PivotBuoy

An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind

Call identifier: H2020-LC-SC3-RES-11-2018

D6.4: Optimal maintenance strategies for single point mooring systems

Due Date of Deliverable:	30/11/2019
Completion Date of Deliverable:	29/11/2019

Start date of project: April 2019 Duration: 36 months

Lead partner for deliverable: WavEC – Offshore Renewables

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including Commission Services)	
CO	Confidential, only for members of the consortium (including Commission Services)	

This project has received funding from the European Union's Horizon H2020 research and innovation programme under grant agreement No 815159

Document History

Issue Date	Version	Changes Made / Reason for this Issue	Lead Author(s)
15/11/2019	1.0	First issue	António Maximiano, F. X. Correia da Fonseca.
20/11/2019	1.1	Review	X1 Wind & PLOCAN
26/11/2019	2.0	Final version	António Maximiano, F. X. Correia da Fonseca.
29/11/2019	2.1	Final review for submission	X1 Wind

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EXECUTIVE SUMMARY

It is commonly known that corrective maintenance usually turns out more expensive than a precautionary approach, and in particular in the offshore environment. The possibility of not being able to perform scheduled inspection or maintenance is high, and consequences of losing key components' functionality may lead to a loss in energy yield. It is therefore important to implement at an early stage the concept of Predictive Maintenance.

This task assesses the impact of different possible maintenance strategies on costs and loss of energy yield (downtime). Due to the fact that floating wind is still in its infancy and there are large uncertainties and limited amount of data, a sensitivity analysis is also included to test the influence of key factors. The results of this task are being fed into the final design of the system.

The Pivotbuoy subsystem integrates the mooring and electrical cable into a single point, that can be quickly connected to a floating structure with a wind turbine. This quick connection systems enables a so-called tow-to-port strategy, where the major replacements of significant components can be carried out at port, by disconnecting the structure and towing it to port.

In this analysis the impact of different connection/disconnection durations and operation limiting conditions (OLC) on the downtime of a reference farm south of the Gran Canary island was evaluated. Other parameters such as port selection, wet tow OLC and maintenance strategy (corrective vs predictive) were considered. Feasibilities for the different durations and OLC were compiled and the resulting waiting times and downtimes were presented.

The operational analysis was restricted to the major replacements of the components that were assumed to require a tow-to-port to repair: hub, blades, generator, gearbox and pitch/hydraulics. It was also assumed that the operations could be carried out using local vessels.

Based on the weather analysis results, the following conclusions seem justified:

- The third trimester is the worse time of the year to carry out operations due to the lowest accessibility and higher energy production, while the fourth trimester shows higher accessibility and lower energy production.

Based on the operation analysis, the following remarks are justified:

- When compared to a long (dis)connection duration (24h), the PivotBuoy quick connection (4h) systems lowers the expected average downtime between 20-30%.
- For the reference OLC (Hs=1,5m; Ws=15m/s), decreasing the connection duration below 6h has a reduction of downtime under 3%. However, a reduction from 24h to 12h has a downtime reduction of 18%.
- Increasing the (dis)connection OLC to (Hs=2m; Ws=15m/s) has a small impact on downtime (under 5%), while reducing the OLC to (Hs=1m; Ws=10m/s) can increases the average downtime by up to threefold.
- The wet tow OLC shows a similar behaviour, with small downtime gains for the high OLC, but a severe penalty for the low OLC (up to a 1.75 factor increase in downtime).

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- Selecting the closer Arinaga port represents a reduction of downtime in the order of 10%. However, this advantage needs to be weighed against other costs not considered such as e.g. crane mobilization costs.
- The time it takes to carry out the repairs at port is the other major contributor to the downtime for all scenarios tested, representing between 30% to over 90% of downtime.
- Implementing an ideal purely predictive maintenance strategy reduces the downtime by up to 26% when compared with a purely corrective maintenance strategy.

1 INTRODUCTION

1.1 Context

The operation and maintenance (O&M) of a wind farm has a significant impact on the overall costs, and ultimately on the cost of energy (see Figure 1). The wind industry has recognized the importance of O&M and has been investigating how to optimize O&M operations, reducing its costs and increasing the overall farm availability.

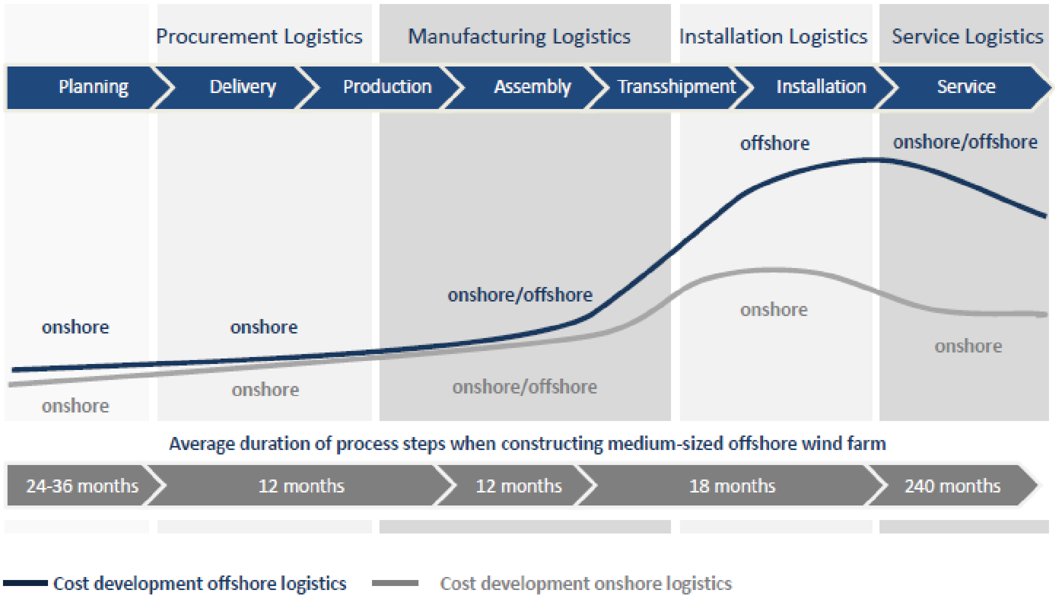

Figure 1 Development of costs over the course of the individual logistics phases in the onshore and the offshore sector for the offshore wind industry (source [1])

For offshore wind farms, some of the main O&M cost drivers are the high vessel rates, site accessibility, and failure rates or mean time between failure (MTBF) and the mean time to repair (MTTR). An ideal O&M strategy is the result of an optimization of these parameters, within certain constraints, to achieve the lowest costs possible. However, this is not a trivial task. The vessel rates are not fixed throughout the farm lifetime, depending on the fleet size and availability at the time of operation. Site accessibility is evaluated statistically using hindcast data, but in practice it will be dependent on the short-term weather forecast. The failure rates are often based on the limited open literature data and likely extrapolated to a different site/turbine model. Therefore, the main input parameters of offshore wind O&M modelling have a non-negligible uncertainty that will be reflected in the outcome of such analysis.

There is a trend in the offshore industry towards larger and higher rated power turbines, installed further offshore and in floating foundations. This trend seeks to increase energy production by exploiting the larger wind resource available in deep water locations further from the coast, where a fixed foundation is not feasible.

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Although the benefits of higher energy production are evident, this trend towards harsher environments located further offshore is a challenge from the O&M perspective. The remote location of the sites, and their harsher climate, reduces the weather windows available to carry out O&M operations. At the same time, O&M operations are becoming more complex due to the need to lift heavier loads to higher heights from a floating vessel to a floating turbine, thus placing more restrictions on vessel selection and driving vessel costs up. Furthermore, the penalties for a subpar O&M strategy are more severe, as the loss of revenue due to turbine downtime increases for larger capacity turbines.

All these factors highlight not only the higher importance of O&M in floating offshore wind costs, but also the increased challenge it poses to O&M modelling, particularly in terms of input uncertainty. Therefore, an efficient O&M strategy is a key factor to enable floating offshore wind to lower its levelized cost of energy and reach its full potential.

1.2 PivotBuoy concept

The PivotBuoy (PB) is a novel subsystem that integrates the mooring system and the electric cable into a single point mooring (SPM). Its modular design is comprised of two bodies, the lower body and upper body, as seen in Figure 2. The lower body of the PB is permanently moored to an anchor through a tension leg system (TLP), while the umbilical cable is hanging from this lower body in a catenary shape, as shown in Figure 2. The upper body of the PB is integrated to the floating platform and can be quickly connected or disconnected from the lower body in case of need.

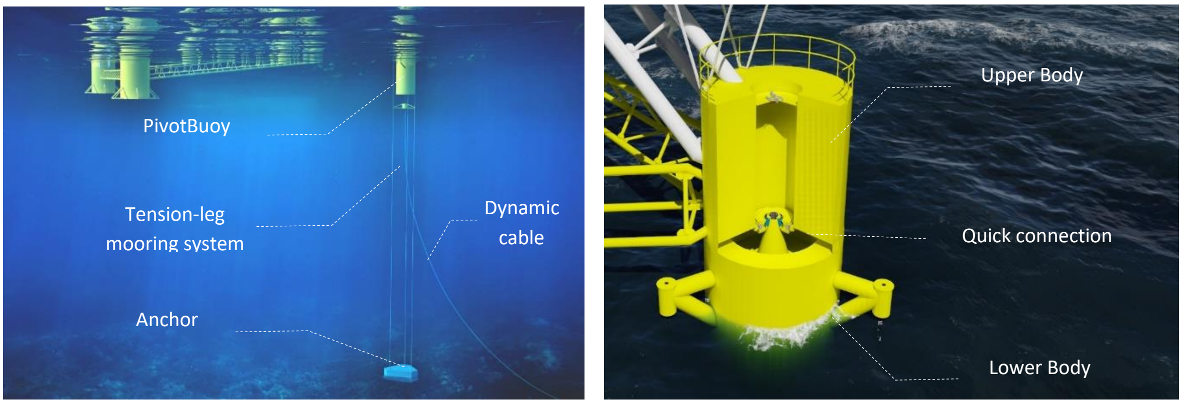

Figure 2 Schematic representation of the PivotBuoy subsystem, showing the mooring system and electrical cable (left) and the connection system to the floating foundation (right).

One advantage of this system is the possibility to quickly and simultaneously disconnect the foundation from its mooring system and electrical cable, tow the foundation to a nearby port or sheltered waters, either to perform complex maintenance operations or to avoid extreme weather, and tow it back to site to resume operation.

Therefore, the PivotBuoy system enables a so-called Tow-to-Port (TTP) maintenance approach, where the large repairs can be carried out at port, which can be an advantage and a significant driver to reduce the O&M costs.

The Pivotbuoy quick connection duration and OLC are design parameters that can be optimized within certain limits. It is therefore of interest to evaluate the impact of such parameters in the context of O&M.

1.3 Objectives

The objective of this deliverable is to carry out a preliminary analysis that quantifies possible cost reductions in the O&M using the PivotBuoy quick (dis)connection system, when compared to a longer duration disconnection and reconnection operation. The cost reductions are here represented by the expected downtime, which can be seen as a proxy variable to the costs when comparing the scenarios considered in this analysis.

Furthermore, the sensitivity of the results to the following parameters are of interest:

- Different connection/disconnection durations and OLC
- Port selection
- Different wet tow OLC
- Different maintenance strategies: corrective maintenance vs ideal predictive maintenance

1.4 Approach

This comparison will be made using a reference wind farm located near the Gran-Canaria island, at a site previously flagged as potentially commercially viable due to its wind resource.

A weather window analysis is carried out for the reference site, including feasibility and weather window analysis

The operational analysis is conducted in terms of expected average downtime for the reference farm, for all the different scenarios tested, and conclusions are drawn.

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2 STATE-OF-THE-ART ON MAINTENANCE STRATEGIES

The maintenance strategy can be divided in two categories: corrective maintenance and preventive maintenance.

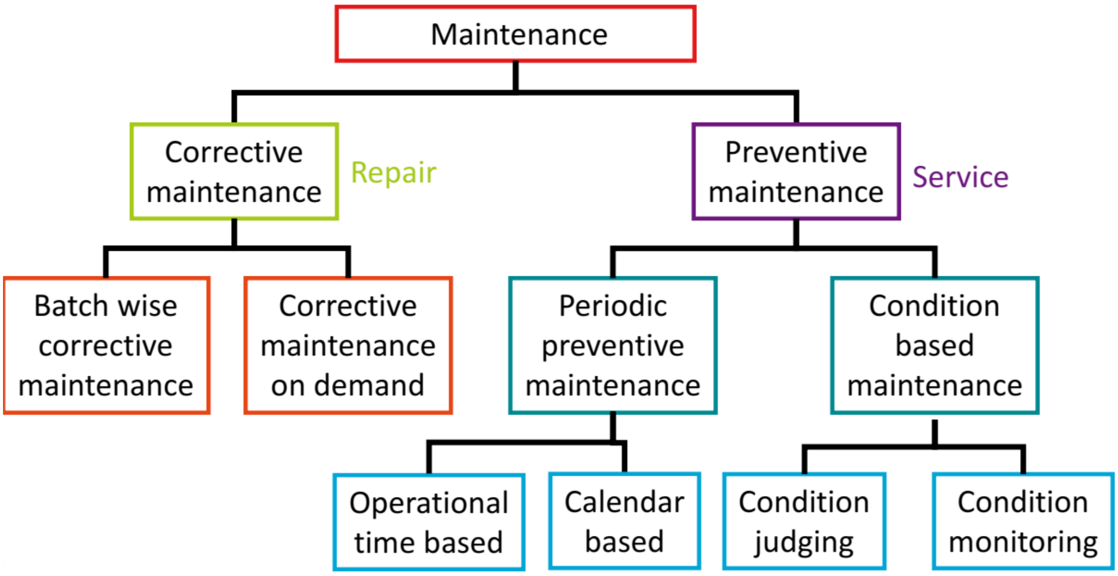

Figure 3 O&M strategy definition and concepts

2.1 Corrective Maintenance

Corrective maintenance actions are carried out after a certain component breaks down, or is no longer able to perform its function, with the objective of returning that component to a functional state. Should the component failure lead to downtime, and consequently to loss of revenue, it is critical that the corrective maintenance action is carried out as quickly as possible, in order to return the turbine to an operational status.

Once the fault is detected, it is necessary to mobilize the resources necessary to carry out the repair mission, such as spare parts, repair equipment, repair crew, and vessel mobilization. Once those resources are in place, there can be a waiting time for a favourable weather window. This waiting time is heavily dependent on the site metocean conditions and the specific repair operation limiting conditions (OLC).

If the failure occurs in a component that leads to turbine shutdown, then the downtime will include the time necessary for vessel and resource mobilization, waiting time for a viable weather window, and mission time, possibly resulting in significant loss of revenue.

2.2 Preventive Maintenance

Preventive maintenance is a pro-active approach to maintenance with the objective of reducing or controlling the probability of component failure. The simplest form of preventive maintenance consists of small maintenance actions that can be planned on a periodic basis, with a prescribed calendar time

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interval or operational time between two consecutive maintenances. Another type of preventive maintenance, condition-based maintenance (CBM), consists of using real-time monitoring (employing sensors to measure vibrations and temperature) to identify components that show signs deterioration, estimate when the loss of function could occur if left unrepaired, and carry out the necessary corrective actions before failure occurs. This approach allows the preparation in advance of repair missions prior to component failure, not only reducing the mission costs, but also reducing the unplanned downtime, as the turbine remains operational until the repair mission is at site.

Preventive maintenance activities can be divided into scheduled maintenance and condition-based maintenance. Scheduled maintenance consists of pre-planned calendar-based maintenance operations, typically carried out during favourable weather seasons, e.g. bolt retightening or filter/oil changes. Condition-based maintenance requires remote monitoring of components using pre-installed sensors, e.g. accelerometers. Should the sensors indicate an anomaly, that component is flagged for a repair mission.

The condition-based maintenance approach relies on a remote monitoring system, transmitting data to specialized operators onshore. The costs of installing a complex and comprehensive remote monitoring system, located in an offshore environment, together with data management, event identification software, and specialized operators needs to be evaluated against the expected savings in terms of O&M operations.

2.3 Tow to Port (TTP)

The current offshore wind practice for replacing large components, such as blades, gearbox or generator, is to carry out a heavy lift operation at site using jack-up vessels. However, the floating wind installations are targeting deeper waters, where the jack-up vessels cannot operate. Furthermore, the tendency to move towards higher capacity wind turbine generators requires higher capacity cranes, able to operate at increasing heights, which restricts vessel selection. Finally, the heavy lift operation needs to be carried out between two floating structures, increasing its complexity. Therefore, using heavy lift vessels to carry out large replacements of floating offshore turbines at site is not without its challenges.

