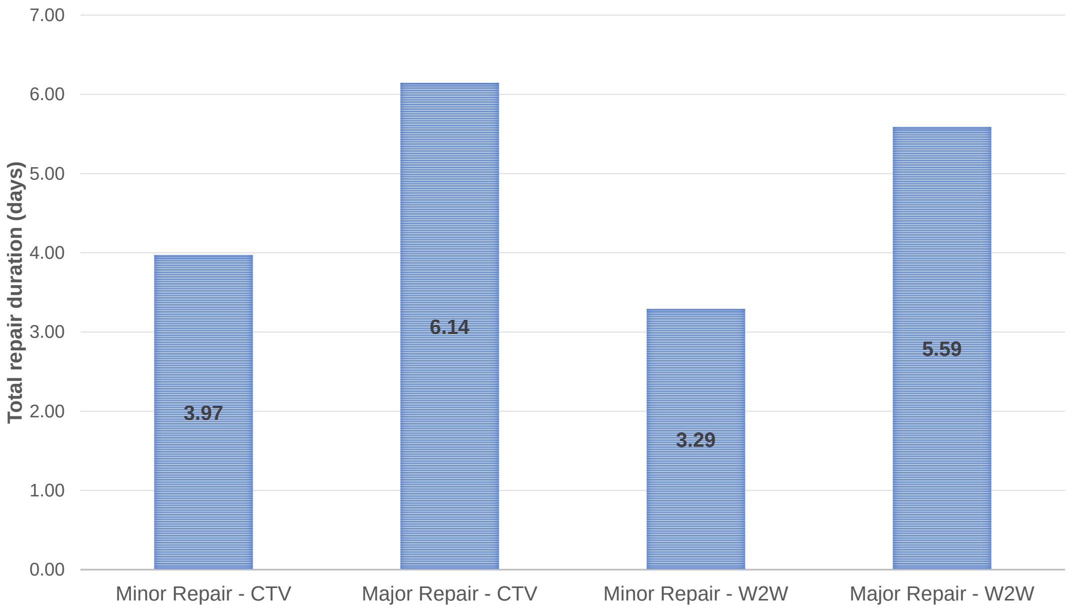


Figure 4.3: Total duration for the base case scenario of the examined repair strategies.

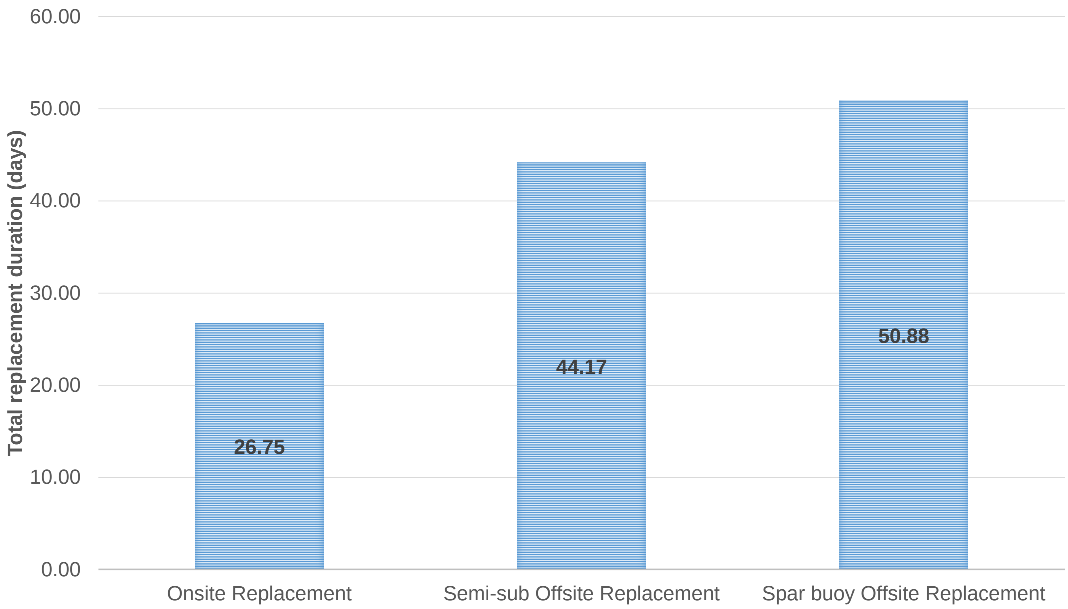


Figure 4.4: Total duration for the base case scenario of the examined replacement strategies.

is accompanied by the highest cost of the three options, due to the deployment of an expensive HLV for the whole duration of the maintenance campaign.

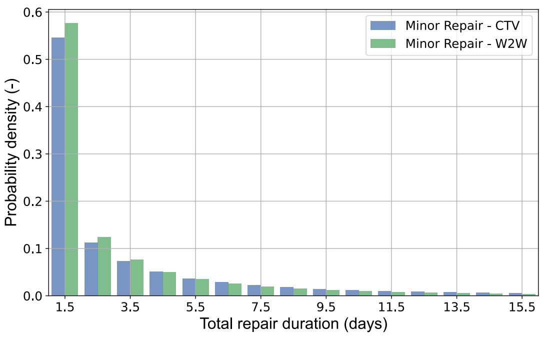
4.2 Weather dependence of O&M strategies for the base case scenario

One of the main topics of interest when dealing with O&M for floating wind farms is the dependence of the different O&M strategies on the weather. In this section, the waiting on weather and the weather delays of all repair and replacement strategies are addressed for the base case scenario. The structure of this section follows; at subsection 4.2.1, the weather dependence of onsite minor/major repair for both CTVs and W2W vessels is introduced. The dependence of the semi-submersible onsite and offsite replacement strategies is presented in subsection 4.2.2. Finally, the weather dependence of the spar buoy onsite and offsite replacement strategies is reported in subsection 4.2.3.

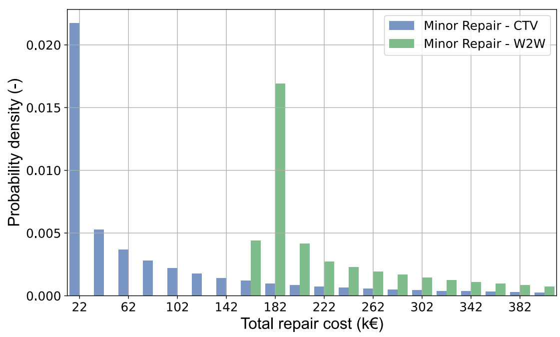
4.2.1 Weather dependence of onsite repair

As it can be observed in Figures 4.5a and 4.6a, the minor/major onsite repairs with the use of a W2W vessel are performed faster compared to the use of a CTV. This is shown by the fact that the left-side bins of the W2W strategy are characterised by higher probability density compared to the CTV ones. This conclusion can be derived both for the minor and the major repairs. In addition, due to the need of a longer weather window in the case of the major repair, the probability density of its left-side bins is lower compared to the case of the minor repair, as it is easier to find a suitable weather window for the latter case. However, despite the lower duration of the W2W strategy, its cost is substantially higher than the CTV strategy for both the minor and major repairs, as it can be seen in Figures 4.5b and 4.6b, respectively. This is clear, as even the first occurrences of the W2W strategy are characterised by higher cost than the majority of the CTV simulations.

As aforementioned, the whole onsite repair strategy with the use of a CTV is treated as a critical sequence, each activity of which has the same weather limit. As a result, there is no scope in analysing all of them separately. In the case of the W2W strategy, the repair activity has the highest waiting on weather (up to 48 h for major repair and 23 h for minor repair), as it is shown in Figure 4.7a. This can be explained by the fact that this is the most limiting activity of the critical sequence. However, position-at-site is characterised by the highest weather delay, as it can be observed in Figure 4.7b, due to its low net theoretical duration.

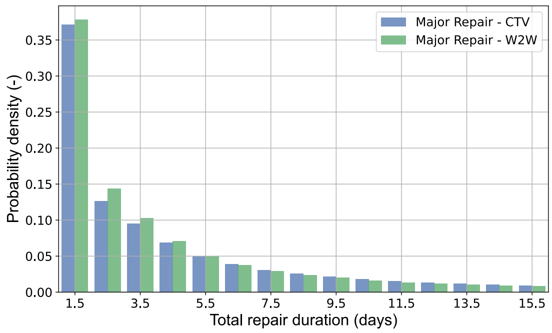


(a) Duration histogram

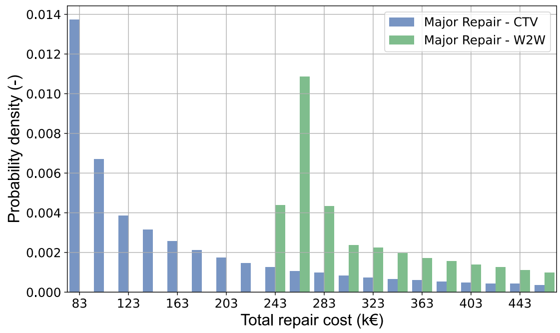


(b) Cost histogram

Figure 4.5: Histograms of repair duration per floating unit and total repair cost of the onsite minor repair strategy with a CTV or a W2W vessel.

