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FOWTs: SEASONAL TECHNO-ECONOMIC REVIEW OF CORRECTIVE MAINTENANCE STRATEGIES – BASED OF HINDCAST MODEL

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Abstract

Maintenance in the offshore wind sector is one of the primary cost drivers, largely due to the harsh marine environment and the logistical challenges of accessing turbines located far from shore. Operations are highly dependent on weather and sea conditions, often leading to long delays and complex management.

The aim of the Thesis is to develop a methodology able to evaluate, from both a technical and economic perspective, the seasonal impact associated with corrective maintenance in the context of floating offshore wind turbines (FOWTs). Although it is not possible to precisely predict when a turbine will experience a failure, the proposed approach allows for a more reliable estimation of the associated intervention costs and expected downtime.

This analysis is based on metocean data, including significant wave height (Hs) and wind speed at 100 m from the ERA5 database. These variables are vital to assess the accessibility and feasibility of maintenance in offshore environments.

One of the main challenges of floating wind power, still an emerging technology, concerns the management of maintenance activities. Although, some models are available for the Opex estimation, they often involve high computational costs and require several input parameters in order to achieve results that reflect real-world operating conditions. For this reason, the present Work aims to provide a preliminary contribution toward defining a methodological basis for future analyses and developments in the field.

The study of a representative "typical year" highlighted a marked seasonality in metocean conditions. Winter emerges as the most severe and limiting season for offshore operations, while summer offers more favourable conditions for performing interventions, particularly preventive ones. For this reason, the analysis is structured on a seasonal basis, with the goal of identifying waiting times, intervention costs, operational windows, and completed maintenance actions.

In summary, the proposed methodology represents a first step toward building a predictive model for the economic and operational management of corrective maintenance in floating offshore wind turbines. In this work, the proposed methodology is applied specifically to the generator and the pitch system, two components that are particularly critical from a maintenance perspective.

In addition, a post-processing approach is presented to define a starting point model to assess the annual Opex related to a corrective maintenance approach. Based on the seasonal average costs provided by the hindcast model, it is possible to estimate the annual Opex of each component by considering four key factors:

- the chosen maintenance strategy,
- the component's annual failure rate,
- the seasonal distribution of failures,
- the site selections.

This approach lets the assessment of the annual Opex of individual components related to corrective maintenance, with the potential to extend the analysis to the entire turbine.
By applying the same methodology to major elements such as the floating platform and electrical cables, by using different corrective strategies, it is also possible to estimate the annual Opex associated with corrective maintenance for a floating offshore wind turbine, and to scale the evaluation to an entire wind farm. Although preliminary, this analysis provides an initial framework for future studies aiming to quantify the operational costs of floating offshore wind farms.

1. Offshore wind status and 2030/2050 perspectives

The floating offshore wind sector benefit is mainly about the possibility to exploit more constant and powerful wind farther from shore. This technical advantage has attracted strong interest from governments, investors, and developers worldwide.
Currently, the installed capacity of floating wind remains limited, with only a few operational projects across the world and 0.23 GW installed [2]. However, the outlook for the coming years is highly ambitious. Global projections forecast an increase to 66 GW/year in annual installations by 2033, aiming to reach 200 GW of cumulative offshore capacity by 2050 [3]. According to DNV, FOWTs could represent 300 GW of capacity by mid-century, covering 6 % of total offshore wind deployment [4].
Nowadays, this growth is leaded by Asia-Pacific and Europe; specifically, Europe is planning to install 187 GW and Asia will achieve 410 GW by 2030 [5]. Nonetheless, also North America forecasts to get 22 GW by 2030 and 86 GW by 2050 [6]. The large-scale adoption of floating wind will help to diversify energy sources and speed up the phase-out of fossil fuels. It also presents an opportunity to drive job creation, industrial innovation, and the development of solid energy infrastructure. In addition, in order to meet the global commitment of limiting warming to 1.5 °C, entities like GWEC, DNV, IRENA, and IEA suggest between 1 400 and 2 000 GW of offshore wind are required by 2050.