Another possibility is to tow the turbine foundation back to port or sheltered waters for major maintenance operations (e.g. blade or gearbox replacements). This is an attractive option if there is a suitable port nearby, and/or if the floating wind farms are located in waters too deep for jack-up vessels. The challenge with this approach lies with repeated (disc)connection of the moorings and umbilical, as well as designing the structure to withstand several tows during its lifetime. The PivotBuoy subsystem is designed for a TTP approach by enabling a quick disconnection/connection system. It should be noted that a TTP approach can be used both with a corrective or predictive maintenance strategy.

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3 METHODOLOGY AND ASSUMPTIONS

In this chapter the scope of the analysis is defined, the assumptions made are stated and their validity briefly discussed.

3.1 Reference offshore wind farm

The analysis is based on a generic baseline farm, located southeast of the Gran-Canaria island, comprised of fifty 5MW wind turbine generators, for a total installed capacity of 250 MW and a project lifetime of 20 years. The general characteristics of the reference farm are given in Table 1.

In order to reduce the number of variables in this study, no effort to optimize the logistic operation (servicing multiple turbines in a single trip) is made.

Table 1 Baseline Farm characteristics

Generic Baseline Farm	
WTG power	5 MW
WTG type	NREL 5MW Reference turbine[2]
Number of WTG	50
Farm Installed Capacity	250 MW
Farm Lifetime	20 years
Maintenance Strategy	Tow to Port for large replacement operations, otherwise maintenance carried out at site.
Site location	Southeast Gran Canaria, approximately 12km offshore (27.75 N; 15.33 W)

Figure 4 Reference farm location, southeast of the Gran Canaria Island. Shown in the red square is the Arinaga Port and the Las Palmas Port is shown in the red circle.

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3.2 Wind turbine

The wind turbine generator (WTG) considered is the NREL 5MW Baseline Wind Turbine[2], whose main properties are given in Table 2. The power curve used in this analysis is given in Figure 5.

Table 2 Selected Properties of the NREL 5MW Baseline Wind Turbine

Selected Wind Turbine Properties	
WTG power	5 MW
WTG type	Upwind, 3 Blades
Rotor diameter	126m
Hub Heigth	90 m
Wind Speed Cut In	3 m/s
Wind Speed Cut Off	25 m/s
Rated wind speed	11,4 m/s
Rotor Mass	110 ton
Nacelle Mass	240 ton

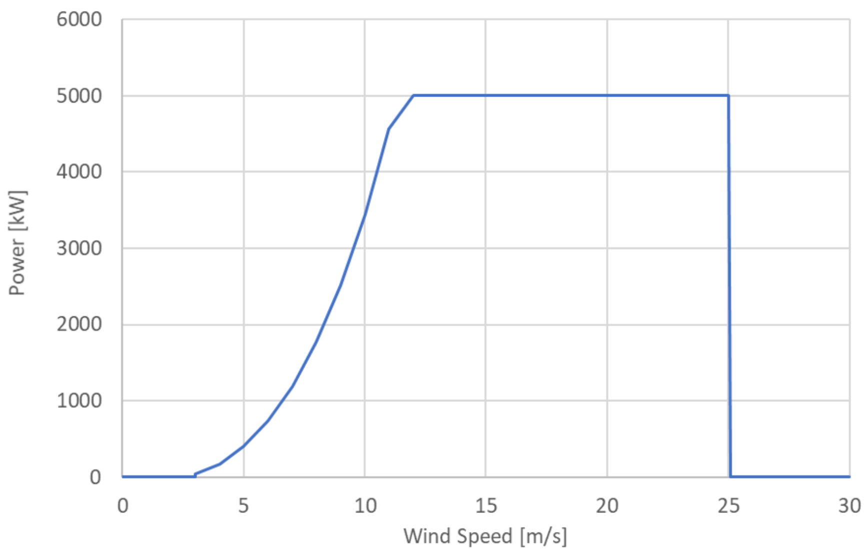

Figure 5 NREL 5MW Baseline Wind Turbine power curve.

3.3 Port Selection

The analysis was restricted to two ports located in the Gran-Canaria Island, the Las Palmas port and the Arinaga port, shown in Figure 4 and summarized in Table 3. Due to its larger size and capacity, the Las Palmas port will be used as the reference port for this analysis.

The Arinaga port is the closest port to site with sufficient quay side capacity. However, it lacks the lifting capacity necessary, and cranes would need to be mobilized. It will be tested as a possible alternative to the Las Palmas port, in order to assess what cost reductions can be expected from using this port. However, that benefit will have to be weighed against e.g. the crane mobilization costs.

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Figure 6 Las Palmas port (left) and Arinaga port (right).[1]

Table 3 Properties of the ports considered in this analysis.[1]

	Arinaga Port	Las Palmas Port
Quay Length and Water Depth	Almost 700m total length, with depths ranging from 7m to 14m	Almost 16km total length, with depths ranging from 3m to 45m
Lifting Capabilities	Possible mobilization of a 600 ton at 11m radius and 187m height	Up to 600 ton at 11m radius and 187m height
Distance from Wind Farm	12 km	45 km
Covered Storage space availability	NA	40,000m^2

3.4 O&M Vessels

A compilation of locally available vessels was carried out. To preserve confidentiality, a typical local vessel of each category with averaged values were used in this analysis. A summary of these vessels can be found in Table 4. Being local vessels, it is assumed that the mobilization and demobilization costs are zero.

Table 4 Local vessels type and cost assumptions.

Vessels	Mob/Demob costs	Daily cost	Transit speed
Tugboat	None	3,000€	12 kn
Anchor Handling Tug Vessel (AHTV)	None	20,000€	12 kn

[1] Taken from https://www.astican.es/services/ and http://www.palmasport.es/en/las-palmas-port/

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3.5 Spare Parts Strategy

The stock management of the spare parts is a topic that falls outside the scope of this study, and it is therefore assumed that all replacement parts (from small components such as bolts to large turbine blades) can always be found on stock, and there is no delay due to procurement time of replacement parts.

Usually the smaller components (under 2,000kg) are found in stock in a nearby site onshore[3]. The large components e.g. a blade or a gearbox are not often found in stock but are ordered as needed. Since their procurement time is typically smaller than the mobilization time of the large vessels (order of months) used to handle these components, the critical factor remains the vessel mobilization time.[3]

However, for a tow-to-port maintenance strategy that employs local vessels, it is expected that the procurement time of large components would exceed the mobilization time, especially if considering the need to ship those parts to the Canary Islands. The stock management strategy should take this into consideration in a future analysis.

3.6 Failure Rates and Repair Time

There is limited open data available for failure rates or mean time between failures (MTBF) of offshore wind turbines. As discussed in [4], from the 13 studies published since 2006 about the topic, only 2 relate to offshore wind turbines. One of which [5] compiles reliability data from approximately 350 offshore wind turbines operating in Europe over a 5-year period with a capacity between 2 and 4 MW. This reliability data will be used in this analysis and the relevant data is shown in Figure 7. It should be noted that the reliability data used is for wind turbines with capacity slightly lower than the 5MW used here. However, despite the increase in industry maturity, an analysis [4] suggests that the failure rates of older turbines is comparable to the more recent and larger turbines.

Tow-to-port maintenance strategies emerged as an attractive alternative to float-to-float heavy lifting maintenance at sea using costly heavy lift crane vessels. In this sense, tow-to-port maintenance only becomes relevant for major maintenance operations and large component replacements. Hence, the present study will focus on the major component replacements that would require towing to port. Minor maintenance tasks, component inspections and other minor farm service activities are typically carried out on-site using small CTVs and do not justify towing to port for maintenance. It is also assumed that the PivotBuoy system does not influence in any way the minor maintenance activities, which are consequently left out of the present study.

It should be noted that the repair times (or mean time to repair MTTR) reported in [5] were obtained for fixed offshore wind turbines, thus using jack-up vessels for lifting operations on site. In this case the repair operations are carried out at port, on a floating foundation moored at quay side, with a crane installed at the quay. This assumption was taken due to lack of better data; however, it can be argued that the repair operations at port can be carried out faster than the same operation carried out from a jack-up vessel at site.

Finally, by using the failure rates reported in [5], it is assumed that the failure rate are constant throughout project lifetime and independent of weather conditions, which is a major simplification.

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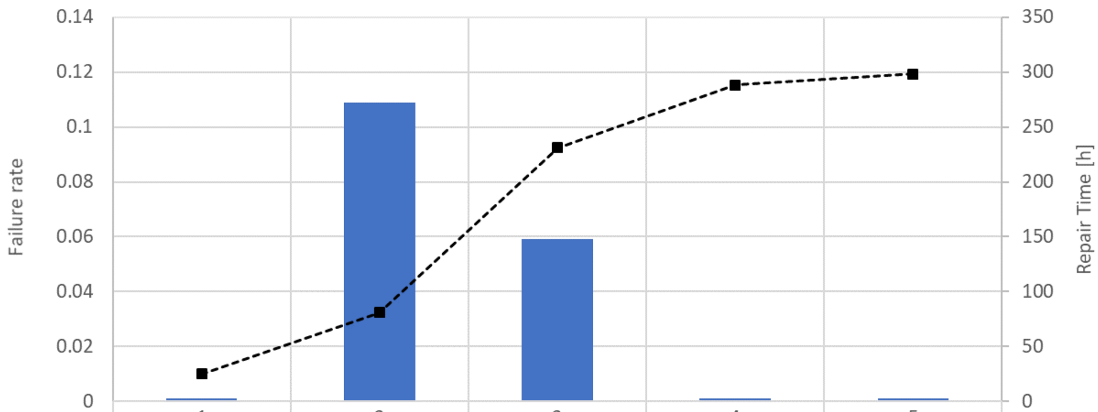

	1	2	3	4	5
Failure rate	0.001	0.109	0.059	0.001	0.001
Repair time [h]	25	81	231	288	298

Figure 7 Failure rates and repair time in hours for the selected components. Reproduced from [5] and [6].

3.7 Marine Operations Breakdown

For any offshore project, marine operations are inherently sensitive to weather conditions due to the potentially large accelerations imposed on the vessels, equipment and structures. Such operations can only be carried out during sufficiently long periods of calm weather, respecting pre-defined operational limits and conditions (OLCs). These limits may be expressed in terms of different combinations of environmental parameters such as wave height, wave period, wind speed and even maximum current speed. In the present analysis only significant wave height and wind speeds were considered.

The maintenance mission related to the tow-to-port approach is divided into two distinct maritime operations: the recovery operation, and the redeployment operation. Each operation is defined by a sequence of activities (e.g. recovery operation is divided into Transit to site, disconnection and towing to port). It is assumed that to carry out either operation, an AHTV vessel and a safety tugboat are required. Between both maritime operations, maintenance at port takes place.

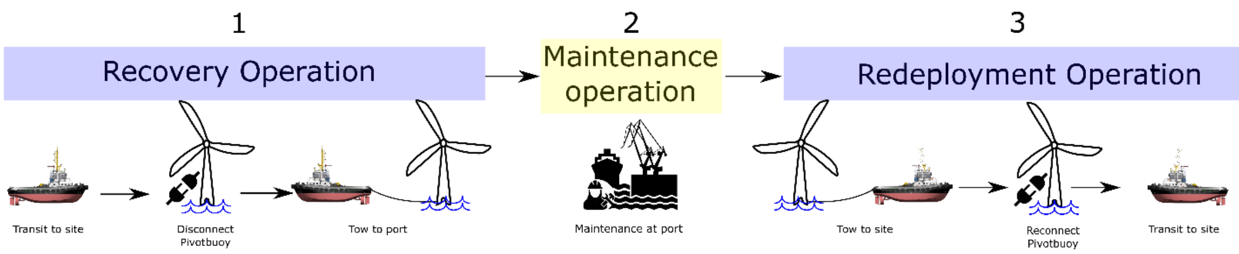

Figure 8 Schematic representation of the tow-to-port maintenance strategy

The recovery mission starts with the vessel transit from port to site, followed by the disconnection of the device to be serviced, and finally the wet tow from site to port. The activity breakdown can be seen in Figure 8 and Table 5.

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Table 5 Recovery operation breakdown, including the reference net durations and operating limiting conditions.

Activity Sequence	Vessel Speed [kn]	Duration [hr]	Wave Height Limit [m]	Wind Speed Limit [m/s]
Transit	12	2.0	2.0	25
Disconnect	NA	2.0	1.5	15
Wet tow	3	8.1	1.5	15

Once the device is at port, the repair time varies according to the component, as shown in Figure 7. No weather restrictions have been included for the repair operations at port, as it is assumed that this work is carried out in sheltered waters and shielded from the wind.

The redeployment mission begins with towing the repaired device back to site, followed by the reconnection to the Pivotbuoy lower body, and ends with the vessels transit back to port. The activity breakdown can be seen in in Figure 8 and Table 6.

Table 6 Redeployment operation breakdown, including the reference duration and operating limiting conditions.

Activity Sequence	Vessel Speed [kn]	Duration [hr]	Wave Height Limit [m]	Wind Speed Limit [m/s]
Wet tow	12	8.1	2.0	15
Connect	NA	4.0	1.5	15
Transit	3	2.0	1.5	25

3.7.1 Transit

The duration of the transit from port to site and vice-versa is dependent on vessel speed and the distance from site to port, shown in Table 3 for both ports considered. The vessel speed is selected by the captain to ensure safety and prevent motion sickness given the local weather conditions. As a simplification, it is here assumed a constant 12 knots [7] regardless of the sea state. Limiting environmental conditions for the transit activity were defined as a maximum significant wave height Hs of 2.0 m and maximum wind speed of 25 m/s. However, these environmental limits should be selected taking into consideration vessel response to incident waves and wind, as well as transit duration.

3.7.2 Connect/Disconnect

The connection and disconnection activities are enabled by the PivotBuoy subsystem. The duration and limiting conditions of such operations are design parameters and can therefore be optimized within certain limits. To better inform the design, several connection and disconnection durations and limiting conditions were tested to assess their impact on the results.

After discussion with the technology developers, the duration of the connect and disconnect activities are varied around a reference duration of 4 hours and 2 hours, respectively.

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It was considered that the PivotBuoy system is such that the disconnection is two times faster than the reconnection. Furthermore, a long connection scenario that requires 24h for both the connection and disconnection duration was included in the analysis to represent a floating wind structure without any quick connection system.

Different weather limits were also considered, covering the whole range of expected maximum weather thresholds for the connection/disconnection operations in question. In respect to the wind, typical vessel crane limits range between 12-15 m/s, were used as a reference [8]. Although no significant lifting occurs during the connection/disconnection activities, these values were adopted for lack of better data.

3.7.3 Wet Tow

Wet tow operations are intrinsically challenging from an engineering point of view, being exceptionally vulnerable to weather conditions. In a wet tow, the structure floats on its own hull and is towed by one or multiple tugs. Wet tows have been extensively studied in the literature, being subject of numerous industry standards and best practices[9]–[13].

Several factors should be considered when designing tow-to-site and tow-to-port operations. These include hull girder strength, motions and accelerations and their effect on the strength of the topside structure, vessel deflections and their impact on the strength of the topside structure, vessel stability, tug bollard pull requirements, strength of tow line connections and seakeeping issues such as yaw motions during tow (fishtailing). These factors also influence the total number of vessels required for wet towing the structure.

Figure 9 On the left, wet towing operation of Windfloat Prototype (1 x 2MW turbine) using a single towing tug. On the right, wet towing operation of Hywind Scotland (5 x 6MW turbines) using multiple tugs.

The selection of the wet tow speed and operational limiting conditions are a compromise between operational feasibility and structural design. If the wet tow needs to be carried out in harsher conditions, then the structural design must be able to withstand the resulting higher loads. Wet transports are typically limited in speed to 3-5 knots. However, due to the lower stability of the TLPs, the reference tow operation was defined using 3 knots towing speed with limiting conditions of 1.5m Hs and 15 m/s wind speed. Sensitivity to these limiting conditions are evaluated as seen in Section 6.3.

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4 METOCEAN CONDITIONS ANALYSIS

4.1 Data pre-processing

The significant wave height (Hs) and average wind speed at 10m height (Ws) were obtained from the simulated time series SIMAR, obtained via Puertos del Estado. The raw timeseries includes simulated data available from 1958 up to the present date.

The reference site location is shown in Figure 4. This location was selected based on its high wind resource, and the precise location was selected to be a calculation node (4038006) of the SIMAR model, from which the wave and wind data was extracted.

Despite the very long number years available in the raw data time series, for some years, long periods of missing measurements (e.g. over 23 days in December 2006) were found. As a result, only 20 (non-consecutive) years of data were analysed: 1992-2005, 2008 and 2011-2015.