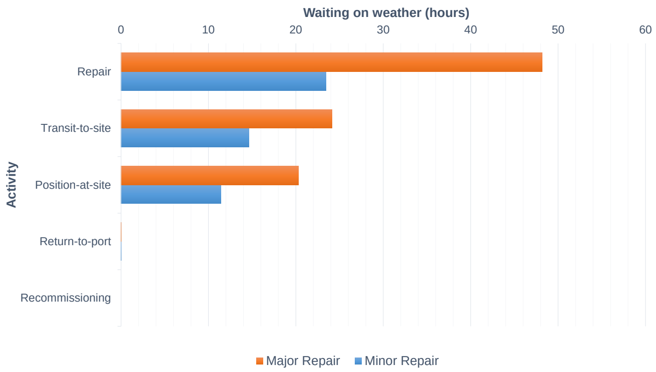


(a) Duration histogram

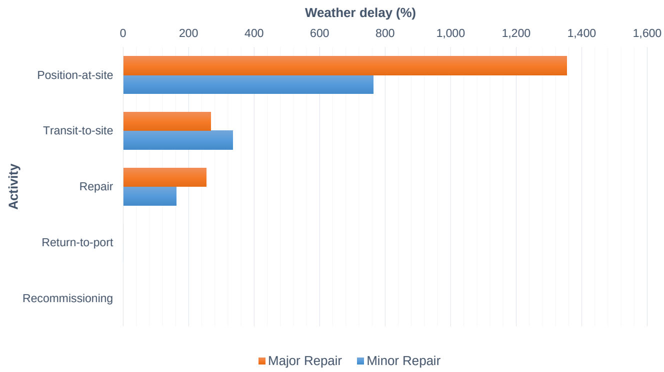


(b) Cost histogram

Figure 4.6: Histograms of repair duration per floating unit and total repair cost of the onsite major repair strategy with a CTV or a W2W vessel.



(a) Waiting on weather



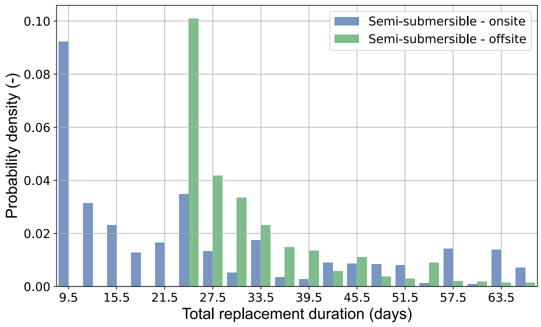
(b) Weather delay

Figure 4.7: Waiting on weather and weather delay of maintenance activities of the onsite minor/major repair strategy with a W2W vessel.

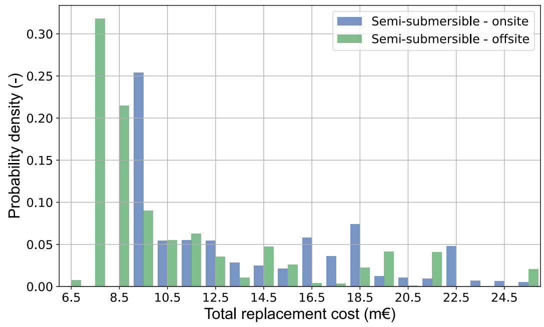
4.2.2 Weather dependence of semi-submersible major replacement

As shown in Figure 4.8a, the onsite major replacement is characterised by lower duration compared to the semi-submersible offsite one. However, due to the long and complicated nature of the whole maintenance sequence, it is observed that the probability density of the bins does not decrease smoothly for longer durations. In addition, it is worth mentioning that the probability density of the first bin of the onsite strategy is lower than the offsite one, proving that the net theoretical duration of the onsite strategy is more difficult to be achieved, due to its dependence on stricter weather limits and more adverse far-offshore weather conditions. Furthermore, as it can be seen in Figure 4.8b, the semi-submersible offsite replacement strategy is characterised by lower cost despite its considerably higher duration. As aforementioned, this is mainly attributed to the fact that no HLV is needed for the semi-submersible offsite replacement campaign.

For the onsite replacement strategy, only the critical sequence of the replacement of the components results in significant waiting on weather (up to 143 h). This is due to the lenient weather limits of the rest of the activities. From Figure 4.9a, it is clear that the critical sequences of connection and disconnection of the floating units from the wind farm site are characterised by the highest waiting on weather for the offsite strategy (up to 64 h and 63 h, respectively). This is related to the restrictive weather limits and high net duration of the activities contained within these sequences, as well as to their execution under adverse far-offshore weather conditions. The next activity with the highest waiting on weather is the quayside replacement of the components, due to its wind speed limitations at hub height. Finally, from Figure 4.9b, it can be observed that the weather delay of the critical sequence of the disconnection of the floating units is higher than the connection one, due to its slightly lower net theoretical duration.

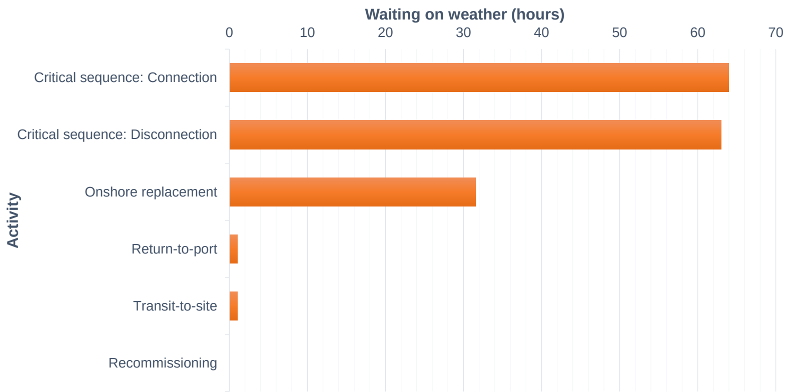


(a) Duration histogram

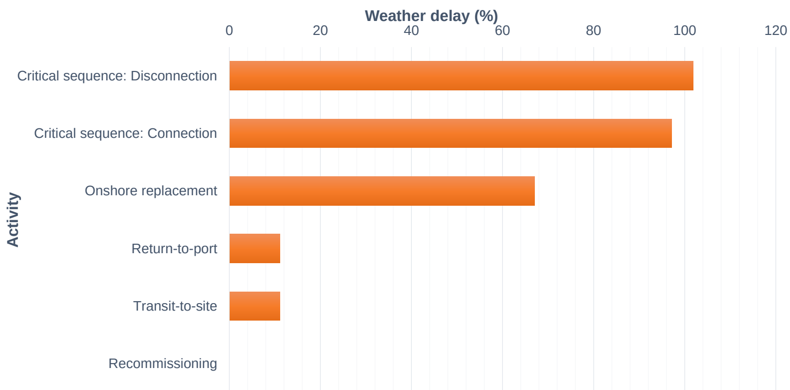


(b) Cost histogram

Figure 4.8: Histograms of replacement duration and total replacement cost of the semi-submersible onsite/offsite major replacement strategies.



(a) Waiting on weather



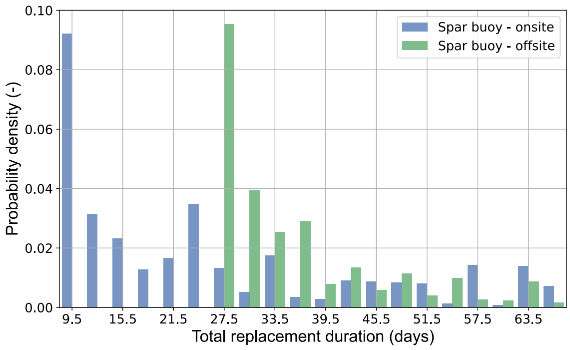
(b) Weather delay

Figure 4.9: Waiting on weather and weather delay of semi-submersible offsite major replacement strategy.