In addition to current national targets, several global energy roadmaps have begun to recognize the strategic role of floating offshore wind in achieving net-zero emissions. Floating wind unlocks access to areas where seabed conditions or water depths make fixed-bottom solutions either unfeasible or economically non-viable. According to report [38] more than 80% of the global offshore wind technical potential lies in waters deeper than 60 meters, where floating technology is essential. This includes vast untapped wind resources off the coasts of Japan, United States, South Korea, Norway and even the Mediterranean Sea.

The flexibility of floating foundations allows turbines to be located farther from shore, where wind resources tend to be stronger, more stable, and less turbulent. This translates into higher capacity factors and potentially lower curtailment risks, especially when connected to integrated energy systems. The technological decoupling from the seabed also reduces certain environmental and geotechnical constraints, accelerating permitting processes.

Despite its relatively low installed base today, the pipeline of floating offshore wind projects is growing rapidly. At the end of 2024, a total of 278 MW of floating wind was installed globally [39], however, are present different projects in various stages of development, from early planning to permitting and pre-commercial deployment.

Looking ahead, floating wind is increasingly being considered not just as a complementary technology, but as a core component of future renewable energy strategies. In addition, this geographic flexibility, positions it as a critical solution in countries with limited shallow seabed or high population density along coastlines. For instance, in California, where fixed-bottom installations are not feasible beyond a few kilometres offshore, floating wind is expected to dominate all future offshore development.

However, several challenges remain before floating offshore wind can reach commercial maturity at gigawatt scale. In particular, some difficulties discuss in this work are: high LCOE, logistical complexity in turbine assembly, towing, and mooring operations, limited availability of suitable port infrastructure, financing risk due to technology novelty and long development timelines.

Overcoming these barriers will require a coordinated approach involving industrial investment, policy support, public-private partnerships, and global knowledge sharing. Initiatives like the Floating Wind Joint Industry Project (JIP) [40], supported by major offshore players, are helping accelerate standardization and best practices across the sector. In parallel, some plans, like REPowerEU [41] by the European Commission, are deployed dedicated funds to stimulate pilot and pre-commercial floating projects.

From a macroeconomic point of view, floating wind also offers significant employment potential. According to a study by the Global Wind Energy Council (GWEC), every gigawatt of floating offshore wind installed could generate up to 17,000 full-time equivalent jobs [42]. The development of local supply chains: blade manufacturing, floating substructure assembly, and dynamic cable production, will play a key role in reducing costs and creating regional economic value.

In conclusion, while current installed capacity remains limited, the growth potential of floating offshore wind is vast. With supportive regulatory frameworks, continued innovation, and targeted infrastructure investments, the sector is on reoad to become one of the pillars of the global clean energy transition. Projections up to 2050 highlight a transition from megawatt-scale farms to multi-gigawatt industrial arrays able to supply affordable and clean electricity. Floating wind is becoming a strategic asset for meeting climate goals, securing energy independence, and enabling sustainable industrial growth.

1.1. Mediterranean Sea & North Sea: main and future projects

As mentioned in the previous paragraph, Europe is leader in the floating technology. Specifically, different installations have been developed and are already operational. The following paragraph aims to introduce the current projects across Europe and the ones in planning to build; mainly divided in Mediterranean Sea and North Sea.

- **Mediterranean Sea**

Initially, the Mediterranean Sea provided the prototype test-based space for the emerging technology. Nowadays, it becomes a strategic region for floating offshore wind deployment. In fact, countries like Italy, France, Spain, Greece, and Malta are targeting deep-water floating projects [2]. In particular, France has awarded two 250 MW floating concessions in the Mediterranean, showing a growing national interest. Furthermore, off the coast of Sicily another European floating project has been approved. 7SeasMed is a floating offshore wind farm with the aim of promoting integrated and sustainable maritime spatial planning and serves as a reference framework for future policy and strategic decisions. In the methodology chapter the site is taken as a reference point to carry out the analysis in the Mediterranean Sea.