It was also observed that the raw data timeseries had variable sampling frequencies for different years (e.g. 1h, 3h, and 6h), which required uniformization. Given that maritime operations are usually planned on an hourly time frame, the environmental conditions were linearly interpolated to produce hourly time series, increasing resolution, as recommended by the DNV norms[9].

4.2 Weather conditions and seasonality trends

Based on the timeseries for the selected years, the Hs/Tp scatter heatmap shown in Figure 10 was obtained. For the purpose of assessing the individual distributions of each parameter, the probability density functions were plotted on the axis. The scatter diagram with probabilities of occurrence is given in Table 7.

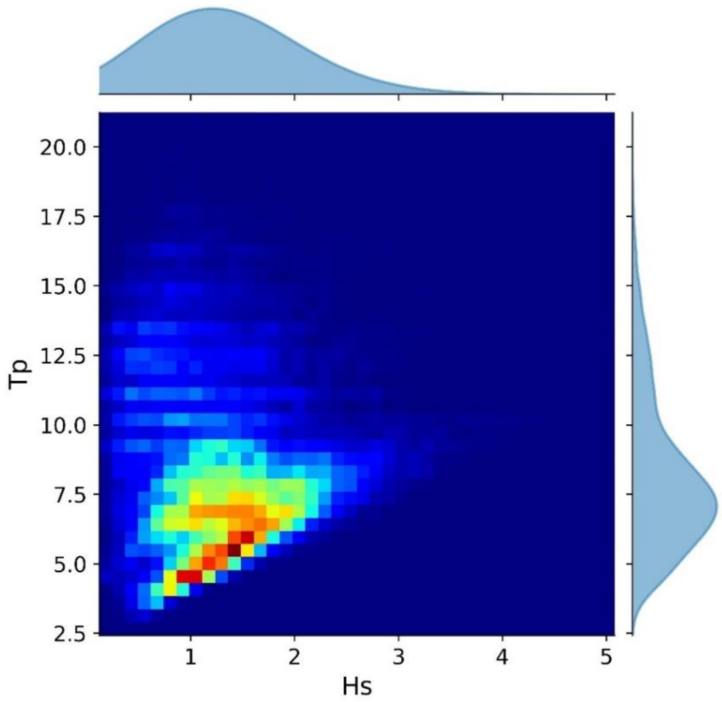

Figure 10 Heatmap of the Tp/Hs distribution considered for this analysis.

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Table 7 Scatter diagram of the wave climate considered for this analysis.

Hs [m] \ Tp [s]	0.00 - 1.00	1.00 - 2.00	2.00 - 3.00	3.00 - 4.00	4.00 - 5.00	5.00 - 6.00	6.00 - 7.00	7.00 - 8.00	8.00 - 9.00	9.00 - 10.00	10.00 - 11.00	11.00 - 12.00	12.00 - 13.00	13.00 - 14.00	14.00 - 15.00	15.00 - 16.00	16.00 - 17.00	17.00 - 18.00	18.00 - 19.00	19.00 - 20.00	20.00 - 21.00	21.00 - 22.00	sum
0.00 - 0.50			0.01%	0.27%	0.42%	0.64%	0.49%	0.48%	0.52%	0.82%	0.66%	0.67%	0.78%	0.47%	0.25%	0.08%	0.05%	0.01%	0.00%	0.00%			6.6%
0.50 - 1.00			0.01%	1.20%	4.06%	2.68%	4.13%	3.26%	1.90%	1.71%	1.54%	1.40%	1.48%	1.12%	0.74%	0.33%	0.34%	0.13%	0.04%	0.04%	0.00%	0.00%	26.1%
1.00 - 1.50				0.01%	3.17%	6.60%	6.11%	5.50%	3.55%	2.66%	1.43%	1.14%	0.97%	0.71%	0.55%	0.27%	0.25%	0.12%	0.03%	0.01%	0.00%	0.00%	33.1%
1.50 - 2.00					0.05%	2.61%	5.94%	5.29%	2.71%	1.50%	0.87%	0.71%	0.67%	0.43%	0.29%	0.10%	0.11%	0.06%	0.01%	0.01%	0.02%	0.00%	21.4%
2.00 - 2.50						0.11%	1.42%	3.12%	2.17%	0.76%	0.35%	0.31%	0.27%	0.13%	0.13%	0.08%	0.04%	0.02%	0.01%	0.01%			8.9%
2.50 - 3.00						0.00%	0.07%	0.69%	1.00%	0.52%	0.15%	0.13%	0.12%	0.07%	0.03%	0.02%	0.04%	0.00%	0.01%	0.00%			2.8%
3.00 - 3.50							0.00%	0.05%	0.27%	0.26%	0.08%	0.01%	0.02%	0.03%	0.02%	0.02%	0.00%	0.00%					0.8%
3.50 - 4.00								0.00%	0.02%	0.09%	0.06%	0.00%					0.00%	0.00%					0.2%
4.00 - 4.50										0.02%	0.04%	0.01%											0.1%
4.50 - 5.00											0.01%	0.01%											0.0%
5.00 - 5.50											0.00%	0.00%											0.0%
5.50 - 6.00																							
sum			0.0%	1.5%	7.7%	12.7%	18.2%	18.4%	12.1%	8.3%	5.2%	4.4%	4.3%	3.0%	2.0%	0.9%	0.8%	0.3%	0.1%	0.1%	0.0%	0.0%	100.0%

The average and maximum significant wave heights per month for the selected years are shown in Figure 11. To illustrate the significant wave height variability and data spread, the interquartile range (IQR), i.e., the range between the twenty-fifth percentile (p25) and the seventy-fifth percentile (p75), was coloured in light blue. To represent the monthly extreme significant wave height variability, the p99-p100 range is coloured in light green. By definition, only 1% of the Hs data may be included in this light green range. A similar analysis for the wind speed is given in Figure 12.

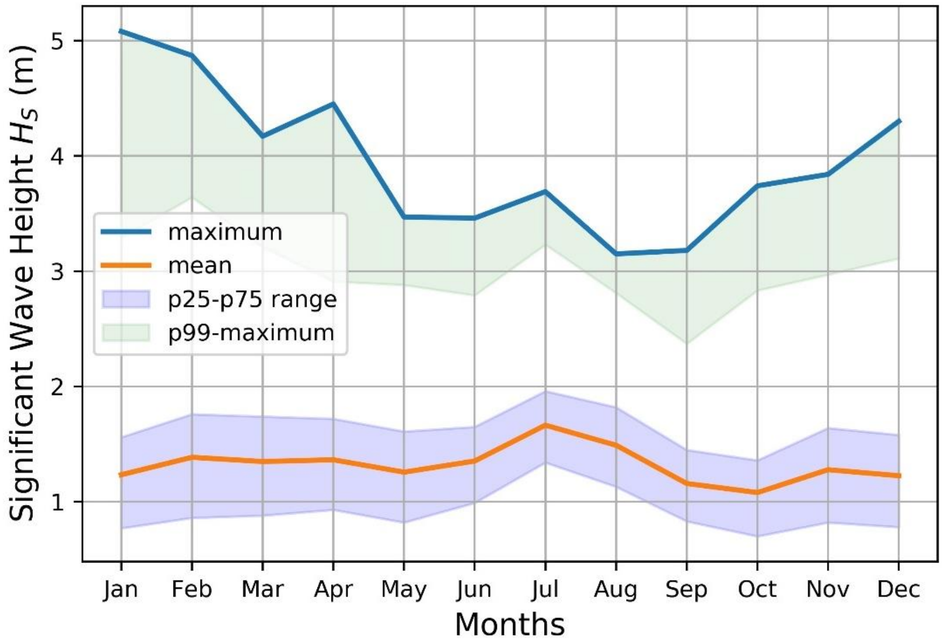

Figure 11 Mean and maximum significant wave heights per month over the selected years of simulated data.

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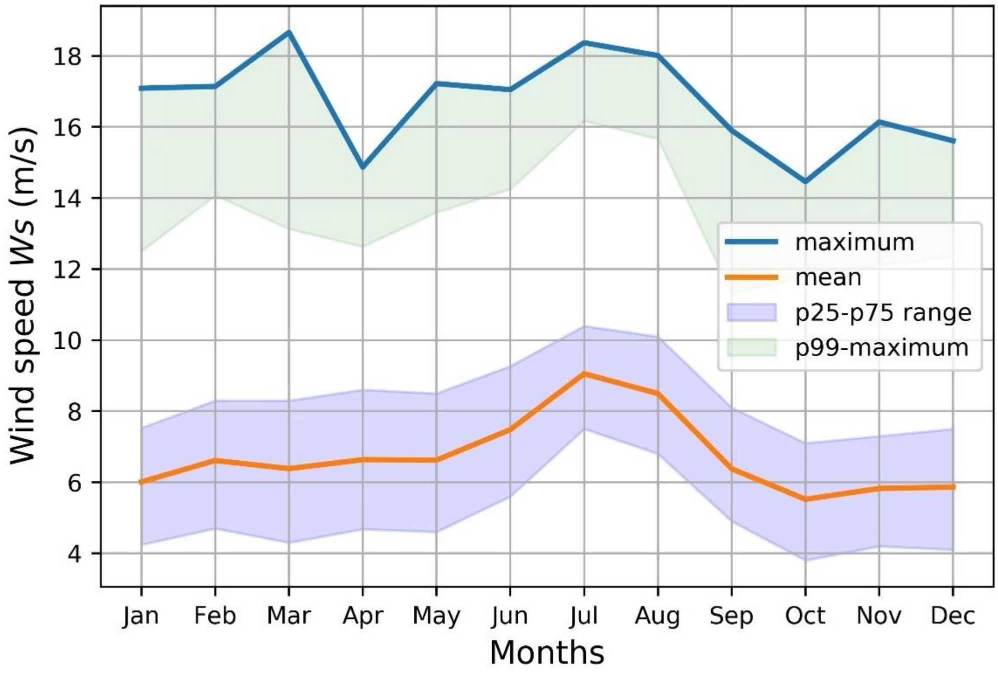

Figure 12 Mean and maximum wind speeds per month over the selected years of simulated data, at 10m height.

It is possible to observe that the deployment site is usually exposed to relatively moderate energy waves. The average significant wave height is fairly constant throughout the year, with the highest values on average occurring between July and August. However, between October and March, large swells originated in the Northern Atlantic occasionally approach the site from north, leading to larger maximum wave heights, despite lower wave heights on average. The maximum significant wave height is approximately 5m, occurring in January. It is interesting to note that the months with the highest average wave heights do not exhibit the highest maximum wave heights.

Similar to the wave climate, the highest average wind speeds occur in July and August. However, the average wind speed variation throughout the year is more pronounced than the average wave height. The maximum wind speeds occur in the months with highest average wind speeds (July and August) and March. It should be noted that Figure 12 shows the wind at 10m height, which is the values used when planning the operations, but for the energy yield the wind speed at hub height is used. It is also worth mentioning that the wind speed simulated through the SIMAR point seems to be significantly lower than the high wind speeds that exist in that area, but no measurements exist at this stage.

In this preliminar stage, it is considered sufficient to bin the weather data per trimester, which means that the operations will be planned per trimester.

4.3 Energy yield estimation

Estimating the energy production of the turbine is fundamental to quantify the impacts of downtime due to failures/maintenance on total revenue losses. For energy production calculations, the wind speed at hub height (90 m) can be obtained by modelling the wind profile using the Prandtl logarithmic law given by:

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$$\frac{u_{hub}}{u_{10}} = \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{10}}{z_0}\right)}$$

Where u_{hub} is the unknown wind speed at hub height z (90 m), and u_{10} is the know wind speed at known height z_{10} (10 m). The parameter z_0 is the roughness length, an empirical coefficient, assumed to be 0.0002 when the profile is developing over open water[14].

Considering the turbine power curve as a function of wind speed given in Figure 5, the energy production was calculated for all time steps and the average energy production per month and trimester were presented in Figure 13 and Table 8.

Table 8 Average power production per trimester

Trimester 1	Trimester 2	Trimester 3	Trimester 4
2010	2466	3128	1619

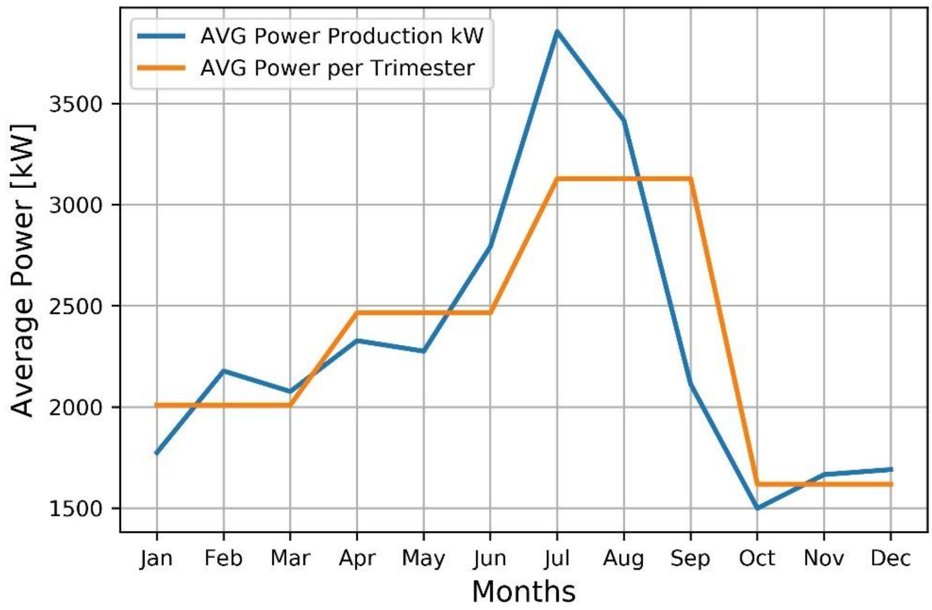

Figure 13 Hourly average power production per month

4.4 Weather windows analysis

For any given marine operation, the probability of operation success is mainly affected by the operation weather restrictions, the operation duration and the time of the year where the operation is performed.

For different weather window durations and operation limiting conditions (OLCs), the activity feasibility percentage was calculated for each trimester. The feasibility percentage was calculated by

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considering every timestep of the metocean time series within a given trimester, for all twenty years of analysed data, and assessing whether for that timestep and for the subsequent ones, the metocean conditions were adequate to safely complete the operation, respecting the vessel and activity OLCs. This metric differs from workability, which does not consider operation duration, being illustrated in Equation 1:

$$feasibility_{OP}[\%] = \frac{\sum_{i}^{n} feas(i)}{n} * 100, \quad (1)$$

where n stands for the total number of timesteps within a given trimester (e.g. the first trimester of the year has typically 90 days, and for a total of 20 years of data, this translates into 20 years× 90 days×24h= 43200 hourly timesteps), and *feas*(i) takes a value of one if the operation could have been started in timestep i and safely executed in the subsequent ones, and zero otherwise. The effects of the activity duration on the activity trimestral feasibility percentages are depicted in Table 9.

4.4.1 Connection and Disconnection activities

The feasibility of the connection and disconnection activities, for the assumed OLCs and durations, can be seen in Table 9 and Figure 14. Based on these results, the following remarks seem justified:

- The 3rd trimester shows the smallest feasibilities for all the conditions considered, and therefore any connection/disconnection operations should be avoided in this trimester whenever possible.
- The 4th trimester shows the highest feasibilities for all conditions and is therefore the preferable time of the year to carry out these operations. Additionally, since this trimester correspond to the months with lowest energy yields as shown in Section 4.3, potential revenue losses are further reduced.
- For the same OLCs, reducing the quick connection duration from 6 hours to 1 hour provides at best a feasibility increase of 4.1%, 3.8%, and 2.4%, for the lower, reference and higher OLCs, respectively.
- Reducing the connection operation duration from 24 hours (no quick connection system) to 4 hours (PB reference value) increases the feasibility by 16%, 15% and 10% for the lower, reference and higher OLCs, respectively. This increase represents a two times higher feasibility when using the PB quick connection system when compared to a 24hr connection duration.
- For the site under analysis, the feasibility is more sensitive to the OLCs than to the operation duration.

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Table 9 Feasibility per trimester for different OLC and durations, consistent with the connection/disconnection activities.