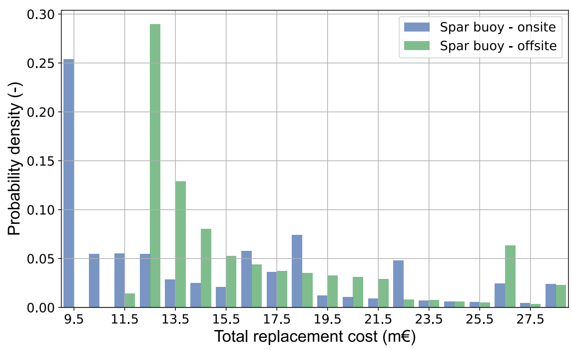
4.2.3 Weather dependence of spar buoy major replacement

As reported in Figure 4.10a, the onsite major replacement is characterised by lower duration compared to the spar buoy offsite one. Similarly to the semi-submersible case, it is worth mentioning that the probability density of the first bin of the onsite strategy is lower than the offsite one, proving that the net theoretical duration of the onsite strategy is more difficult to be achieved, due to its dependence on stricter weather limits and more adverse far-offshore weather conditions. Furthermore, in Figure 4.10b, no clear conclusion can be derived about which strategy is more cost-effective, despite the fact that the left-side bins of the onsite strategy have higher probability density than the offsite ones. Due to some extreme values occurring for the onsite strategy, because of adverse far-offshore weather conditions, its average cost ends up being slightly higher than the offsite one, as it was mentioned in section 4.1.

Moreover, in Figure 4.11a, it is shown that the critical sequences of connection and disconnection of the floating units from the wind farm site are characterised by the highest waiting on weather (up to 81 h and 76 h, respectively). This is related to the restrictive weather limits and high net duration of the activities contained within these sequences, as well as to their execution under adverse far-offshore weather conditions. The next activity with the highest waiting on weather is the replacement of the components at the sheltered location, due to the wind speed limitations at hub height. In Figure 4.11b, the weather delay of the critical sequence of the disconnection of the floating units is higher than for their connection, due to its slightly lower net theoretical duration.

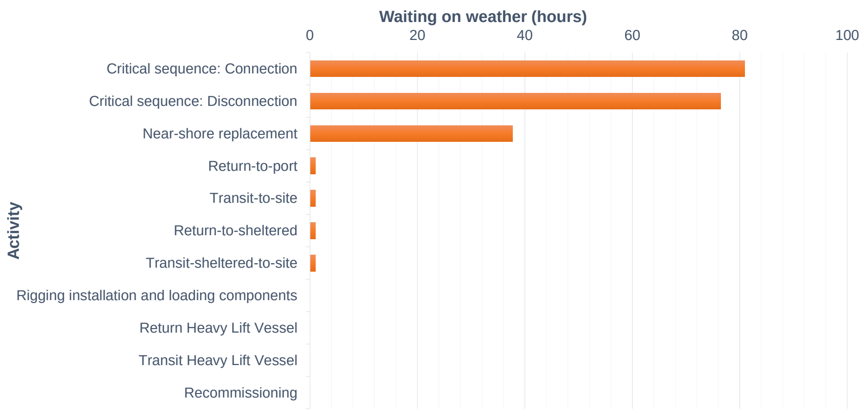


(a) Duration histogram

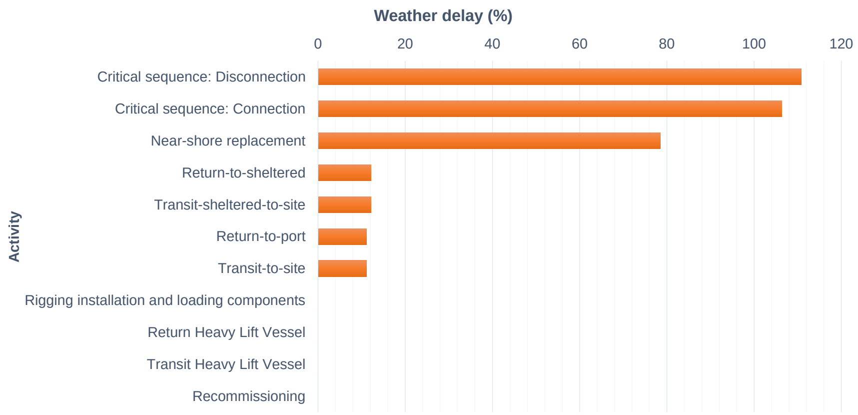


(b) Cost histogram

Figure 4.10: Histograms of the replacement duration and total replacement cost of the spar buoy onsite/offsite major replacement strategies.



(a) Waiting on weather



(b) Weather delay

Figure 4.11: Waiting on weather and weather delay of spar buoy offsite major replacement strategy.

4.3 Sensitivity analysis of O&M strategies

Distance from shore/port, weather conditions and the operational limits for the maintenance activities, are the most significant parameters that affect the total maintenance cost and duration of floating wind farms. For this reason, a sensitivity analysis is performed on these parameters, as already presented in subsection 2.3.2. The results of this analysis, are presented in two subsections; subsection 4.3.1 refers to the onsite minor/major repair, and subsection 4.3.2 refers to the onsite/offsite major replacement.

For every examined strategy, the following general conclusions hold. Similarly to the installation scenarios previously considered, a nearly linear relation exists between the total maintenance cost and duration and the distance from shore/port for all strategies. Moreover, it can be concluded that for all strategies there is no linear relation between the total maintenance cost and duration and the operational weather limits. When stricter weather limits are applied, higher costs are observed; when weather limits are equal to 50% of the base case scenario, the maintenance cost increases exponentially for all implemented strategies. As a result, the cost difference between the different strategies is increased when stringent weather limits are applied. Furthermore, when the weather limits are relaxed compared to the nominal ones, the cost difference is much smaller, as the cost curve becomes nearly horizontal and close to its net theoretical value.

4.3.1 Sensitivity analysis of onsite repair

At first, the repair cost results of all implemented strategies are presented; in Figure 4.12a with respect to changing distance, and in Figure 4.12b in respect of changing weather limits.

As it can be observed in Figure 4.12a, the use of a CTV in order to perform an onsite minor/major repair is always the most cost-effective option compared to the use of a W2W vessel, independently from the distance from port. However, the sensitivity of the cost of the CTV to the distance from shore/port is higher than for the W2W. A repair cost increase of 9-17% occurs with an increase of 50% of the distance for the CTV, while a cost increase of 3-5% is observed for the W2W vessel. The smaller value refers to the major repair, since the total repair cost is mainly influenced by the repair activity rather than the transit to site. Similarly, a cost decrease of 5-15% is observed in the case of CTV, as opposed to a cost decrease of 3-4% in the case of W2W vessel, with a distance decrease of 50% compared to the nominal case. The higher impact of sailing distance on the CTV strategy was expected, due to its stricter weather limits during its transit compared to the W2W vessel.

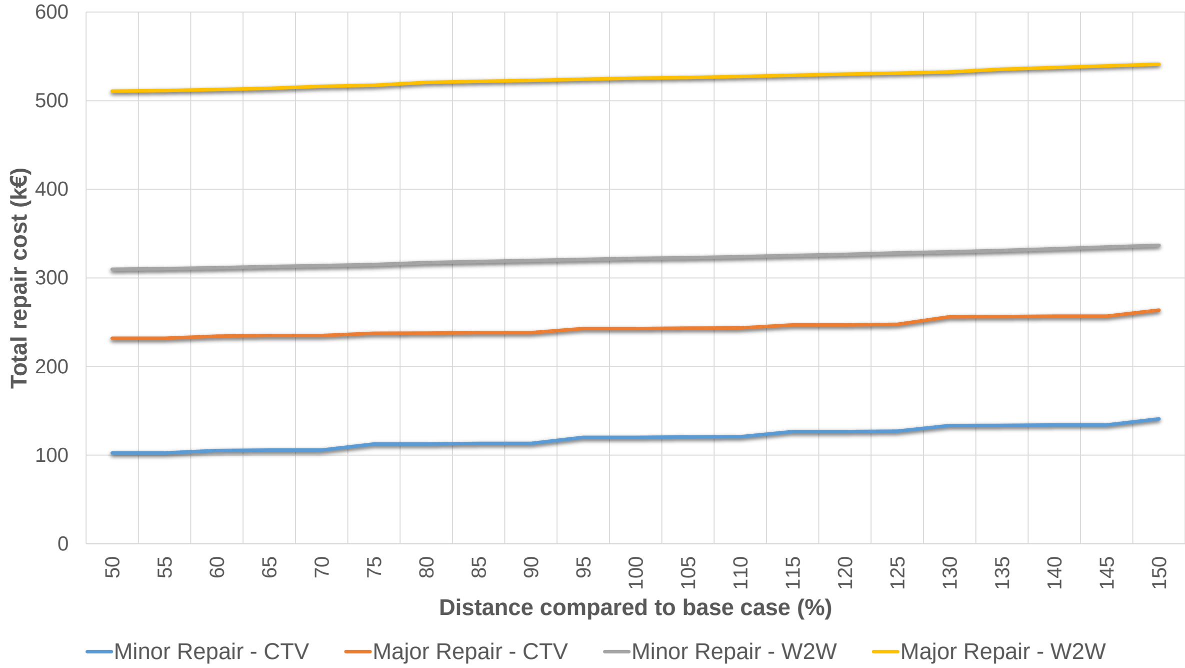
Furthermore, as it can be observed from Figure 4.12b, CTV is again the most cost-effective strategy, irrespective of the weather limits. When weather limits are equal to 50% of the base case scenario ones, a repair cost increase of 494-519% is observed for the CTV repair strategy, while an increase of 330-400% is observed in the W2W case. In this sensitivity analysis, the lower value of each respective range refers to the minor repair, as due to stricter weather limits, it is even harder to satisfy the extended weather window of major repair. When weather limits are relaxed by 50% compared to the nominal case, CTV onsite repair cost decreases by 43-59%, while the W2W onsite repair cost decreases by 32-36%.