However, the first operational wind plant is EolMed, located off the coast of Gruissan in southern France. It is a semi-submersible wind plant with an installed capacity of 30 MW [7]. Another pilot project is Provence Grand Large, also in France, near Port-Saint-Louis-du-Rhône. It presents a capacity of around 24 MW, with three turbines anchored using Tension Leg Platform (TLP) technology and provides to more than 40,000 households in France [8]

- **North Sea**

The North Sea represents the epicentre of floating wind innovation in Europe. Several projects are present and operational:

- **Hywind Scotland** (30 MW, Spar type, Siemens direct-drive turbines) has operated since 2017 with a remarkable capacity factor of **54–57%** [9].
- Hywind Tampen (88 MW, Spar technology), online since 2022, represents the world's first floating wind farm supplying offshore oil platforms [10].
- Kincardine FOWT (49.5 MW, Semi-Submersible type) off the coast Aberdeen, which tested in-situ maintenance strategies, along with tow-to-port for heavy repairs and installation and for this reason it represents the site taken into consideration in the methodological chapter.

In addition, several projects will be implemented in the coming years, including:

- Aspen, Beech & Cedar, 3 GW and Semi-Submersible platform,
- GreenVolt, 560 MW and Semi-Submersible platform like WindFloat type
- Culzean Pilot, 3 MW and Semi-Submersible technology
- Denmark Energy Island, around 10 GW and involving Semi-Submersible, TLP and Spar technologies

1.2. State of art of floating offshore wind

Over the past two decades, offshore wind energy sector has experienced a rapid growth, becoming one of the most promising renewable sources for the global energy transition. Offshore wind turbines benefit from stronger and more consistent wind conditions compared to onshore ones, resulting in higher yields and greater energy production stability.

The first offshore installations, built in the 2000s, involved turbines with capacities between 2 and 4 MW, anchored to the seabed using monopile or jacket foundations, around 50 meters water depth. As technology has advanced, turbine sizes is significantly increased, with modern models exceeding 15 MW of rated power, featuring blades over 100 meters long and rotor diameters of more than 220 meters.

In addition, the operational water depth of offshore wind farms has increased, thanks to the development of more robust and complex foundation systems. However, bottom-fixed wind turbines (BFWTs) become technically and economically unfeasible beyond depths of 60–70 meters. For this reason, recent years have seen a growing focus on Floating Offshore Wind Turbines (FOWTs). Unlike bottom-fixed, which are built on foundations like monopiles or jackets anchored directly into the seabed, as showed in the figure 1, FOWTs rely on floating substructures. According to the floating platform, turbine takes the resulting name. The main ones are spar, semi-submersibles, tension-leg platforms (TLP) and barge and by using anchor systems and flexible mooring line they are moored to the ocean floor.

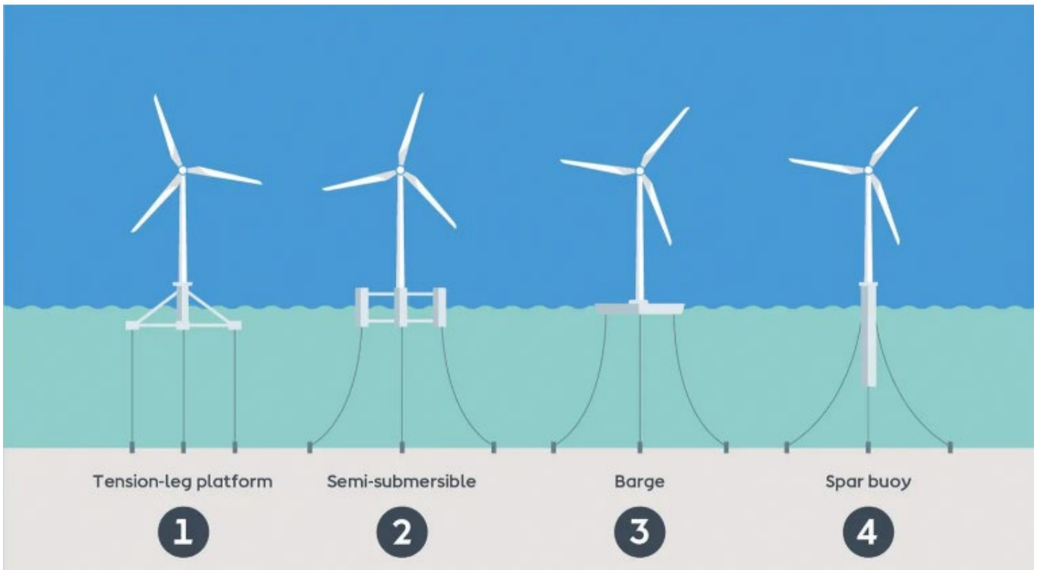


Figure 1. FOWT different substructures

Floating Offshore Wind Turbines integrate different advanced technologies to work in deep and complex marine environments. The upper part of the turbine (rotor, nacelle, and tower) is like the conventional turbines, the key innovation lies in the floating platform. The latter is important to ensure structural stability under dynamic conditions such as waves, wind, and ocean currents.