Hs [m]	Ws [m/s]	dur [h]	Feasibility			
			Trimester 1	Trimester 2	Trimester 3	Trimester 4
1.0	10	1	36%	30%	22%	43%
1.0	10	2	35%	30%	21%	42%
1.0	10	3	34%	29%	21%	41%
1.0	10	4	33%	29%	20%	40%
1.0	10	6	32%	28%	20%	39%
1.0	10	12	27%	24%	17%	34%
1.0	10	24	17%	18%	12%	24%
1.5	15	1	67%	65%	56%	74%
1.5	15	2	66%	64%	56%	74%
1.5	15	3	65%	64%	55%	73%
1.5	15	4	64%	63%	54%	72%
1.5	15	6	63%	62%	53%	71%
1.5	15	12	58%	58%	48%	67%
1.5	15	24	49%	50%	40%	60%
2.0	15	1	85%	86%	81%	89%
2.0	15	2	85%	86%	81%	89%
2.0	15	3	84%	85%	80%	89%
2.0	15	4	84%	85%	80%	88%
2.0	15	6	83%	84%	79%	87%
2.0	15	12	80%	82%	77%	85%
2.0	15	24	74%	77%	71%	81%

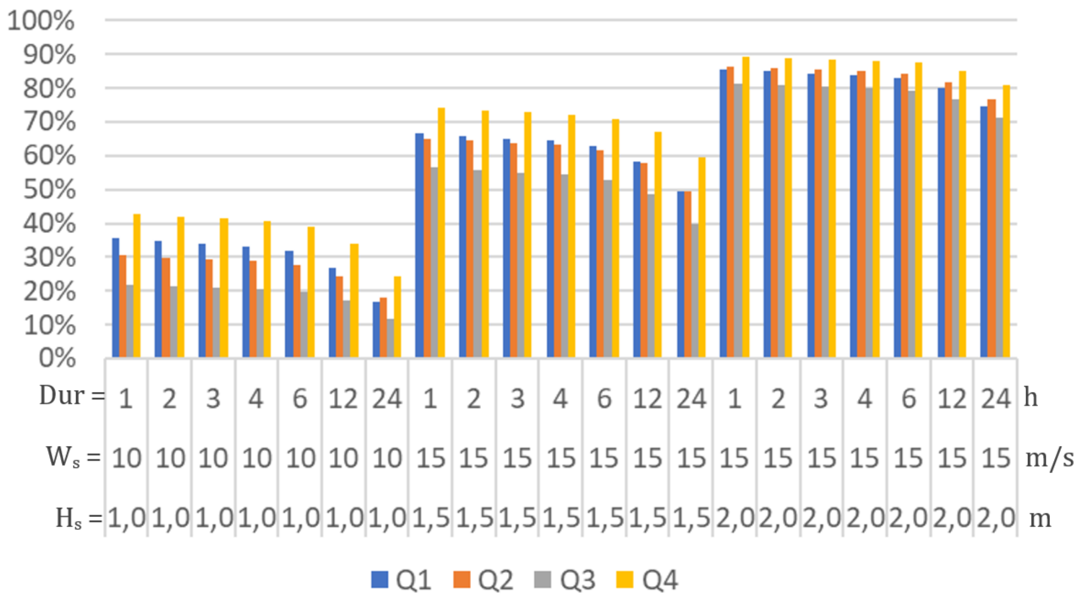

Figure 14 Feasibility per trimester(Q1-Q4) for different OLCs and durations, consistent with the connection/disconnection operation

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4.4.2 Transit and Wet Tow

The feasibility of the transit and wet tow operations, for the assumed OLC and durations, can be seen in Table 10, Figure 15, and Figure 16. Based on these results, the following remarks seem justified:

- The 3rd trimester shows the lowest feasibilities for all the conditions considered, and therefore any operations should be avoided in this trimester whenever possible.
- Similarly to feasibilities obtained for the connection/disconnection operations, the 4th trimester shows the highest feasibilities for all conditions and is therefore the preferable time of the year to carry out these operations. Once again, this corresponds to the trimester with lowest energy yield, resulting in lower downtimes due to waiting on weather.
- The feasibility of the wet tow activity is smaller than the feasibility of the transit.
- For the Las Palmas Port the OLC has a significant impact on the feasibility, with an over threefold increase in feasibility if the wet tow can be carried out in Hs=2m and Ws=15 m/s instead of Hs=1m and Ws=10m/s.

Table 10 Feasibility per trimeste for different OLC and durations, consistent with the transit (first two rows), wet tow to Arinaga Port (third line), and wet tow to Las Palmas Port with different OLC (last three lines).

	Hs [m]	Ws [m/s]	Dur [h]	Feasibility			
				Trimester 1	Trimester 2	Trimester 3	Trimester 4
Transit Las Palmas	2.0	25	2.0	84.9%	85.8%	80.7%	88.9%
Transit Arinaga	2.0	25	0.5	85.6%	86.4%	81.4%	89.4%
Tow Arinaga	1.5	15	2.2	65.7%	64.3%	55.6%	73.4%
Tow Las Palmas	1.5	15	8.1	61.3%	60.3%	51.3%	69.7%
	2.0	15	8.1	82.0%	83.3%	78.2%	86.7%
	1.0	10	8.1	29.9%	26.6%	18.7%	37.2%

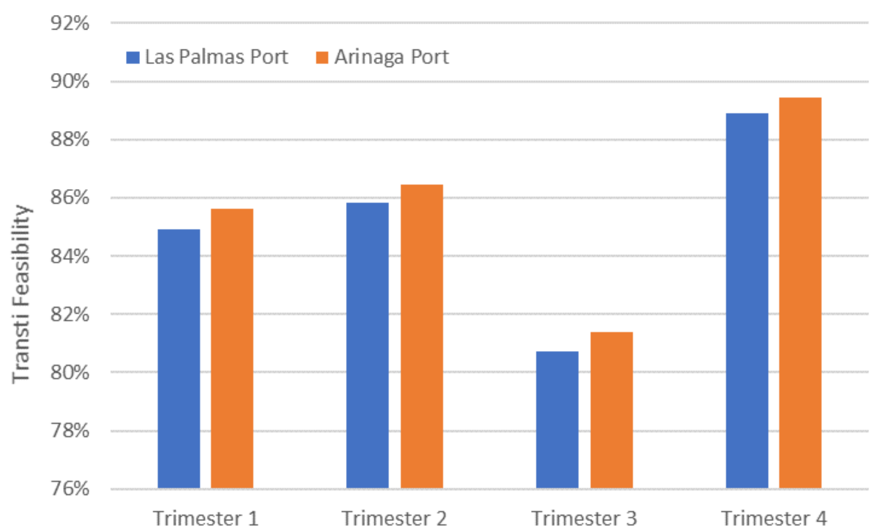

Figure 15 Feasibility per trimester for the vessel transit from both ports used in the analysis.

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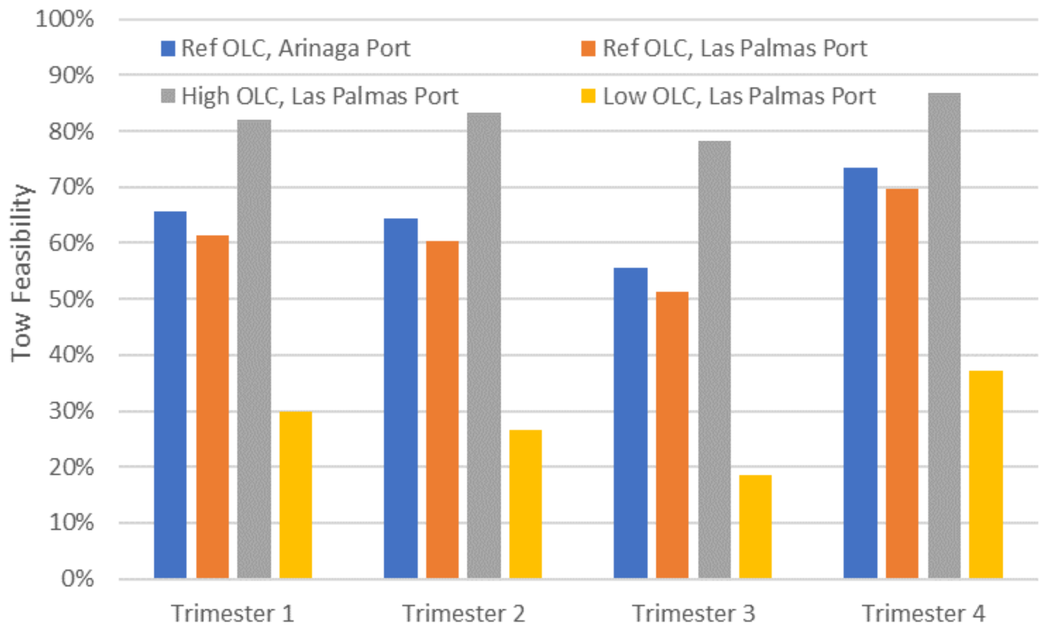

Figure 16 Feasibility per trimester for the wet tow activity.

4.5 Connection and Disconnection Waiting Time Statistics

To illustrate the waiting time variability and spread, the interquartile range (IQR), i.e., the range between the twenty-fifth percentile (p25), the median (p50), and the seventy-fifth percentile (p75) were calculated. The values for the first trimester, second trimester, third trimester, and forth trimester can be found in Figure 17, Figure 18, Figure 19, and Figure 20 respectively. Based on these results, the following remarks seem justified:

- As expected, the highest waiting times occur in the third trimester, while the lowest waiting times occur in the fourth trimester.
- The waiting times are dominated by the OLC. The waiting time variation with operation duration is more pronounced between 6hours and 24 hours, with minor variations for durations under 6 hours.
- Reducing the connection operation duration from 24 hours (no PB) to 4 hours (PB reference value) reduces the median waiting time by 40% to 70%, depending on the OLC and trimester.

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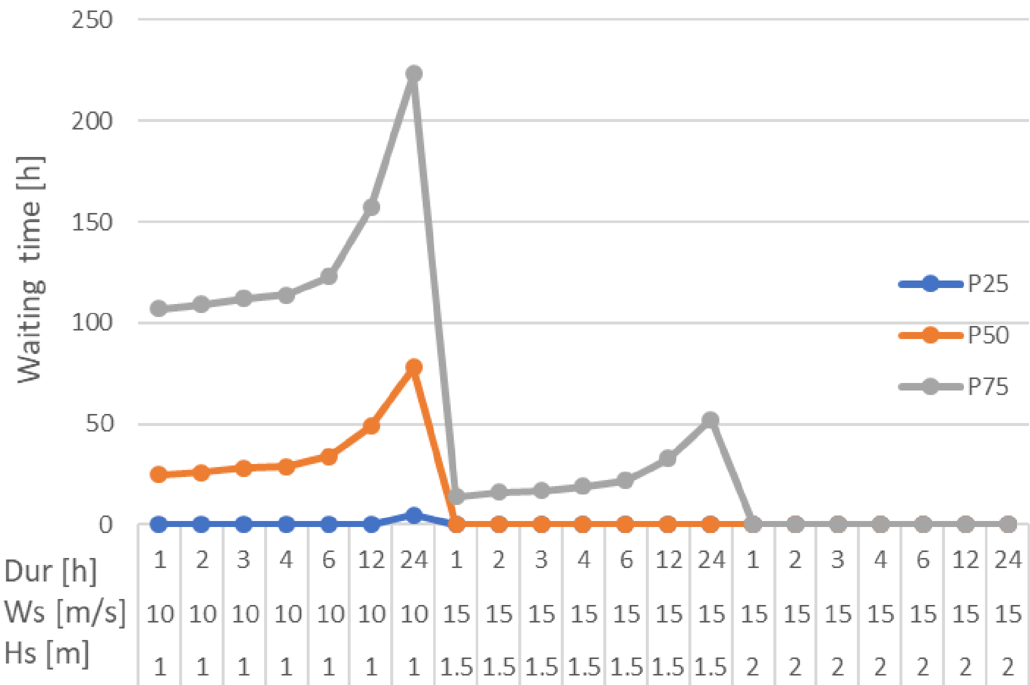

Figure 17 Waiting time statistics for all the different connection / disconnection weather windows required, when carried out during the first trimester.

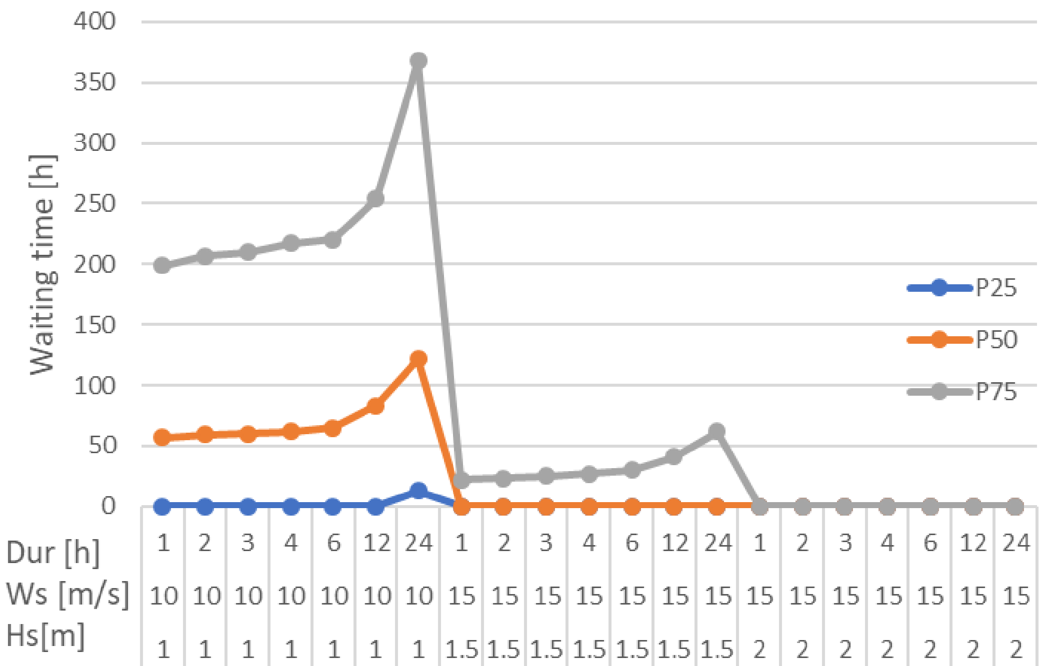

Figure 18 Waiting time statistics for all the different connection / disconnection weather windows required, when carried out during the second trimester.

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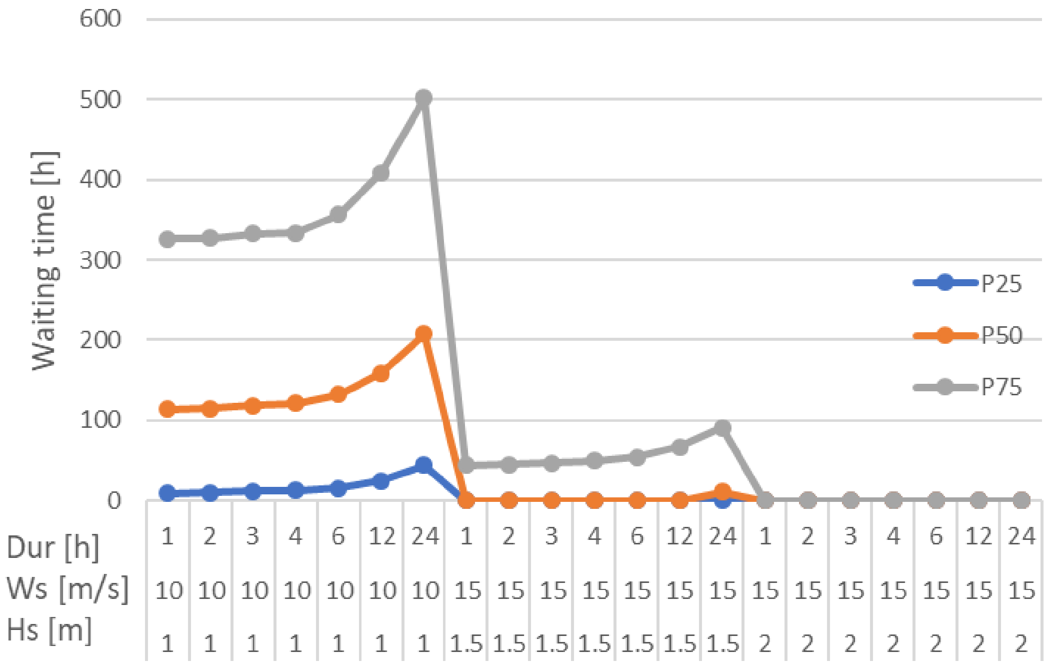

Figure 19 Waiting time statistics for all the different connection / disconnection weather windows required, when carried out during the third trimester.