Moreover, the repair duration results of all implemented strategies are presented; in Figure 4.13a with respect to changing distance, and in Figure 4.13b in respect of changing weather limits.

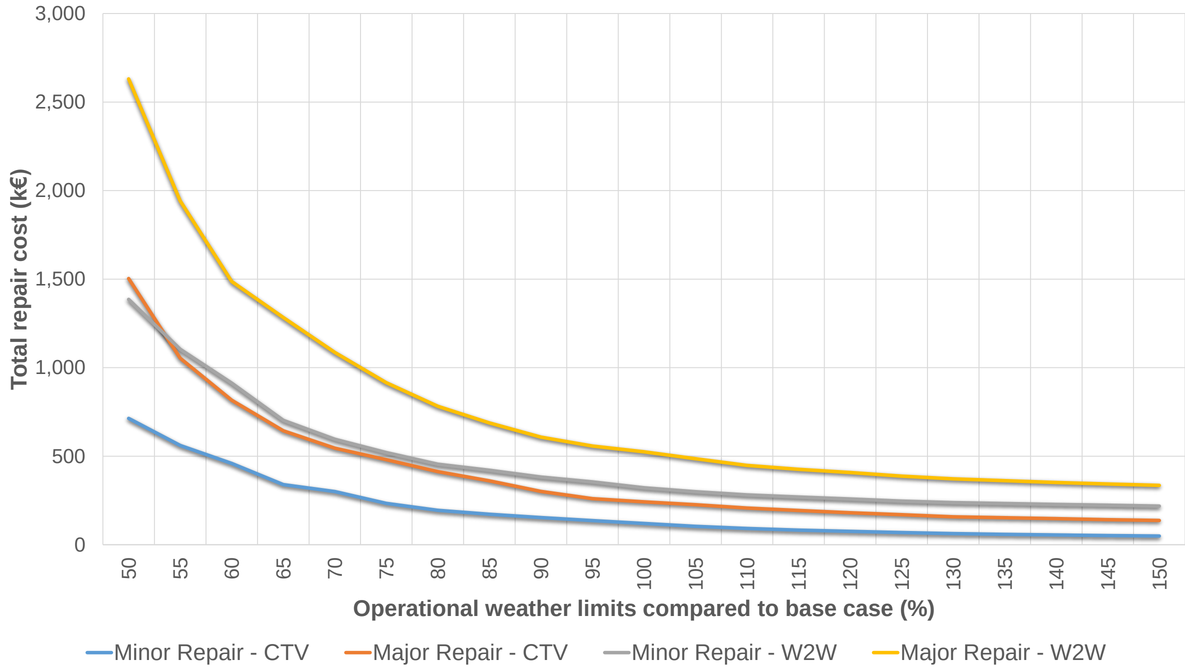
From Figure 4.13a, it is clear that for all the examined distances, the W2W repair strategy is faster compared to the CTV one. The difference in operational time increases for longer distances, due to CTV limitations for long transits. In fact, a 50% decrease of distance compared to the nominal one results in a duration decrease of 6-14% for the CTV repair strategy, while a decrease of 4-6% is observed in the W2W case. Similarly to the cost analysis, the lower value refers to the major repair. Coherently, a 50% increase of distance compared to the nominal one, results in an increase of 11-17% for the CTV strategy and an increase of 5-8% for the W2W case. Therefore, it is evident that the CTVs are more dependent on the distance from shore/port compared to the W2W vessels.

Finally, from Figure 4.13b, it can be concluded that W2W strategy is again the fastest one, irrespective of the operational weather limits. When a weather-limit decrease of 50% is applied, the duration of CTV repair campaign is increased by 524-734%, while the duration of W2W repair strategy is increased by 522-616%. This trend is similar with the installation cost with respect to the weather limits. Moreover, the CTV strategy also shows the highest decrease of repair duration, when weather limits are relaxed, with a general decrease of 55% compared to a decrease of 48-53% for the W2W strategy.

In conclusion, irrespective of the examined range of distance and weather limits, the use of CTVs is always a more cost-effective, albeit slower strategy compared to W2W vessels.