These platforms are engineered to withstand pitch, roll and heave motions through ballast systems, mass distribution, and optimized geometric configurations. Each platform type (Spar, TLP, Semi-submersible, Barge) uses a different combination of passive buoyancy, active stability, and flexible mooring systems to keep proper positioning.

Moreover, mooring system is vital and typically involves synthetic or steel cables anchored to the seabed, often arranged in multiple-line configurations to withstand cyclic loads. The dynamic cable, which connects the turbine to the grid, is specially designed to bear constant mechanical stress and movement.

Another important feature is about the generator. Traditional onshore turbines involve a generator coupled with a gearbox in order to increase the rotational speed before the energy conversion. However, this configuration introduces mechanical difficulties especially in offshore contexts, making components fragile and maintenance intensive. As a result, there has been a growing shift toward direct drive generators, which work without a gearbox. In this configuration, the rotor is directly coupled to a low-speed generator, typically a Permanent Magnet Synchronous Generator (PMSG). The main benefit is mechanical simplicity: by eliminating the gearbox, the number of moving parts is reduced, lowering the risk of failure and maintenance needs. In addition, PMSGs are compact, efficient at low speeds, and require less cooling, features that are highly desirable in offshore installations.

1.2.1. Technological Challenges in Floating Offshore Wind

The present paragraph will discuss the main technological challenges that floating offshore wind presents. As mentioned in the previous rows, FOWTs differ significantly from BFW ones, involving challenges mainly based on withstanding loads from wave and wind sources.

1. Stability issue

FOWT platforms are subject to dynamic loads, experiencing pitch, roll and heave motions due to wind and wave interaction. These motions affect rotor operability and introduce additional loads on the tower, blades, and support structures. According to [11]: semi-submersible platforms are more sensitive to wave-induced motion, making aerodynamic control more difficult. Spar-type platforms can exhibit “nodding” movements (vertical oscillation), which can lead to negative aerodynamic damping and stability issues.

These movements do not only challenge the structural integrity of the components but also have a direct impact on power production. Excessive pitch and roll affect the angle of attack of the rotor blades, which reduces aerodynamic efficiency and can lead to additional output losses. Moreover, continuous motion can make the turbine’s control systems less responsive, particularly under gusty or turbulent wind conditions, which increases the probability of operational curtailment for safety reasons. Platform instability also complicates the development of planned or corrective maintenance, increasing weather dependency and reducing accessibility windows. In the long run, this can decrease turbine availability and contribute significantly to higher Opex, thereby negatively impacting the LCOE.

2. Mooring Systems and Materials

Mooring lines must withstand complex loads to keep the turbine's position. Their mechanical resistance and fatigue life are vital. The materials involved, typically steel chains or synthetic fibers, even though they must be specifically designed for fatigue, corrosion, and marine environment. Innovation in lighter, stronger mooring materials is key to improving cost-efficiency and reducing operational issues.

In addition, the water depth at the site greatly influences the mooring system design. As floating offshore wind expands into deeper waters (often >500 m), traditional mooring configurations become unfeasible or expensive. Deeper installations require longer mooring lines and more anchor tension, which means higher material costs and more complex dynamic behaviour. Deeper waters also limit the types of anchoring systems that can be used (e.g., suction piles vs drag anchors) and influence the stress and fatigue response of the lines.

These depth-related factors also affect installation procedures, as deeper moorings require specialized vessels and more time-consuming deployment actions. From an O&M point of view, inspecting or replacing mooring lines becomes increasingly difficult in deep waters, contributing to higher Opex and downtime risk. The development of advanced simulation tools, dynamic analysis, and monitoring systems is essential to ensure long-term reliability and reduce unexpected mooring failures that could compromise the operational stability of the FOWT.