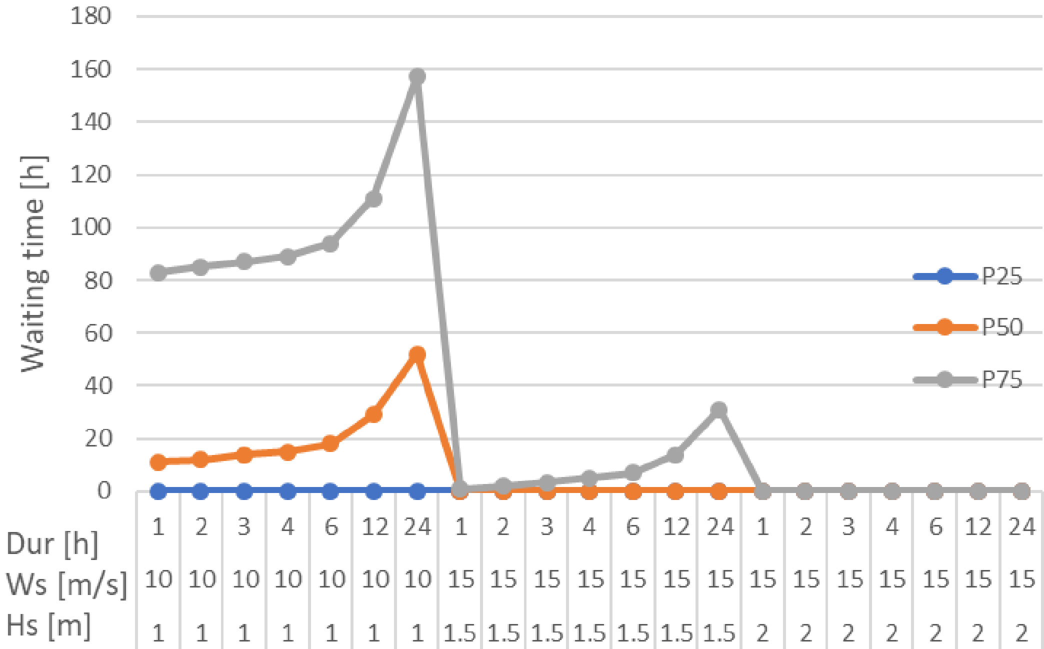

Figure 20 Waiting time statistics for all the different connection / disconnection weather windows required, when carried out during the fourth trimester

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5 OPERATIONAL ANALYSIS

5.1 Description of analysis

In order to quantify the potential impacts of changing the connection/disconnection durations, OLCs and base port on the total project downtime, maintenance costs and revenue losses, an analysis must be performed at a farm level for the whole duration of the project lifetime (reference project described in detail in Section 3). In the present analysis, a purely corrective maintenance approach is assumed for major component failures, based on the following assumptions:

1. The O&M operator is instantly informed when a major component fails.
2. After major component failure, O&M operator attempts to schedule corrective maintenance as soon as possible (i.e. in the nearest sufficiently long weather window).

Taking into consideration the reference farm of 50 turbines, operating for 20 years, and the reliability data presented in Section 3.6, the expected number of major failures for the whole duration of the project lifetime was calculated for each major component and compiled in Table 11.

In a first approach, it is assumed that these failure rates remain constant throughout project lifetime and are independent on weather conditions to provide a common base of comparison. These remain constant for all scenarios and are used to establish a common base of comparison.

Table 11 Expected failures for the reference farm during its operational lifetime (20 years).

Component	Failure rate	Repair time at port [h]	Number of failures
Generator	0.109	81	109
Gearbox	0.059	231	59
Blades	0.001	288	1
Hub	0.001	298	1
Pitch/Hyd	0.001	25	1
TOTAL			171

It should be reminded that the present study aims to quantify the impacts of implementing the PivotBuoy subsystem on the project's O&M costs, where major component replacements could be achieved through a tow-to-port maintenance strategy. Consequently, the present study is restricted to the major replacements of the components shown in Table 11. It follows that the total project downtime hours and energy yield losses for the entire project lifetime is expected to be significantly larger due to the minor repairs and major repairs on site not being considered in this analysis.

The operation analysis is performed assuming the reference case of tow-to-port maintenances described in Section 3.7. The downtime is calculated for all the turbines and for the total operational lifetime of the reference farm. To increase readability, the total downtime is then divided by the number of turbines and operational years, resulting in an average downtime in hours per turbine per year.

The failures can occur at any time throughout the year. In this analysis it was assumed that all failures and respective operations need to be carried out in the same trimester, and the results for different

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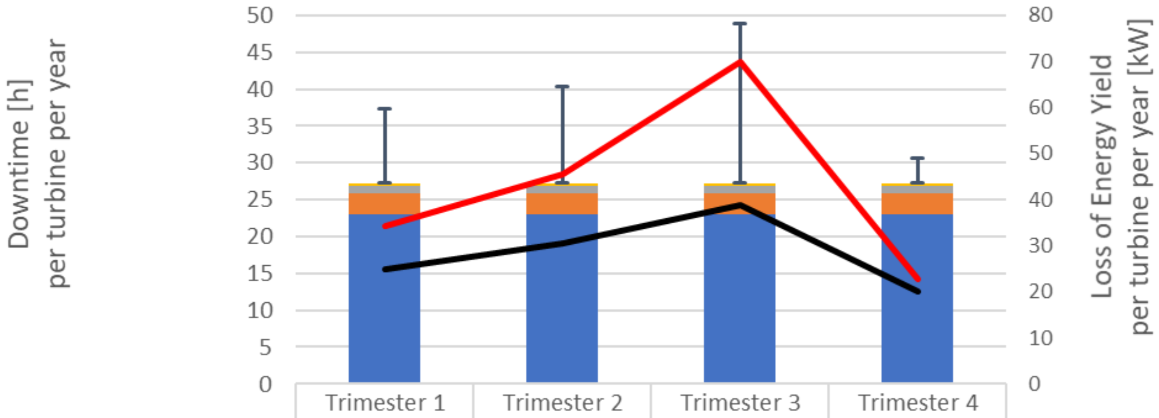
trimester are shown. Finally, for the scheduling of each operation (e.g. recovery), it is assumed that weather must be favourable for the whole duration of each activity (e.g. transit, disconnection, towing), which must be carried out in an exact sequence without any waiting times at sea.

5.2 Reference case

The downtime in hours, per turbine per year, due to major replacements was calculated as shown in Figure 21, for each trimester. Given that the waiting times due to weather are not normally distributed around the mean, the median values (p50) of the waiting time, as well as the first and third quartile (p25 and p57 respectively) were shown to illustrate the data spread. The relative contributions of each activity are given in Figure 22.



	Trimester 1	Trimester 2	Trimester 3	Trimester 4
Waiting time (p50)	0.0	0.0	0.0	0.0
Transit	0.3	0.3	0.3	0.3
C/D	1.0	1.0	1.0	1.0
Tow	2.8	2.8	2.8	2.8
Repair@Port	23.1	23.1	23.1	23.1
TOTAL [h]	27	27	27	27
Energy Yield Loss p50	25	31	39	20
Energy Yield Loss p75	34	45	70	23

Figure 21 Average downtime in hours, per turbine per year, due to major replacements for the reference farm with the PivotBuoy Baseline scenario (ID02), discretized by activity with error bars representing the first quartile (p25) and third quartile (p75) of the waiting time per each trimester.

According to Figure 21 and Figure 22., it is possible to observe that:

- The largest contributor to downtime is the duration of the repair operations carried out at port, which are typically long for the large component replacements considered in the present study (see Section 3.6)
- It should be noted that the repair time values used in this analysis were taken from on-site repairs using jack-up vessels[5]. If faster repair procedures can be applied at port, an appreciable reduction in downtime can be expected.

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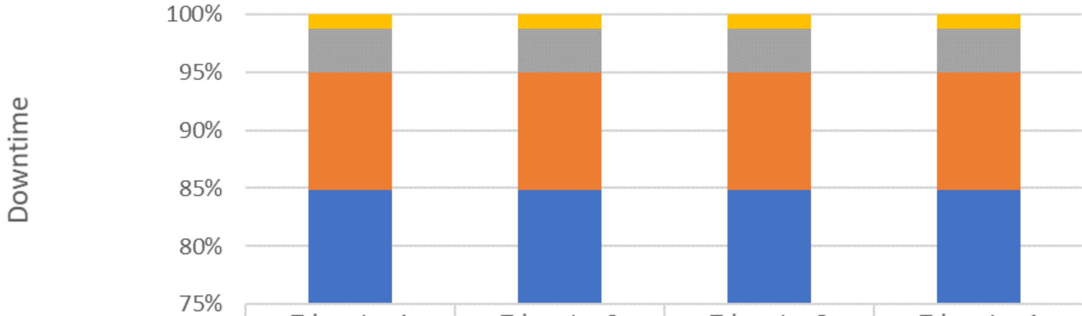

	Trimester 1	Trimester 2	Trimester 3	Trimester 4
Waiting time (p50)	0.0	0.0	0.0	0.0
Transit	0.3	0.3	0.3	0.3
C/D	1.0	1.0	1.0	1.0
Tow	2.8	2.8	2.8	2.8
Repair@Port	23.1	23.1	23.1	23.1
TOTAL [h]	27	27	27	27

Figure 22 Contribution to downtime for the reference farm with the PivotBuoy Baseline scenario (ID02) per trimester. Note that the vertical axis starts at 75% to show the detailed contributions from the different activities.

- The expected waiting on weather (p50 median) for all trimesters is negligible. However, the plots show significant variability in the waiting time for some trimesters of the year. For the third trimester, there is a 25% probability that the downtime may exceed 50 hours (p75), while there is an equivalent probability that the downtime may exceed 30 hours during the fourth trimester.
- It follows that the third trimester exhibits the largest risks in terms of unexpected waiting times, being the worse months to carry out maintenance. This is further aggravated by the fact that these are the months with highest wind speeds and energy yields, with the expected average energy yield loss (p50 median) of 39kW per turbine per year, while the third quartile(p75) is 70 kW per turbine per year.
- The repair time while at port represents between 47% of the downtime, if the third quartile waiting time is used, to 85% of the downtime, if the median(p50) or less is considered. This is the most significant contributor to the downtime.
- The operational net duration, which includes the transit, connection/disconnection (C/D), and tow, accounts for 8% (using p75 waiting time) to 15% of the total waiting time, with the tow operation being the longest. After having connected the PivotBuoy, the production of energy restarts and consequently the final vessel transit back to port does not represent downtime.
- The third trimester shows the highest downtime and higher potential energy yield losses. Conversely, the fourth trimester exhibits the lowest downtime and smallest potential energy yield loss. In other words, trimester 3 represents the most conservative scenario while trimester 4 is the most optimistic scenario. For brevity purposes, only these two trimesters are shown in the sensitivity analysis, unless mentioned otherwise.

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6 SENSITIVITY ANALYSIS

6.1 Sensitivity to the Connection/Disconnection duration

In this section, the influence of different connection/disconnection durations, for a fixed OLC of Hs=1,5m and Ws=15m/s, on the average downtime is analysed. The maintenance port also remains constant as the Las Palmas. The different scenarios tested (with different scenario IDs, fully described in Table 26) with variable connection and disconnection durations were summarized in Table 12. It is restated that it was assumed that the disconnection operation takes half the time of connecting operation.

Table 12 Different scenarios tested (scenario IDs) for different connection and disconnection durations and fixed operation limiting conditions (OLCs). Full description of these scenarios can be found in Table 26.

OLC		Duration [h] of Connection / Disconnection				
Hs [m]	Ws [m/s]	2 / 1	4 / 2	6 / 3	12 / 6	24 / 24
1.5	15	ID04	ID02 (PB Ref)	ID08	ID10	ID01 (No PB)

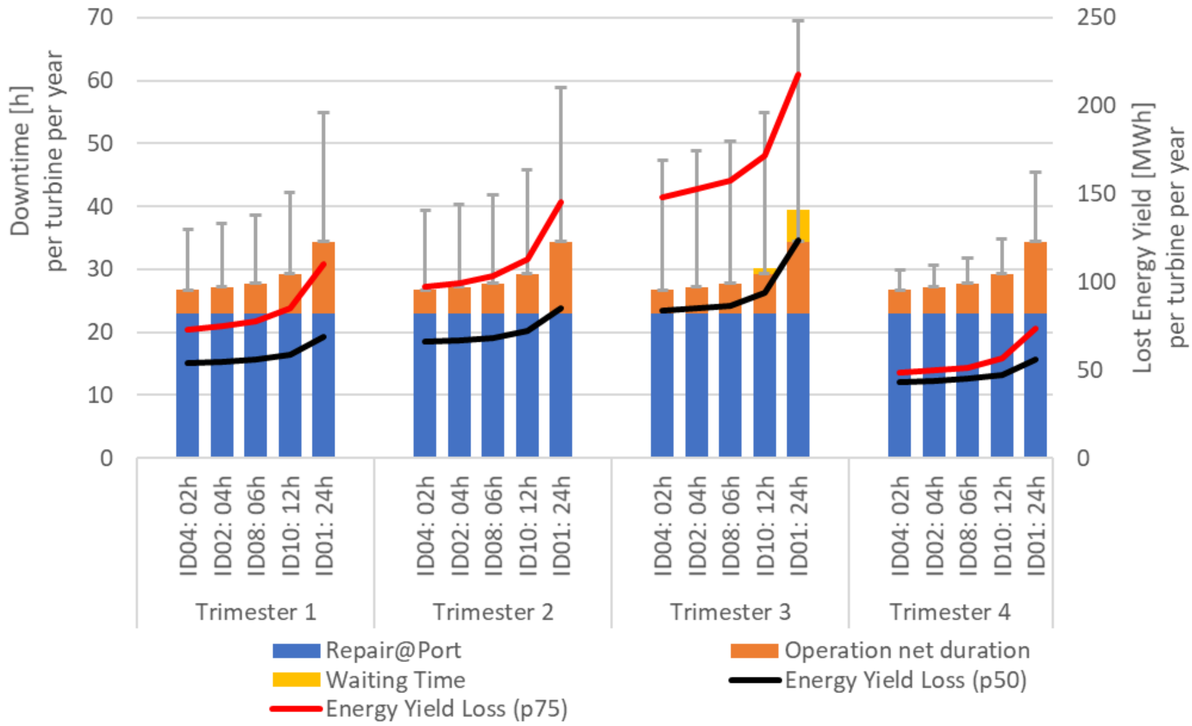

Figure 23 Influence of the duration of the connection operation on the average downtime per turbine per year due to major replacements only, for the same OLC of Hs=1.5m and Ws=15m/s. The error bars represent the first quartile (p25) and third quartile (p75) of the waiting time per each trimester.

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In Figure 23, the expected total project downtimes (due to major component failures) expressed in hours per turbine per year were calculated for the scenarios presented in Table 12. It is possible to observe that:

- Increasing the operation duration always increases the expected downtime, as could be anticipated.
- The third trimester still exhibits larger downtimes due to waiting on weather, and larger waiting time variability expressed by the error bars, while the fourth trimester remains the best for carrying out maintenance activities.
- For increasing connection/disconnection activity durations, the total downtime does not vary linearly. The impacts of a percentual change in the connection/disconnection duration are negligible for short durations but significant for longer ones. There is an increasing downtime elasticity in respect to operation duration, which ultimately suggests that potential benefits from reducing the connection/disconnection below 4/2 hours (or even increasing to 6/3) may be negligible (1-hour downtime difference per turbine per year for all trimesters, except the third which results in a 2-hour difference).
- It follows however, that these conclusions may only remain valid within the current context of the whole operation sequence, for the specified OLCs, transit speeds, towing speeds and durations. As suggested by the downtime increasing elasticity, in case the towing or transit durations are significantly increased, then a small change in connection/disconnection durations may impact heavily the expected downtime of the whole project lifetime.
- Further decreasing the connection duration from 4h (ID02) to 2h (ID04) can represent a challenging design problem to further reduce the expected downtime by approximately 2%.
- Increasing the connection duration from 4h (ID02) to 6h (ID08) results in an average downtime increase of 2.5%.
- When comparing the PivotBuoy base case (ID02 with 4/2h) with the reference case without PivotBuoy system (ID01, 24/24h), it is possible to observe lower downtimes when employing the PivotBuoy. For the fourth trimester, implementing the Pivotbuoy system (ID02) leads to a 11% reduction in total expected downtime (due to major component failures). These differences are exacerbated for trimester 3, where the Pivotbuoy system leads to 31% reduction in the total expected downtime.
- The potential energy losses due to downtime were presented per turbine per year, for each trimester, assuming that the whole list of failure events always occur in the same trimester. Naturally, the energy yield losses follow the downtime patterns, being however more significant during Trimester 3, where the wind resource is also higher.

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Table 13 Impact of different connection/ disconnection (C/D) durations on the average downtime, per year per turbine, due to major replacements only, for the same OLC of Hs=1.5m and Ws=15m/s.