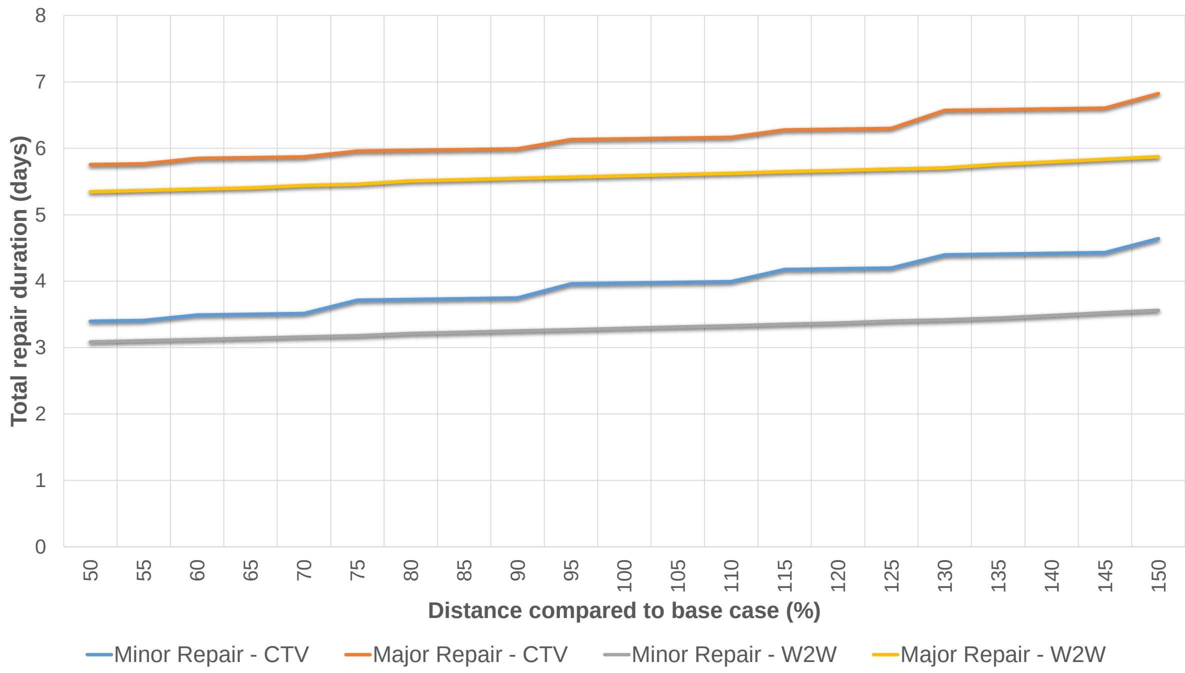


(a) Total onsite repair cost as a function of distance

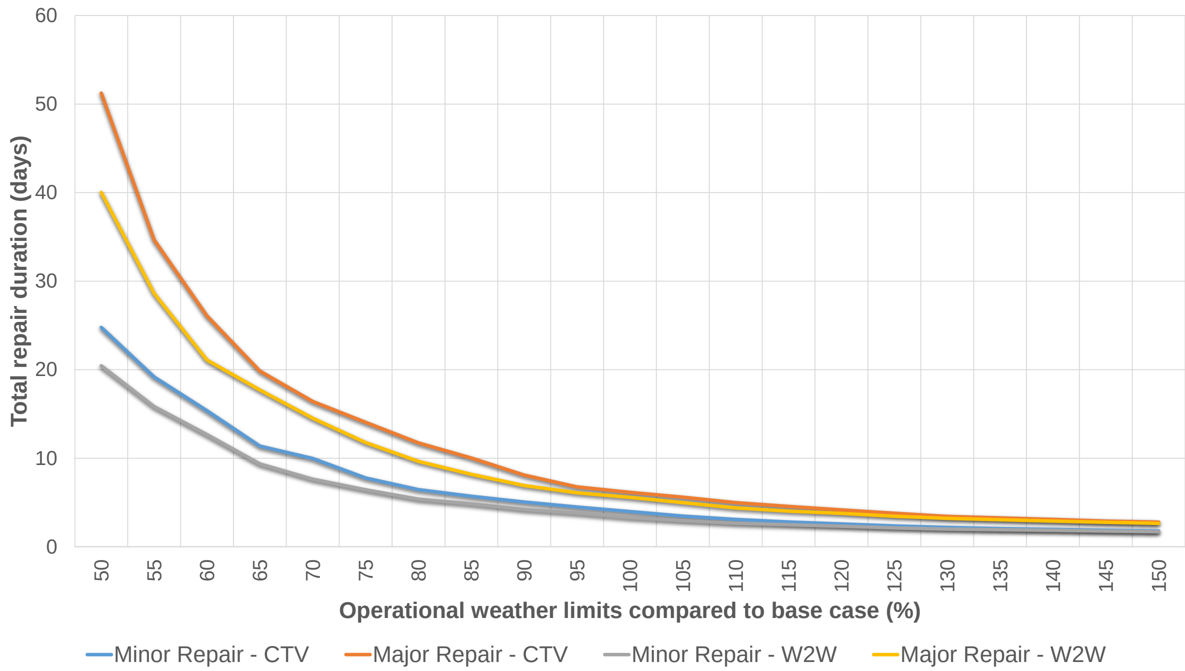


(b) Total onsite repair cost as a function of operational weather limits

Figure 4.12: Sensitivity analysis of the onsite minor/major repair cost of the different examined repair strategies.



(a) Onsite repair duration as a function of distance



(b) Onsite repair duration as a function of operational weather limits

Figure 4.13: Sensitivity analysis of the onsite minor/major repair duration per floating unit of the different examined repair strategies.

4.3.2 Sensitivity analysis of major replacement

At first, the replacement cost results of all implemented strategies are presented; in Figure 4.14a with respect to changing distance, and in Figure 4.14b in respect of changing weather limits.

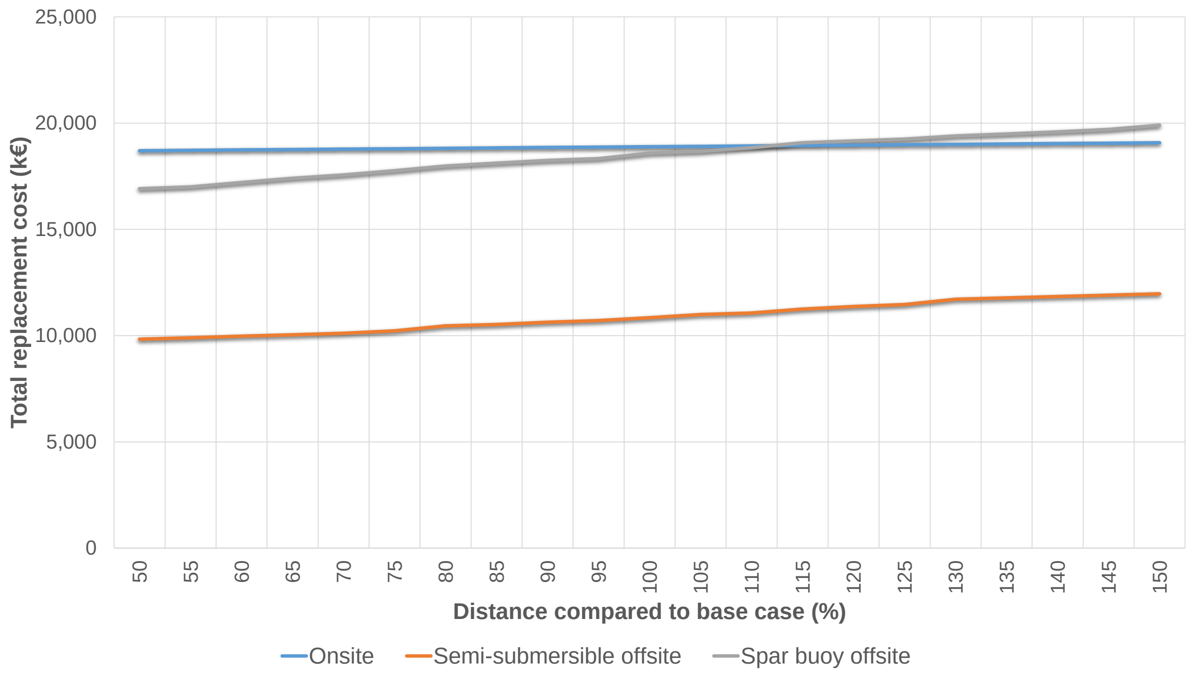
As it can be observed in Figure 4.14a, the semi-submersible offsite replacement strategy is the most cost-effective strategy for all examined distances. The onsite strategy becomes cheaper than the spar buoy offsite replacement strategy, when the distance from shore/port is larger than 110% of the base case. When distance is decreased by 50%, offsite strategies are characterised by a cost decrease of 9%, while onsite strategy only by 1%. This relates to the longer weather window required for towing the floating assemblies for the offsite replacement strategies. When the distance is increased by 50%, the maintenance cost increase of all three strategies shows the same order of magnitude as their respective decrease. Thus, the onsite strategy is the least dependent on distance from shore.

Nevertheless, as it can be observed in Figure 4.14b, onsite replacement strategy is the most affected by changing weather limits. When weather limits are equal to 50% of their nominal case, a cost increase of 726% is observed for the onsite strategy, followed by 453% for the spar buoy offsite one and by 300% for the semi-submersible offsite replacement. This high replacement cost increase for the onsite strategy is attributed to the far-offshore adverse weather conditions, under which all the replacement operations take place. When comparing the offsite replacement strategy for spar buoys and semi-submersibles, the towing speed of spar buoy units is lower compared to the semi-submersibles and thus longer weather windows are required. Furthermore, semi-submersible offsite replacement takes place at the quayside, while spar buoy offsite replacements are performed at a sheltered location. Therefore, the latter strategy is more exposed to adverse weather conditions. When weather limits are increased by 50% compared to the nominal ones, onsite strategy shows the highest cost decrease of 38%, followed by spar buoy offsite strategy with a decrease of 27% and the semi-submersible offsite one with a decrease of 24%. This proves again the high dependence on weather conditions of the onsite strategy. The semi-submersible offsite strategy is the most cost-effective replacement strategy, irrespective of the weather limits, while the onsite one becomes cheaper than the spar buoy offsite strategy, when weather limits become larger than 125% of the base case.

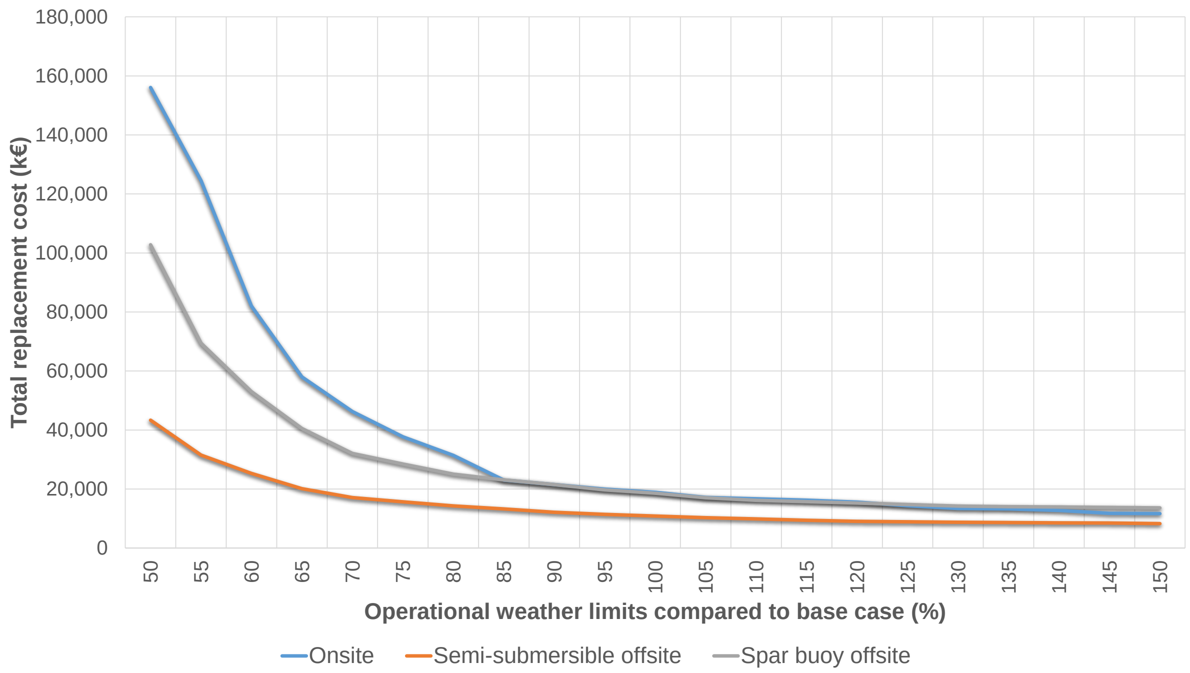
Moreover, the duration of the replacements for all implemented strategies are presented; in Figure 4.15a with respect to changing distance, and in Figure 4.15b in respect of changing weather limits.

From Figure, 4.15a, it is clear that for all the examined distances, the onsite replacement strategy is the fastest one, followed by the semi-submersible offsite replacement campaign. However, the differences in duration between the implemented strategies do not remain constant. When the distance is decreased by 50%, the replacement duration of onsite strategy is decreased by 1%, while the duration of the offsite strategies of the semi-submersible and the spar buoy floating units is decreased by 15% and 22%, respectively. As aforementioned, this is due to the fact that for the onsite strategy no towing operations are required. When the distance is increased by 50%, the maintenance duration increase of all three strategies, has the same order of magnitude as their respective decrease.

Finally, in Figure 4.15b, it can be noticed that when weather limits decrease by 50%, the duration of the onsite replacement strategy increases by 989%, followed by the spar buoy and the semi-submersible offsite strategies with an increase in required time of 469% and 428%, respectively. This conclusion is similar to the one obtained from the sensitivity analysis of the replacement cost with respect to the weather limits. Furthermore, when weather limits are increased by 50% compared to the nominal ones, the onsite strategy shows the highest duration decrease of 52%, followed by spar buoy and semi-submersible offsite strategies with a duration decrease of 38% and 37%, respectively. It is worth mentioning that the semi-submersible offsite strategy is



(a) Total replacement cost as a function of distance

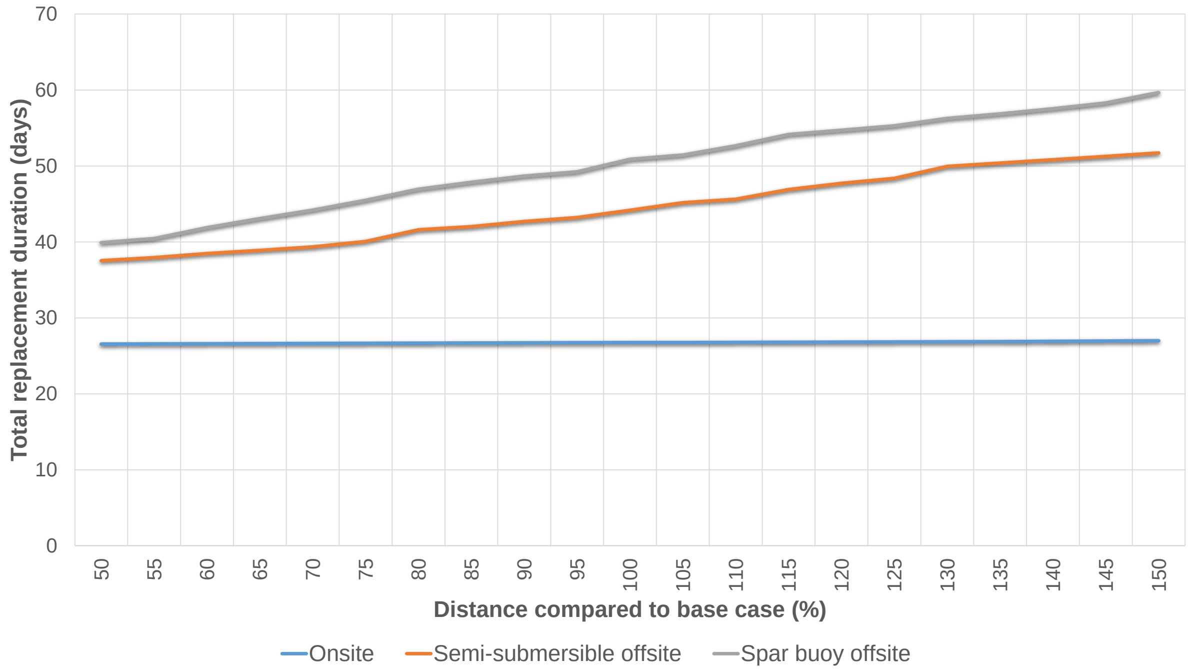


(b) Total replacement cost a function of operational weather limits

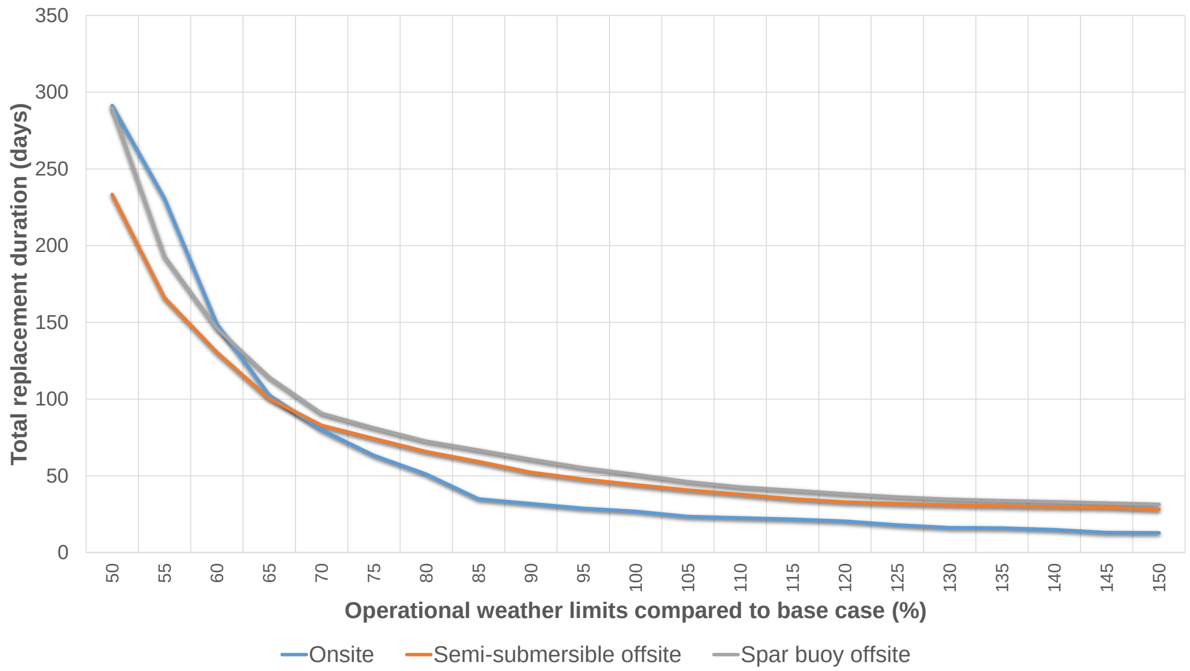
Figure 4.14: Sensitivity analysis of the replacement cost of the different examined replacement strategies.

always faster than the spar buoy offsite one, irrespective of the weather limits, while the onsite strategy becomes the fastest one in general when weather limits are higher than 70% of their nominal case, despite being the slowest one for weather limits up to 60% of the base case.