ID	C/D Dur [h]	Trimester 1			Trimester 2			Trimester 3			Trimester 4		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
ID04	2 /1	27	27	36	27	27	39	27	27	47	27	27	30
ID02	4 / 2	27	27	37	27	27	40	27	27	49	27	27	31
ID08	6 / 3	28	28	39	28	28	42	28	28	50	28	28	32
ID10	12 / 6	29	29	42	29	29	46	29	30	55	29	29	35
ID01	24 / 24	34	34	55	34	34	59	34	40	70	34	34	46

Table 14 Impact of different connection/ disconnection (C/D) durations on the average loss of energy in MWh, per year per turbine, due to major replacements only, for the same OLC of Hs=1.5m and Ws=15m/s.

ID	C/D Dur [h]	Trimester 1			Trimester 2			Trimester 3			Trimester 4		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
ID04	2 /1	54	54	73	66	66	97	84	84	148	43	43	48
ID02	4 / 2	55	55	75	67	67	100	85	85	153	44	44	50
ID08	6 / 3	56	56	78	68	68	103	87	87	157	45	45	52
ID10	12 / 6	59	59	85	72	72	113	92	94	172	47	47	56
ID01	24 / 24	69	69	110	85	85	145	108	124	218	56	56	74

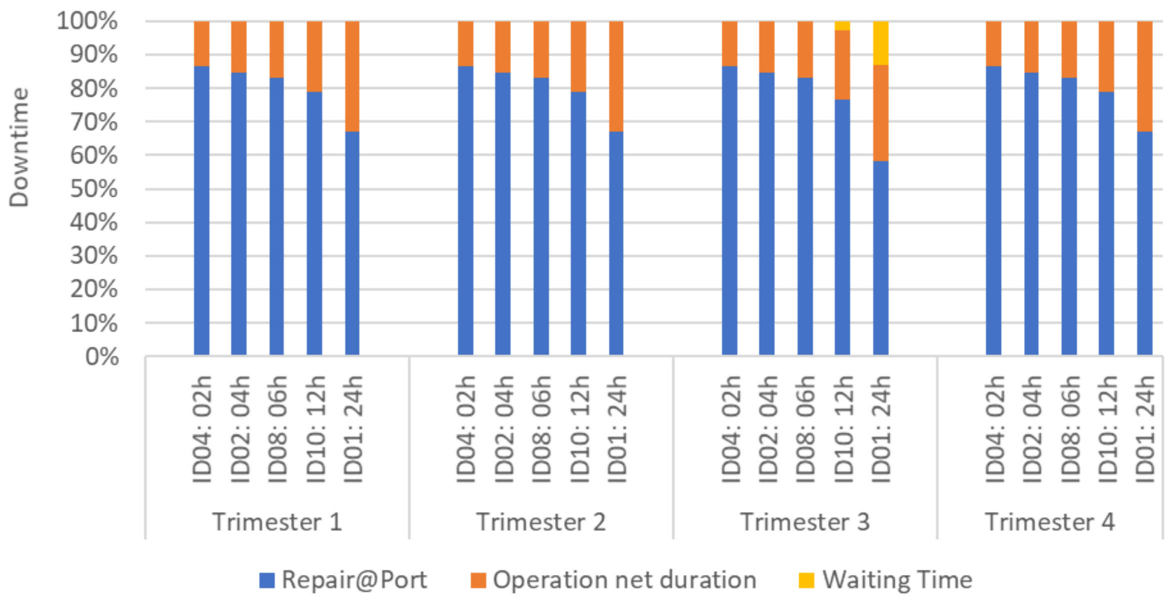

Figure 24 Contribution to the downtime per trimester, for different connection durations, with the same OLC of Hs=1.5m and Ws=15m/s.

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6.2 Sensitivity to the Connection/Disconnection OLCs

For brevity sake, the downtime is shown only for the third and fourth trimester, which are the most and least energetic trimester, respectively.

Table 15 Different scenarios tested (scenario IDs) for different operation limiting conditions (OLCs) and different durations of the connection/disconnection activity. Full description of these scenarios can be found in Table 26.

	OLC		Duration [h] of Connection / Disconnection			
	Hs [m]	Ws [m/s]	2 / 1	4 / 2	6 / 3	12 / 6
High OLC	**2,0**	**15**	ID03	ID06	ID09	
Ref OLC	**1.5**	**15**	ID04	ID02 (PB Ref)	ID08	
Low OLC	**1.0**	**10**	ID07	ID05	ID11	ID11

The influence of different connection/disconnection OLC on the downtime and loss of energy yield, at different connection/disconnection durations, is shown in Figure 25, Figure 26,

Table 16 and Table 17. It is here restated that the durations shown in the figures represent the duration of the connection operation, and the respective disconnection operation takes half that time. Based on these results the following remarks can be made:

- The reduction of downtime when increasing from the reference OLC (Hs=1.5m; Ws=15m/s) to the high OLC (Hs=2.0m; Ws=15m/s) is very small. However, when lowering the OLC to (Hs=1.0m; Ws=10m/s), a large increase of the downtime can be seen for all connection/disconnection durations. This is shown to occur for all durations tested.
- Changes in the connection/disconnection durations have lower impacts on the total downtime than changes in OLCs. However, for operations with the most restrictive OLCs (Hs=1.0m; Ws=10m/s), increasing the duration significantly impacts the downtime.
- For the reference connection/disconnection OLC (Hs=1.5m; Ws=15m/s), the median waiting time is negligible, regardless of the connection/disconnection duration. In these cases, the downtime is dominated by the duration of the repairs at port and, to a lesser extent, the operation net duration.
- Results suggest that the tow-to-port maintenance operations are strongly dominated by OLC, and therefore focusing development efforts towards increasing the maximum environmental thresholds will be more beneficial than further reducing connection/disconnection times from the PivotBuoy reference case.
- Again, the potential energy losses due to downtime were presented per turbine per year, for each trimester, assuming that the whole list of failure events always occur in the same trimester. Naturally, Trimester 3 exhibits the largest potential energy losses due to major downtime.

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Table 16 Impact of different connection/ disconnection OLC, at different durations, on the average downtime, per year per turbine, due to major replacements only.

ID	C/D Dur [h]	OLC		Trimester 3			Trimester 4		
		Hs [m]	Ws [m/s]	P25	P50	P75	P25	P50	P75
ID03	**2 /1**	**2.0**	**15**	27	27	47	27	27	30
ID04	**2 /1**	**1.5**	**15**	27	27	47	27	27	30
ID07	**2 /1**	**1.0**	**10**	30	65	138	27	31	56
ID06	**4 / 2**	**2.0**	**15**	27	27	47	27	27	30
ID02	**4 / 2**	**1.5**	**15**	27	27	49	27	27	31
ID05	**4 / 2**	**1.0**	**10**	31	67	140	27	32	57
ID09	**6 / 3**	**2.0**	**15**	28	28	48	28	28	31
ID08	**6 / 3**	**1.5**	**15**	28	28	50	28	28	32
ID11	**12 / 6**	**1.0**	**10**	36	79	159	29	37	65

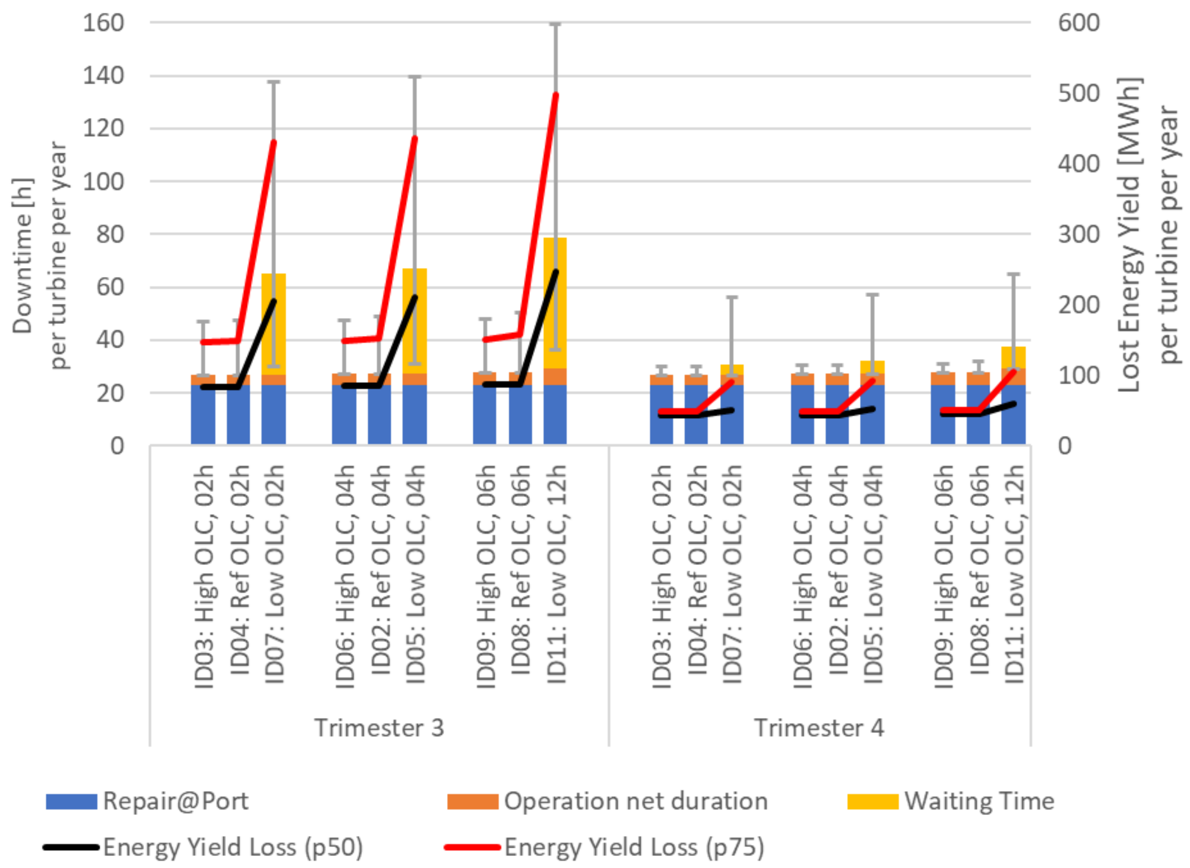

Figure 25 Influence of the OLC of the connection/disconnection, at different durations, on the average downtime per turbine per year. The error bars represent the first quartile (p25) and third quartile (p75) of the waiting time.

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Table 17 Impact of different connection/ disconnection OLC, at different durations, on the average loss of energy yield in MWh, per year per turbine, due to major replacements only.

ID	C/D Dur [h]	OLC		Trimester 3			Trimester 4		
		Hs [m]	Ws [m/s]	P25	P50	P75	P25	P50	P75
ID03	2 /1	2.0	15	84	84	147	43	43	48
ID04	2 /1	1.5	15	84	84	148	43	43	48
ID07	2 /1	1.0	10	94	204	430	43	50	91
ID06	4 / 2	2.0	15	85	85	148	44	44	49
ID02	4 / 2	1.5	15	85	85	153	44	44	50
ID05	4 / 2	1.0	10	97	210	437	44	52	93
ID09	6 / 3	2.0	15	87	87	150	45	45	50
ID08	6 / 3	1.5	15	87	87	157	45	45	52
ID11	12 / 6	1.0	10	113	246	499	47	61	105

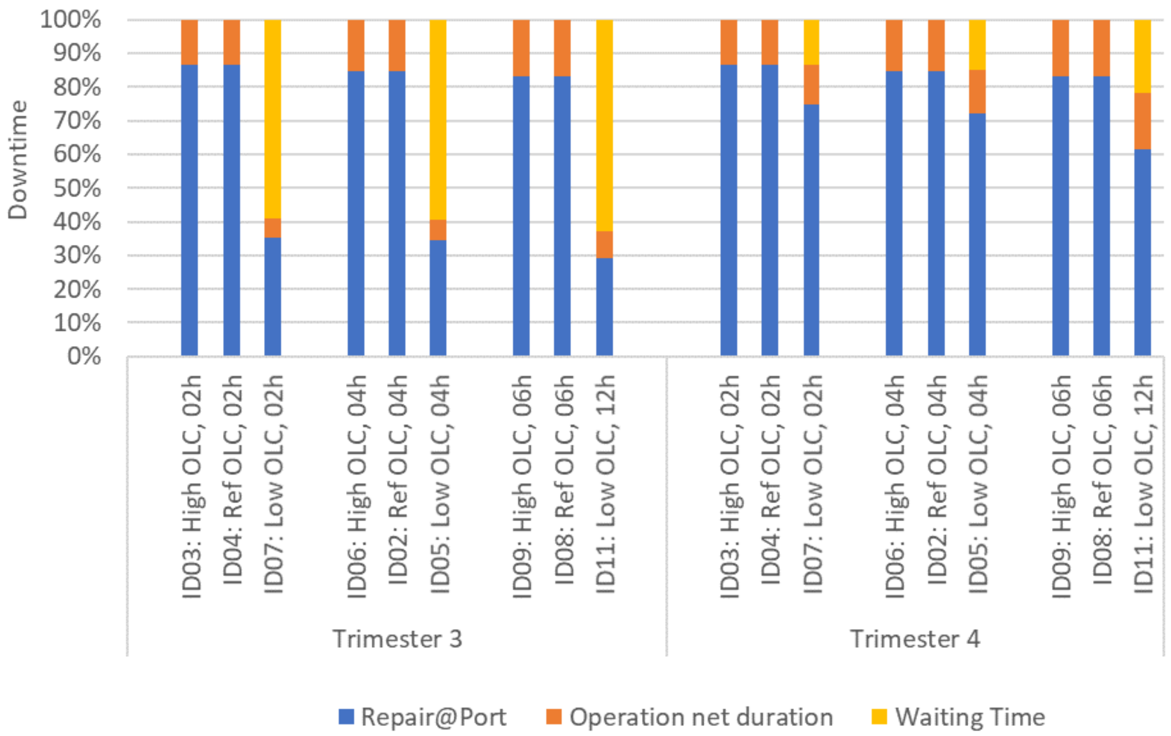

Figure 26 Contribution to the downtime per trimester, for different OLC of the connection/disconnection, at different durations.

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6.3 Sensitivity to the Tow OLC

The wet tow operation can be carried out with different OLC or towing speed, provided that the structure and operation are designed to safely withstand the resulting loads. Therefore, the tow OLC are a design parameter that can be optimized for certain conditions.

A sensitivity analysis was performed on the wet tow OLCs for the reference port (Las Palmas, 8-hour tow duration, see Section 3.3) and reference cases with PivotBuoy (see Section 3.7) and without PivotBuoy (24/24 hours connection/disconnection durations).

Table 18 Different wet tow durations (assuming a 3knots towing speed) for each port, and operation limiting conditions (OLCs) tested. Full description of the scenarios can be found in Table 26.

OLC		Duration [h] of Connection / Disconnection	
Hs [m]	**Ws [m/s]**	**4/2**	**24/24**
2.0	**15**	ID14	ID16
1.5	**15**	ID02	ID01
1.0	**10**	ID15	ID17

In this subsection, the influence of the tow OLC, at two different connection / disconnection durations, on the average downtime per turbine per year is shown in Figure 27, Figure 28, and Table 19. For brevity sake, the downtime is shown only for the third and fourth trimester, which are the most and least energetic trimester, respectively.

It is here restated that the durations shown in the figures represent the duration of the connection operation, and the respective disconnection operation takes half that time. Based on these results the following remarks can be made:

- Similar to the connection/disconnection, the reduction of downtime when increasing from the reference OLC (Hs=1.5m; Ws=15m/s) to the high OLC (Hs=2.0m; Ws=15m/s) is very small.
- However, when lowering from the reference OLC to a stricter OLC (Hs=1.0m; Ws=10m/s), an increase of 28% – 175% in the expected downtime (p50) for the 4th and the 3rd Trimesters, respectively, can be observed for a connection duration of 4h.
- However, the waiting time variability also significantly increases when reducing the OLCs. In the third trimester, there is a 25% probability that the downtime may exceed 155 hours per turbine per year, whilst for there reference 4/2 connection/disconnection case, the p75 value is 49 hours.
- For the connection duration of 24 hours (without PivotBuoy), the increase in expected downtime is not so significant (108% and 25% increase for the 3RD and 4th trimesters, respectively). For a connection duration of 24h, this increase in downtime ranges between 20%-130%.
- For the reference tow OLC (Hs=1.5m; Ws=15m/s), the median waiting time is negligible, and the downtime is dominated by the duration of the repairs at port and, to a lesser extent, the operation net duration.

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- The lost energy yield per turbine per year due to downtime were also represented. Naturally, Trimester 3 exhibits the largest potential energy losses due to major downtime and higher resource availability during that period.

Table 19 Impact of tow OLC, for two different connection/disconnection durations, on the average downtime, per year per turbine, due to major replacements only.