Irrespective of the range of distance and weather limits, semi-submersible offsite strategy is always the most cost-effective strategy, while the onsite strategy is the fastest one for all distances and weather limits higher than 70% of the base case ones.



(a) Replacement duration as a function of distance



(b) Replacement duration as a function of operational weather limits

Figure 4.15: Sensitivity analysis of the replacement duration of the different examined replacement strategies.

5 | Conclusion and Recommendations

The purpose of this MSc thesis is to gain understanding on what are the optimum strategies for the installation and O&M of far-offshore floating wind farms, from a techno-economic point of view. Towards this direction, different installation and maintenance strategies have been investigated in this report, both for semi-submersible as well as for spar buoy floating units. The installation strategies include the semi-submersible installation with wind turbine assembly at quayside or at wind farm site, as well as the spar buoy installation with the use of a HLV or with a crane barge. The maintenance strategies include the minor/major repairs using a CTV or a W2W vessel, as well as the onsite or offsite major replacement for semi-submersibles and spar buoys. A script to simulate the installation and O&M strategies mentioned above has been developed, which takes into account weather time series, vessel and facilities costs, personnel and replacement component costs as well as electricity prices to calculate the lost revenue due to downtime. In order to examine the most cost-effective strategies for both the installation and the maintenance phase of the wind farm, a base case scenario is defined. In addition, a sensitivity analysis is performed on the main factors that influence the cost and the duration of offshore activities: distance from shore/port and operational limits for the different activities.

As far as the installation cost and duration are concerned, the semi-submersible installation with wind turbine assembly at quayside is the fastest and most economically viable strategy for all the cases taken into account in this thesis. This conclusion is in agreement with previous literature on the topic, as according to [6], semi-submersibles are expected to yield the lowest installation cost, mainly due to the fact that their low draft allows for quayside turbine assembly. On the other hand, the semi-submersible installation with wind turbine assembly at wind farm site, is the most expensive option, irrespective of the distance from shore/port and weather limits. This is attributed to the high number of activities performed at site, which makes it susceptible to adverse far-offshore weather conditions. Nevertheless, the duration of this strategy is highly dependent on the applicable weather limits. When the operational weather limits of the activities are at their minimum, this strategy is characterised by the highest duration for all the examined time periods, while it becomes competitive or even faster than the two strategies examined for the spar buoys when the weather limits are more relaxed.

Moreover, the spar buoy installation with HLV is faster and more cost-effective than the spar buoy installation with crane barge. The increased number of trips required to assemble the wind turbine on the spar buoy with a crane barge, results in a higher overall duration and cost despite the higher mobilisation cost and daily rate of a HLV. In addition, both strategies result in higher installation cost compared to the semi-submersible installation with wind turbine assembly at quayside, mainly due to the use of an additional vessel, either the HLV or the crane barge, to assemble the wind turbine on the spar buoy at the sheltered location [16]. In general, it is considered of utmost importance to increase the weather limits of all offshore activities due to their high impact on the overall cost and duration of the installation of floating wind farms. This is proven by the exponential relation of the installation cost and duration with the applied weather limits.

Onsite maintenance campaigns for minor and major repairs of wind turbine components were examined with the use of either a CTV or a W2W vessel. For all examined distances and weather limits, the CTV repair campaign is more cost-effective, albeit slower, than the W2W one. Nevertheless, the deployment of a CTV to perform operations in far-offshore locations might not be possible, unless progress in its operational capabilities is undertaken in the following years. Furthermore, the results are based on a single wind turbine repair campaign. In a larger wind farm this might not be the case, and the vessels will need to perform offshore activities for a longer duration, thus making the W2W vessel a necessity, due to its accommodation and higher sea capabilities. Finally, in the scope of this thesis, it is assumed that the O&M vessels are chartered on a case to case basis. In reality, a wind farm operator might invest in their own vessels or sign a long-term contract for the use of third-party vessels for the wind farm lifetime. In that case, the high mobilisation cost and daily rate of the W2W vessel will not have such a significant impact, as its investment cost will be spread over the lifetime of the vessel or the length of the long-term charter contract.

Replacement of major components of wind turbines were examined for both an onsite and on offsite strategy. It is found that the semi-submersible offsite replacement strategy is the most cost-effective option among all examined distances and weather limits. For the spar buoy, onsite replacement strategy becomes cheaper than the offsite strategy when distance from shore is increased or weather limits are relaxed. This is due to the significant amount of time required for towing operations for the spar buoy offsite strategy and the high dependence on far-offshore weather conditions of the onsite strategy, respectively. A previous study [15] concluded that the ideal maintenance strategy for spar buoys is significantly affected by the weather conditions. Harsh weather conditions dictate that offsite repair works in a sheltered area should be pursued, while in medium weather conditions, it is more economically viable to perform maintenance activities onsite. However, the cost difference is marginal and thus the selection of the optimal strategy is subject to the volatility of the HLV daily rate and the electricity price. In case of marginal cost difference between the onsite and the offsite replacement strategy, the wind farm developer should also take into consideration the actual weather risk and a more thorough examination of the cost allocation to avoid excessive expenditure [15]. In general, offsite maintenance is expected to be the best strategy at the time being, but in the following years, development of new technologies could make onsite operations more economically viable [27].

Furthermore, the onsite replacement strategy is the fastest replacement strategy throughout the sensitivity analyses, apart from the simulations where the weather limits are lower than 70% of their nominal values. This is due to the fact that in the onsite replacement strategy the HLV has to transit only once to site, while in the offsite strategies the floating units have to be towed to port/sheltered location and then back to wind farm site. In addition, the semi-submersible offsite replacement strategy is proven to be faster than the spar buoy offsite one for all examined distances and weather limits, mainly due to its higher towing speed.

Overall, the installation and the maintenance campaigns of semi-submersible floating units are more cost-effective than the spar buoy ones. Nevertheless, the production cost of semi-submersibles is higher than spar buoys, so the final selection of the type of the floater should be the result of the overall life-time costs of the floating wind farm, from the development and consenting phase up to the decommissioning phase [6].

Future work could extend and verify the content of this thesis. First of all, a validation of the results with a higher fidelity simulation model is essential. By comparing with detailed models, which include various cost input data that are not taken into consideration in the scope of this thesis, as for example project and management personnel cost, a better understanding of the trends of the different installation and maintenance strategies can be obtained. In the case of the maintenance campaigns, a stochastic approach to failure with Monte Carlo simulations could be pursued, to get a more realistic insight into the actual operation phase of a floating wind farm. Furthermore, the concurrent execution of independent activities could be considered, as this is the expected approach in complex projects with multiple stakeholders. Moreover, a sensitivity analysis could be performed also on the various costs, like vessels and facilities costs, and on the electricity price for the lost revenue calculation, as it is suggested that these variables have a high impact on the selection of the optimum strategy. In addition, the installation and maintenance of the other components of the wind farm, including the floater, the anchoring and mooring system as well as the electrical balance of plant, could be added to achieve a full model representation. Finally, another step forward would be the addition of hydrogen components in the far-offshore floating wind farm, in order to acquire better insight into the wind turbine - hydrogen production configuration, which is expected to make its first steps in far-offshore locations in the imminent future.

References

[1] UNFCCC. *The Paris Agreement.* 2022. URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[2] Joyce Lee and Feng Zhao. "Global Wind Report 2021". In: *Global Wind Energy Council* (2021), pp. 1–80. URL: http://www.gwec.net/global-figures/wind-energy-global-status/.

[3] IEA. *Data tables – Data & Statistics.* 2022. URL: https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Electricity&year=2019.

[4] Catho Bjerkseter and Anders Ågotnes. "Levelised costs of energy for offshore floating wind turbine concepts". Doctoral dissertation. 2013.

[5] IRENA. *Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects.* 2019, pp. 1–88. ISBN: 9789292601553. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf.

[6] J Harrison. "Floating Offshore Wind : Installation, Operation & Maintenance Challenges". In: *Blackfish Engineering Design Ltd* (2020), pp. 1–53. URL: https://blackfishengineering.com/wp-content/uploads/2020/07/Blackfish-Engineering_FOW_Installation_OM.pdf.

[7] J. Murphy et al. "Site selection Analysis for offshore combined Resource Projects in Europe". In: *Orecca* October (2011), p. 123.

[8] Samuel Torres-Rincón, Emilio Bastidas-Arteaga, and Mauricio Sánchez-Silva. "A flexibility-based approach for the design and management of floating offshore wind farms". In: *Renewable Energy* 175 (Sept. 2021), pp. 910–925. ISSN: 18790682. DOI: 10.1016/J.RENENE.2021.04.121. URL: https://doi.org/10.1016/j.renene.2021.04.121.

[9] Alessandro Singlitico, Jacob Østergaard, and Spyros Chatzivasileiadis. "Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs". In: *Renewable and Sustainable Energy Transition* 1 (Aug. 2021), p. 100005. ISSN: 2667095X. DOI: 10.1016/J.RSET.2021.100005. URL: https://doi.org/10.1016/j.rset.2021.100005.

[10] European Commission. "A hydrogen strategy for a climate-neutral Europe". In: (2020).

[11] Adnan Durakovic. *First Turbines Assembled for Hywind Tampen Floating Offshore Wind Farm.* 2022. URL: https://www.offshorewind.biz/2022/05/23/first-turbines-assembled-for-hywind-tampen-floating-offshore-wind-farm/.

[12] Adnan Durakovic. *World's Largest Floating Offshore Wind Farm Fully Operational.* 2021. URL: https://www.offshorewind.biz/2021/10/19/worlds-largest-floating-offshore-wind-farm-fully-operational/.

[13] Evan Gaertner et al. "Definition of the IEA 15-Megawatt Offshore Reference Wind". In: (2020).

[14] Mohammad Youssef Mahfouz et al. "Public design and FAST models of the two 15MW floater-turbine concepts". In: April (2020), p. 99.

[15] Innovation Hub. "Floating wind: Cost modelling of major repair strategies". In: (2020). URL: https://offshorewindinnovationhub.com/industry_insight/floating-wind-cost-modelling-of-major-repair-strategies/.

[16] Rhodri James and Marc Costa Ros. "Floating Offshore Wind: Market and Technology Review". In: (2015), pp. 1–168.

[17] Anders Myhr et al. "Levelised cost of energy for offshore floating wind turbines in a lifecycle perspective". In: *Renewable Energy* 66 (2014), pp. 714–728. ISSN: 09601481. DOI: 10.1016/J.RENENE.2014.01.017. URL: http://dx.doi.org/10.1016/j.renene.2014.01.017.

[18] A. Martinez and G. Iglesias. "Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic". In: *Renewable and Sustainable Energy Reviews* 154 (Feb. 2022). ISSN: 18790690. DOI: 10.1016/J.RSER.2021.111889. URL: https://doi.org/10.1016/j.rser.2021.111889.

[19] European Wind Energy Association. "Wind in our sails". In: *ABA Journal* November (2011), pp. 1–93.

[20] C. Maienza et al. "A life cycle cost model for floating offshore wind farms". In: *Applied Energy* 266 (May 2020). ISSN: 03062619. DOI: 10.1016/J.APENERGY.2020.114716. URL: https://doi.org/10.1016/j.apenergy.2020.114716.

[21] T Ackermann et al. "Evaluation of Electrical Transmission Concepts for Large Offshore Wind Farms". In: *Proceedings of Copenhagen Offshore Wind* (2005), pp. 1–10.

[22] BVG Associates. "Guide to an Offshore Wind Farm". In: *Published on behalf of The Crown Estate and the Offshore Renewable Energy Catapult* January (2019), pp. 1–128.

[23] Giovanni Rinaldi et al. "Incorporating stochastic operation and maintenance models into the techno-economic analysis of floating offshore wind farms". In: *Applied Energy* 301 (Nov. 2021). ISSN: 03062619. DOI: 10.1016/J.APENERGY.2021.117420. URL: https://doi.org/10.1016/j.apenergy.2021.117420.

[24] Friedemann Borisade, Jayesh Bhat, and Denis Matha. "Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m". In: (2015).

[25] Rahul Chitteth Ramachandran et al. "Floating offshore wind turbines: Installation, operation, maintenance and decommissioning challenges and opportunities". In: (2021). DOI: 10.5194/wes-2021-120. URL: https://doi.org/10.5194/wes-2021-120.

[26] Lucy Wyatt. "Spatio-Temporal Metocean Measurements for Offshore Wind Power". In: *Journal of Energy and Power Technology* 3.1 (2021). DOI: 10.21926/jept.2101005.

[27] Marie-Antoinette Schwarzkopf et al. "Identification of floating-wind- specific O & M requirements and monitoring technologies". In: August (2020), pp. 1–98.

[28] Laura Castro-Santos et al. "Methodology to calculate the installation costs of offshore wind farms located in deep waters". In: *Journal of Cleaner Production* 170 (Jan. 2018), pp. 1124–1135. ISSN: 09596526. DOI: 10.1016/J.JCLEPRO.2017.09.219. URL: https://doi.org/10.1016/j.jclepro.2017.09.219.

[29] I Andrić et al. "Fabrication and installation constraints for floating wind and implications on current infrastructure and design". In: *Energy Procedia* 137 (2017), pp. 299–306. ISSN: 18766102. DOI: 10.1016/J.EGYPRO.2017.10.354. URL: www.sciencedirect.comAvailableonlineatwww.sciencedirect.comwww.elsevier.com/locate/procedia1876-6102www.sciencedirect.comwww.elsevier.com/locate/procedia1876-6102.

[30] IRENA. "Floating Foundations: A Game Changer for Offshore Wind Power". In: (2016), pp. 1–8. URL: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Offshore_Wind_Floating_Foundations_2016.pdf.

[31] Anna Garcia-Teruel et al. “Life cycle assessment of floating offshore wind farms: An evaluation of operation and maintenance”. In: *Applied Energy* 307 (Feb. 2022), p. 118067. ISSN: 03062619. DOI: 10.1016/J.APENERGY.2021.118067. URL: https://doi.org/10.1016/j.apenergy.2021.118067.

[32] L. Castro-Santos, S. Ferreño González, and V. Diaz-Casas. “Methodology to calculate mooring and anchoring costs of floating offshore wind devices”. In: *Renewable Energy and Power Quality Journal* 1.11 (Mar. 2013), pp. 268–272. ISSN: 2172038X. DOI: 10.24084/REPQJ11.276.

[33] Nick Augusteijn and Mariska Buitendijk. *Boskalis: Kincardine is a prelude to more floating wind projects | Project Cargo Journal*. 2021. URL: https://www.projectcargojournal.com/offshore/2021/02/18/boskalis-kincardine-is-a-prelude-to-more-floating-wind-projects/?gdpr=accept.

[34] Anthony Gray. “WHAT ARE OPERATIONS AND MAINTENANCE SIMULATION TOOLS?” In: (2020).

[35] IRENA. “Wind Power”. In: (2012), pp. 1–64.

[36] DNV. *Opportunistic Maintenance*. 2022. URL: https://www.dnv.com/article/opportunistic-maintenance-207906.

[37] Naunidh Mangat et al. “Optimal offshore wind turbine size and standardisation study”. In: March (2022). URL: www.tki-windopzee.nl.

[38] Zhiyu Jiang. “Installation of offshore wind turbines: A technical review”. In: *Renewable and Sustainable Energy Reviews* 139 (Apr. 2021), p. 110576. ISSN: 18790690. DOI: 10.1016/J.RSER.2020.110576. URL: http://creativecommons.org/licenses/by/4.0/.

[39] Nadezda Avanessova et al. “Analysing the effectiveness of different offshore maintenance base options for floating wind farms”. In: *Wind Energy Science* 7.2 (2022), pp. 887–901. ISSN: 23667451. DOI: 10.5194/wes-7-887-2022.

[40] M Asgarpour, A Dewan, and L B Savenije. “Commercial Proof of Innovative Installation Concepts using ECN Installlation Tool”. In: *European Wind Energy Association (EWEA)* March (2015). URL: http://www.naun.org/main/NAUN/energy/b012001-201.pdf.

[41] ORBIT. *Moored Substructure Installation Methodology*. 2020. URL: https://wisdem.github.io/ORBIT/source/phases/install/quayside_towout/doc_MooredSubInstallation.html.

[42] James Carroll, Alasdair McDonald, and David McMillan. “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines”. In: *Wind Energy* 19.6 (June 2016), pp. 1107–1119. ISSN: 10991824. DOI: 10.1002/we.1887.

[43] LAUTEC. *ESOX - Map: Download and Analyze Metocean Data*. 2022. URL: https://esox.lautec.com/map/.

[44] Port of Cromarty Firth. “Rates and Charges”. In: January (2022), pp. 1–11.

[45] Forth Ports Limited. “Marine rates and Charges”. In: January (2021), pp. 1–20. URL: https://www.forthports.co.uk/marine/tariffs/.