ID	C/D Dur [h]	TOW OLC		Trimester 3			Trimester 4		
		Hs [m]	Ws [m/s]	P25	P50	P75	P25	P50	P75
ID14	4 / 2	2.0	15	27	27	43	27	27	29
ID02	4 / 2	1.5	15	27	27	49	27	27	31
ID15	4 / 2	1.0	10	34	75	155	27	35	62
ID16	24 / 24	2.0	15	34	38	65	34	34	45
ID01	24 / 24	1.5	15	34	40	70	34	34	46
ID17	24 / 24	1.0	10	41	82	163	34	43	71

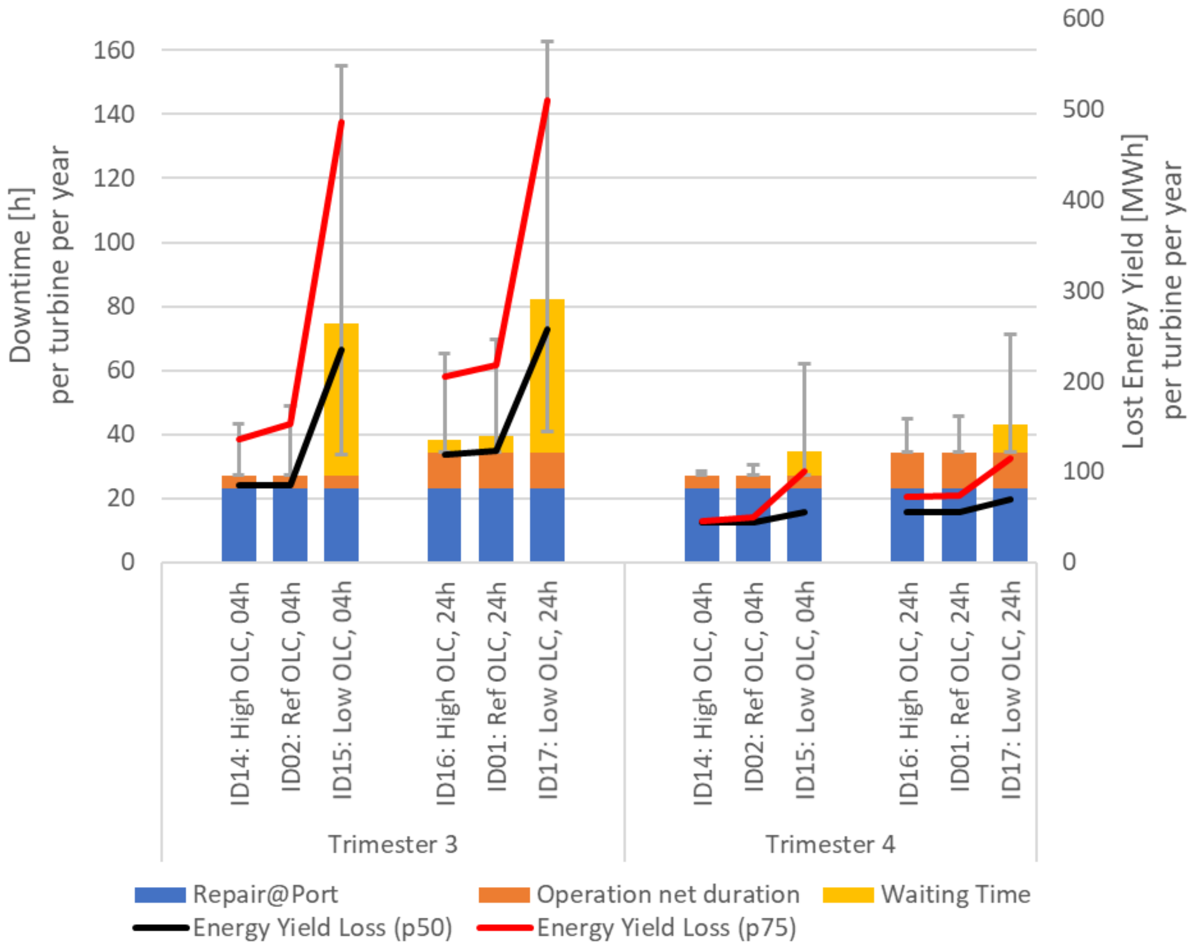

Figure 27 Influence of the tow OLC, at two different connection/disconnection durations, on the on the average downtime per turbine per year. The error bars represent the first quartile (p25) and third quartile (p75) of the waiting time.

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Table 20 Impact of tow OLC, for two different connection/disconnection durations, on the average loss of energy yield in MWh, per year per turbine, due to major replacements only.

ID	C/D Dur [h]	TOW OLC		Trimester 3			Trimester 4		
		Hs [m]	Ws [m/s]	P25	P50	P75	P25	P50	P75
ID14	4 / 2	2.0	15	85	85	135	44	44	46
ID02	4 / 2	1.5	15	85	85	153	44	44	50
ID15	4 / 2	1.0	10	105	234	485	44	56	100
ID16	24 / 24	2.0	15	108	119	204	56	56	73
ID01	24 / 24	1.5	15	108	124	218	56	56	74
ID17	24 / 24	1.0	10	128	257	509	56	70	115

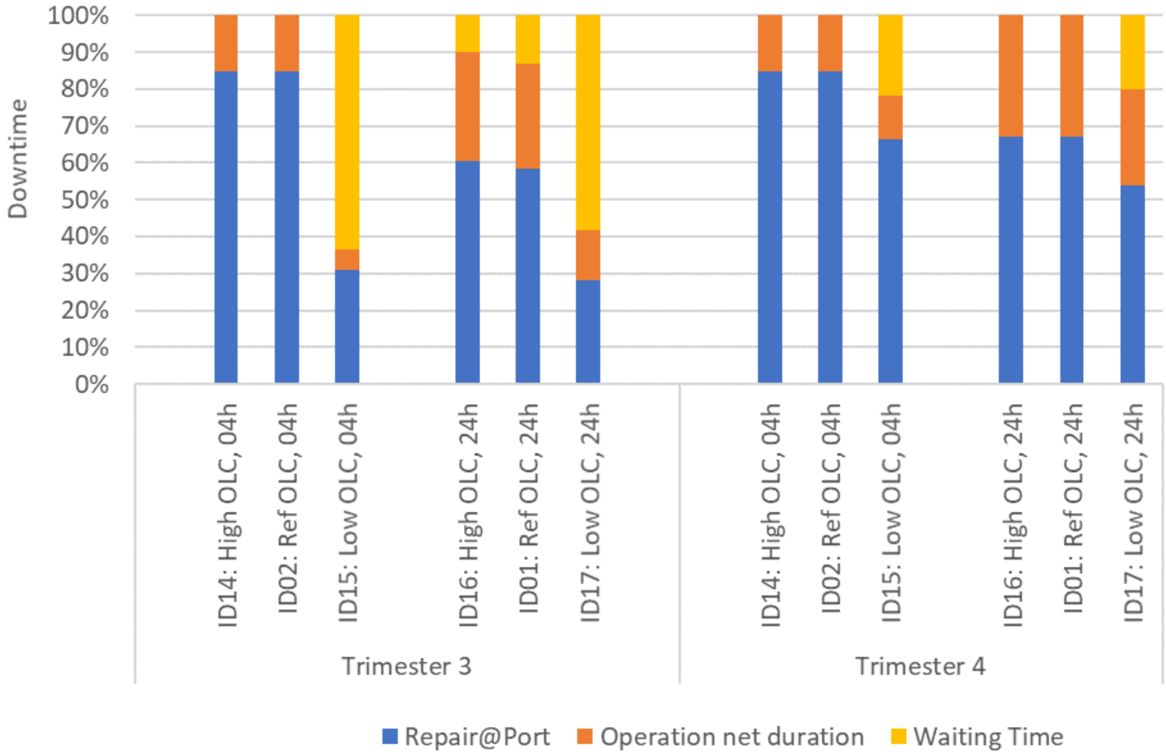

Figure 28 Contribution to the downtime per trimester, for different tow OLC at two different connection/disconnection durations.

6.4 Sensitivity to the Port Selection

In Section 3.3, the Port of Las Palmas was selected as the base port for O&M operations, despite being located further away from the deployment site than the Port of Arinaga. All the results shown so far were obtained assuming that the Las Palmas port is used. However, a closer port named Arinaga might be used, upon further review of its suitability, e.g. crane mobilization possibilities.

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In the present section, a sensitivity analysis to the port selection is carried out. Sensitivity analysis was performed by fixing the OLCs and operation durations. Again, the impacts of changing ports are analysed for both the PivotBuoy reference case (ID02) and the reference scenario without PivotBuoy (ID01).

Table 21 Different wet tow durations (assuming a 3knots towing speed) for each port, and operation limiting conditions (OLCs) tested. Full description of the scenarios can be found in Table 26.

Port Selection	Duration [h] of Connection / Disconnection	
	4/2	24/24
Las Palmas	ID02	ID01
Arinaga	ID12	ID13

The influence of port selection on the project downtime due to major maintenance is analysed for different trimesters of the year. However, for brevity sake, the downtime is shown only for the third and fourth trimester, which are the most and least energetic trimester, respectively. According to Figure 29, Figure 30, Table 22, and Table 23, it is possible to observe that:

- As expected, selecting the Port of Arigana leads to reduction in the operation net duration due to the shorter transit and tow operations, thus reducing the downtime.
- Selecting the Arinaga port, instead of the Las Palmas port, results in about 8% reduction in expected downtime and a 13% reduction if considering the (p75) value for the PivotBuoy reference case.
- For the no-PivotBuoy (24/24h connect/disconnect duration) reference scenario, the reduction in expected downtime is about 7-9% depending on the trimester.
- The choice of the Arinaga port can be expected to reduce the average downtime by approximately 10%. However, it needs to be investigated if this port is readily suitable to carry out major replacements, and if not, at what costs can it be made ready (e.g. crane mobilization).

Table 22 Impact of port selection on the average downtime, per year per turbine, due to major replacements only.

ID	C/D Dur [h]	OLC		Port	Trimester 3			Trimester 4		
		Hs [m]	Ws [m/s]		P25	P50	P75	P25	P50	P75
ID12	4 / 2	1.5	15	Arinaga	25	25	43	25	25	27
ID02	4 / 2	1.5	15	Las Palmas	27	27	49	27	27	31
ID13	24 / 24	1.5	15	Arinaga	32	36	64	32	32	42
ID01	24 / 24	1.5	15	Las Palmas	34	40	70	34	34	46

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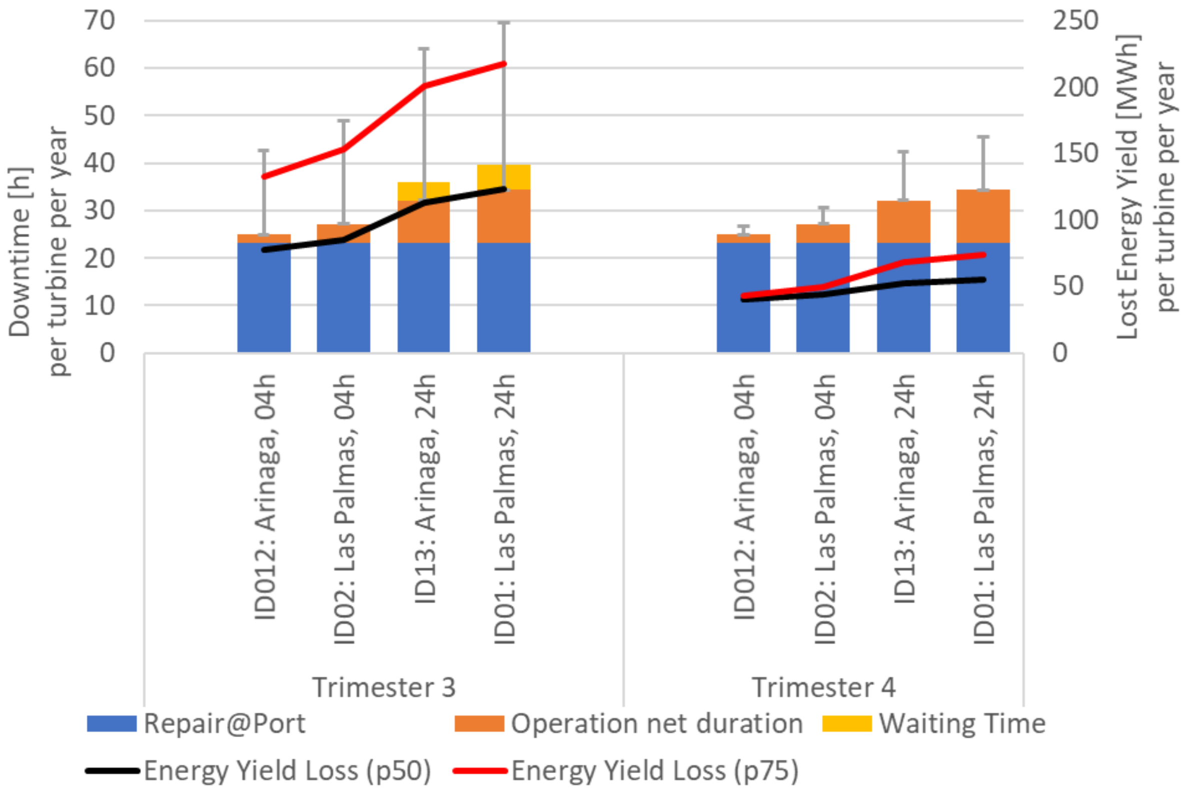

Figure 29 Influence of the port selection at two different connection/disconnection durations on the average downtime per turbine per year. The error bars represent the first quartile (p25) and third quartile (p75) of the waiting time.

Table 23 Impact of port selection on the average loss of energy yield in MWh, per year per turbine, due to major replacements only.

ID	C/D Dur [h]	OLC		Port	Trimester 3			Trimester 4		
		Hs [m]	Ws [m/s]		P25	P50	P75	P25	P50	P75
ID12	4 / 2	1.5	15	Arinaga	78	78	133	40	40	43
ID02	4 / 2	1.5	15	Las Palmas	85	85	153	44	44	50
ID13	24 / 24	1.5	15	Arinaga	100	113	200	52	52	69
ID01	24 / 24	1.5	15	Las Palmas	108	124	218	56	56	74

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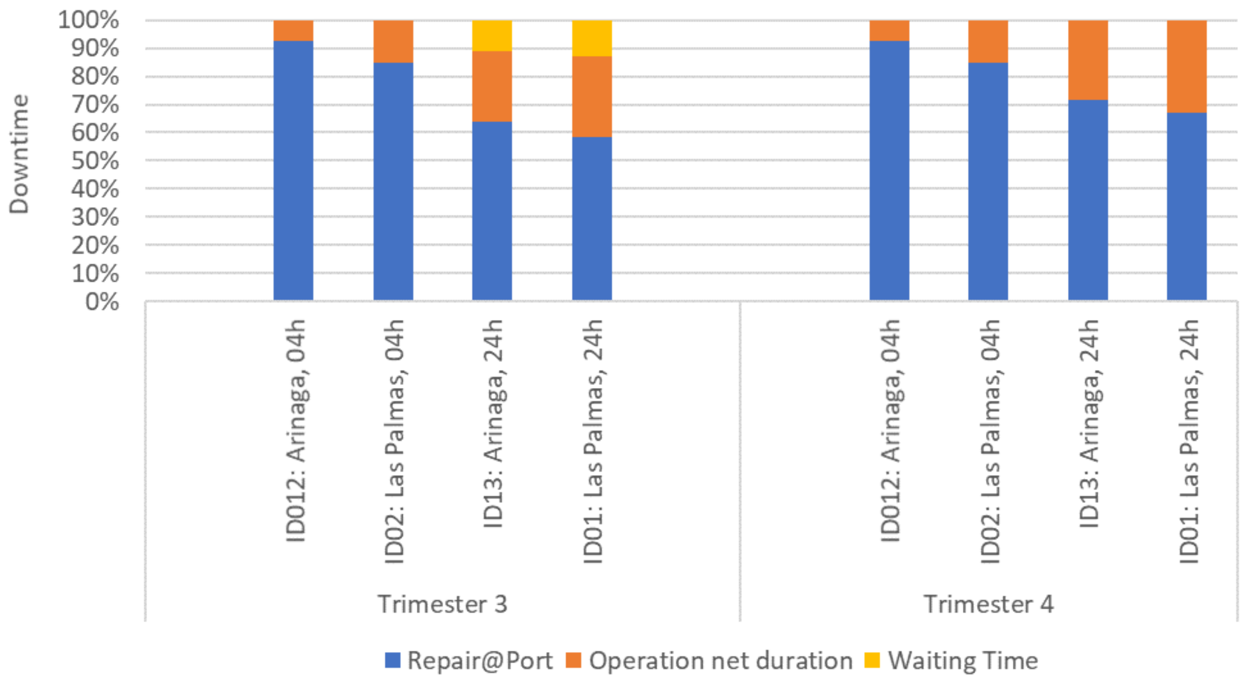

Figure 30 Contribution to the downtime per trimester, for different port selection at two different connection/ disconnection durations.

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7 CORRECTIVE VS PREDICTIVE MAINTENANCE

In order to evaluate the potential benefits of implementing a condition-based maintenance solution, using advanced sensors and monitoring systems that detect anomalies before they evolve into major component failures, a simplified analysis is proposed.

The extreme case of an ideal predictive maintenance scenario can be imagined, where all failures can be anticipated sufficiently in advance such maintenance is scheduled before component failure and no unplanned downtime occurs. In other words, every deteriorating component is subjected to maintenance before it loses its function. In this ideal scenario with predictive maintenance, the downtime only starts when the repair crew arrives on site and shuts down the turbine to initiate the turbine disconnection procedure. This greatly contrasts with a purely corrective maintenance strategy, where corrective maintenance is scheduled after component failure and downtime starts as soon as the failure occurs. In the latter case, the entire recovery operation, including waiting time, maintenance at port, and towing back to site contribute to the downtime.

The difference between corrective maintenance (Corr) and predictive maintenance (Pred) was assessed for two different scenarios: PivotBuoy base case (ID02) and no-PivotBuoy reference scenario (ID01), which have connection/disconnection durations equal to 4/2h and 24/24h respectively. The analysis was carried out for different trimesters of the year, however, for brevity sake, the downtime is shown only for the third and fourth trimester, which are the most and least energetic trimester, respectively.

From Figure 31, Figure 32, Table 24, and Table 25, it is possible to observe that:

- Using an ideal predictive maintenance, the expected reduction in the downtime can be negligible when there is no expected waiting time and if a vessel mobilization time equal to zero is considered.
- In cases where the waiting time is significant, i.e. for the no-PivotBuoy scenario, a 26% reduction on the expected downtime was observed in Trimester 3. This is an expected result, since the main different between both maintenance strategies is whether the waiting time and transit of the recovery operation are part of the downtime or not. If no waiting time is required, the only difference between both strategies is that the transit (short) duration of the recovery operation counts as downtime for the corrective maintenance.
- It follows that the potential benefits of using predictive maintenance when failures are occurring during the fourth trimester are not as significant as when failures occur during the third trimester.
- Despite not bearing significant impacts on the expected downtime value (p50 median), implementing a predictive maintenance solution has significant impacts on the downtime variability and upper limits.
- For the PivotBuoy reference case, there is a 25% probability that the downtime is larger than 49 hours in the third trimester. However, when implementing a predictive maintenance strategy this value is reduced to 38 hours (a 22% reduction). Similarly, for the no-PivotBuoy reference scenario, there is a 25% probability that the downtime may exceed 153 hours, which could be instantly reduced 119 hours by implementing a perfect predictive maintenance solution (26% reduction).

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- Finally, the impacts of implementing a predictive maintenance solution on the energy yield losses are proportional to the number of hours and depend on the average power production for each trimester. It follows that implementing a predictive maintenance system will result in significant reductions on energy yield losses, when failures are expected to occur in the months or trimesters with lowest availability.

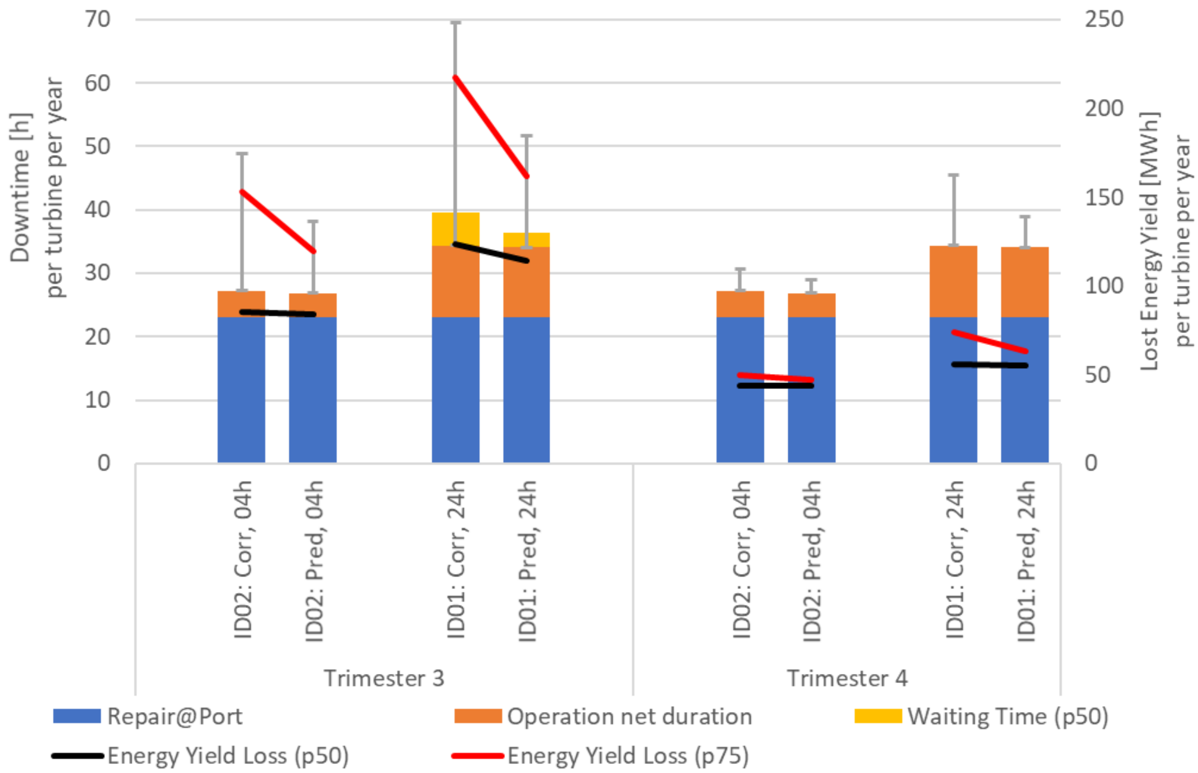

Figure 31 Influence of the maintenance strategy for two different connection/disconnection durations on the average downtime per turbine per year. The error bars represent the first quartile (p25) and third quartile (p75) of the waiting time

Table 24 Impact of the maintenance strategy, at two different connection /disconnection durations, on the average downtime, per year per turbine, due to major replacements only.

ID	Strategy	C/D Dur [h]	Trimester 3			Trimester 4		
			P25	P50	P75	P25	P50	P75
ID02	Corrective	4 / 2	27	27	49	27	27	31
ID02	Predictive	4 / 2	27	27	38	27	27	29
Relative Difference			1%	1%	22%	1%	1%	6%
ID04	Corrective	24 / 24	34	40	70	34	34	46
ID04	Predictive	24 / 24	34	36	52	34	34	39
Relative Difference			1%	8%	26%	1%	1%	14%

Table 25 Impact of the maintenance strategy, at two different connection /disconnection durations, on the lost energy yield in MWh, per year per turbine, due to major replacements only.

ID	Strategy	C/D Dur [h]	Trimester 3			Trimester 4		
			P25	P50	P75	P25	P50	P75
ID02	Corrective	4 / 2	85	85	153	44	44	50
ID02	Predictive	4 / 2	84	84	119	43	43	47
Relative Difference			1%	1%	22%	1%	1%	6%
ID04	Corrective	24 / 24	108	124	218	56	56	74
ID04	Predictive	24 / 24	107	114	162	55	55	63
Relative Difference			1%	8%	26%	1%	1%	14%

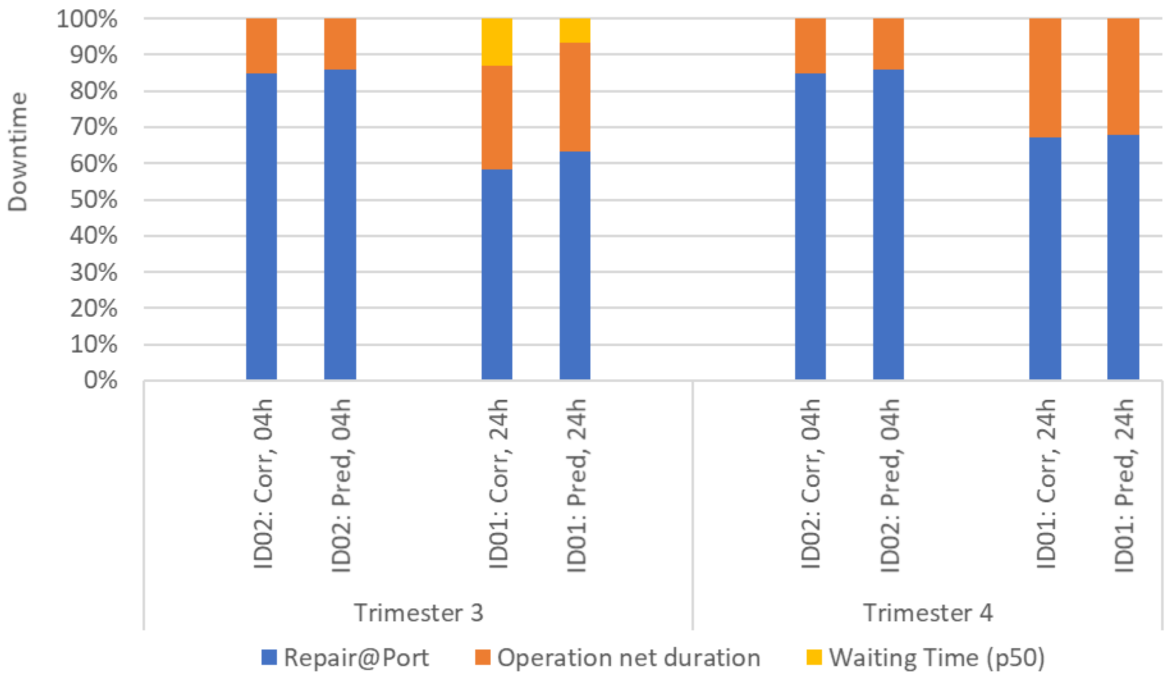

Figure 32 Contribution to the downtime per trimester, for different maintenance strategies at two different connection/ disconnection durations.

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8 CONCLUSIONS

One main motivation for implementing the PivotBuoy system in a floating offshore wind turbine is to simplify heavy maintenance operations, which are traditionally performed on site, using costly (and low on availability) heavy lift crane vessels. With the PivotBuoy quick disconnection system, the wind turbine may be disconnected and towed back to port for maintenance, using relatively cheap and highly available tug vessels.

For the purpose of evaluating what are the potential benefits of implementing a PivotBuoy system on the O&M stage, an operational analysis based on hindcast data was carried out comparing a PivotBuoy solution and a standard (no-PivotBuoy) reference solution. The study was based on a reference farm situated southeast of the Gran Canary Island. In this study, connection and disconnection durations were defined as 4 hours and 2 hours respectively, and the Port of Las Palmas was selected as the base O&M port. Typical failure rates and repair durations were defined and the breakdown of marine operations for retrieving and redeploying the floating wind turbine was described in detail.

A sensitivity analysis was then performed to assess the impacts of changing the connection durations and the Operation Limits and Conditions (OLCs) associated with the PivotBuoy system.

It was found that for the considered site, when compared to the reference weather limits (Hs =1,5m and Ws=15m/s), selecting a slightly more restrictive OLC (Hs =1,0m and Ws=10m/s), greatly increases the waiting time due to weather and total downtime of the farm. On the other hand, increasing the OLC to (Hs =2.0m and Ws=15m/s) lead to relatively small reductions on total downtime (below 5%), suggesting that for the site under analysis, the minimum OLC should not be under Hs=1.5m and Ws=15m/s. This is valid both for the connection/disconnection and wet tow activities.

Results also suggest that the downtime is less sensitive to the disconnection/connection duration than it is to the Operation Limits and Conditions. It can be expected that a quick connection system (4-hour duration) such as the one enabled by the PivotBuoy can reduce the downtime between 20% and 30% when compared to a scenario without a quick connection system, which is here assumed to take 24 hours.

Different scenarios were evaluated in terms of expected downtime and respective energy yield loss for the reference farm. Furthermore, a sensitivity to port selection, wet tow OLC and maintenance strategy (corrective vs predictive) was also evaluated.

Despite being the closest to site, the Port of Arinaga was not considered as the O&M base port due to insufficient crane capabilities at port. However, in the event that external cranes could be hired and mobilized to that port, a 10% reduction of downtime could be expected. Still, the possibility of mobilizing large cranes and the existence of storage facilities nearby need to be further investigated and adequately weighed against the 10% reduction in downtime.

The potential benefits of implementing a predictive maintenance system were found to represent a potential downtime (due to large maintenance) reduction of up to 26% when compared to a corrective strategy. Its main advantage is to avoid unplanned downtime, which in the context of this analysis represents the recovery operation transit and waiting time. Since the expected waiting time (median p50) is zero, it limits the impact of the predictive maintenance. Furthermore, it was assumed a perfect

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predictive strategy, i.e., all failures can be flawlessly predicted and repaired before loss of function. Therefore, the downtime reduction in this analysis is overpredicted.

In all scenarios considered, the repair at port is a significant contributor to the downtime. In this analysis, for lack of more relevant data, the repair times were taken from a survey of repair times on fixed offshore turbines using jack up vessels. It is worth investigating procedures to minimizing the time it takes to perform a major replacement on a floating offshore wind turbine while at port, since for the case under analysis it would result in a significant reduction in the expected downtime.

This preliminary analysis was intended to inform the design of the Pivotbuoy quick disconnection regarding its duration and OLC. A more complete study can be carried out in a more advance stage of project, where the different activities duration, OLC, vessel requirements, wind turbine model, etc. are known. The metocean data used was obtained from low resolution simulated data, which is reasonable for a first preliminary study, but insufficient for more detailed analysis, where local measured data is often required. Such a study could include the minor and major repairs of a wider range of components and estimate the O&M costs of a reference farm.

This project has received funding from the European Union's Horizon H2020 research and innovation programme under grant agreement No 815159

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10 APPENDIX I –CALCULATION MATRIX

Table 26 Calculation matrix with all the different scenarios tested regarding the duration and operation limiting conditions for all the activities considered in this analysis.

ID	Connect/Disconnect			Wet Tow			Transit		
	T [h]	Hs [m]	Ws [m/s]	T [h]	Hs [m]	Ws [m/s]	T [h]	Hs [m]	Ws [m/s]
01	24 / 24	1.5	15	8.1	1.5	15	2.0	2.0	25
02	4 / 2	1.5	15	8.1	1.5	15	2.0	2.0	25
03	2 / 1	2.0	15	8.1	1.5	15	2.0	2.0	25
04	2 /1	1.5	15	8.1	1.5	15	2.0	2.0	25
05	4 / 2	1.0	10	8.1	1.5	15	2.0	2.0	25
06	4 / 2	2,.0	15	8.1	1.5	15	2.0	2.0	25
07	2 / 1	1.0	10	8.1	1.5	15	2.0	2.0	25
08	6 / 3	1.5	15	8.1	1.5	15	2.0	2.0	25
09	6 / 3	2.0	15	8.1	1.5	15	2.0	2.0	25
10	12 / 6	1.5	15	8.1	1.5	15	2.0	2.0	25
11	12 / 6	1.0	10	8.1	1.5	15	2.0	2.0	25
12	4 / 2	1.5	15	2.2	1.5	15	0.5	2.0	25
13	24 / 24	1.5	15	2.2	1.5	15	0.5	2.0	25
14	4 / 2	1.5	15	8.1	2.0	15	2.0	2.0	25
15	4 / 2	1.5	15	8.1	1.0	15	2.0	2.0	25
16	24 / 24	1.5	15	8.1	2.0	15	2.0	2.0	25
17	24 / 24	1.5	15	8.1	1.0	15	2.0	2.0	25

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11 APPENDIX II – LIST OF ABBREVIATIONS

AHTV	Anchor Handling Tug Vessel
C/D	Connection/Disconnection
CBM	Condition Based Maintenance
Corr	Corrective Maintenance
CTV	Crew Transfer Vessel
IQR	Inter Quartile Range
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
O&M	Operation and Maintenance
OLC(s)	Operational Limits and Conditions
PB	PivotBuoy
Pred	Predictive Maintenance
SPM	Single Point Mooring
TLP	Tension Leg Platform
TTP	Tow to Port
WTG	Wind turbine Generator

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