3. Marine Operations and Accessibility

Installation and maintenance at sea are still very complex to manage, requiring favourable weather windows and advanced planning. According to [12], accessibility is one of the most relevant aspects for O&M, assessing the feasibility to access the ORE farm. It is based mainly on metocean conditions and therefore, on the sea where turbines are installed. In-situ approach is the best way to carry out a maintenance intervention, even though could result risky from a safety point of view. Instead, T2P approach could include massive downtime.

Accessibility directly determines the success of any maintenance strategy. High wind speeds, strong wave conditions (significant wave height, Hs), and rough sea states often prevent safe vessel access to the turbine, especially when using smaller crew transfer vessels (CTVs). Even Service Operation Vessels (SOVs), which are more resistent, are constrained by certain metocean thresholds. As a result, maintenance interventions may be delayed for several days or even weeks, depending on seasonal weather patterns. These delays increase corrective maintenance costs and reduce turbine availability.

Furthermore, floating turbines introduce additional complexity to accessibility. Unlike fixed-bottom turbines, floating platforms are in constant motion. This limits the types of maintenance that can be done safely offshore. For complex repairs, the turbine often needs to be towed back to port (T2P approach), which involves detachment of mooring lines, long towing operations, and full disconnection from the grid—resulting in downtime that can last weeks or even months.

These challenges make accessibility a central cost driver in Opex modelling and risk assessment. Improving accessibility through better vessel technology, real-time metocean monitoring, and autonomous inspection systems (e.g., drones, ROVs) is therefore a priority. However, until these technologies mature and are widely adopted, accessibility constraints will continue to be one of the biggest bottlenecks in floating offshore wind O&M.

4. Vessel Availability and Port Facility

Although several projects are planning to build in the next years, FOWTs remain a still emerging technology. For this reason, it requires great efforts about planning decisions on adequate port infrastructure and standardized component manufacturing.

Vessel availability and port facility readiness play a fundamental role in both installation and maintenance operations. Floating wind turbines, especially those based on semi-submersible or spar designs, have very large footprints and require deep-water ports with heavy-lift capabilities, assembly space, and quayside access for large components and mooring lines. At present, only a limited number of ports around the world meet these requirements, leading to congestion, increased transit times and higher logistics costs.

Moreover, the availability of specialized vessels, such as anchor handling tug supply (AHTS) ships, dynamic positioning vessels, and towing barges, is limited. These vessels are in high demand across offshore sectors (including oil & gas), and their charter rates are variable. If a corrective maintenance task requires urgent towing or mooring work and a vessel is unavailable, response time increases, leading to longer turbine downtime and higher unplanned costs.

Therefore, investment in floating-wind-ready port infrastructure and the scaling up of a dedicated fleet of vessels is essential to support the industrialization of the sector. These elements will be discussed in more detail in the following chapters, focusing on how they impact logistical flexibility and overall O&M effectiveness.

All the technological challenges described above have a direct and cumulative impact on the Levelized Cost of Energy (LCOE) for floating offshore wind. Compared to more mature renewable technologies like onshore wind or solar PV, the LCOE for floating wind is still considerably high, between €100 and €160/MWh [36] [37], depending on location, technology type, and scale. This is due to both high Capex and elevated Opex driven by accessibility constraints, vessel costs, and maintenance delays.

The instability of the platform affects turbine efficiency, reducing output and increasing mechanical stress. Mooring complexity raises both initial costs and long-term inspections. Accessibility limits fast interventions and increases downtime, which reduces energy production while costs continue to be present. Logistical bottlenecks related to vessels and ports delay operations and raise uncertainties, which are then priced into risk and costs.

Together, these factors explain why floating wind, despite its enormous potential, is currently one of the least cost-competitive renewable technology. However, as each technological barrier is progressively faced through: innovation, standardization, and industrial scaling, floating offshore wind will follow a similar LCOE reduction curve as fixed-bottom did over the past decade. The integration of solutions to the challenges outlined in this section is therefore critical not only for technical viability, but for economic sustainability and global scalability.

1.3. FOWTs: main components

Floating Offshore Wind Turbine components are described by dividing the overall turbine in three main categories:

- **Conventional wind turbine**: which involves the same components included in onshore wind turbine, even though capacity is much larger,
- **Floating Platform**: the foundation that support the wind turbine, ensuring stability and floatability
- **Electrical system**: similar to that of an onshore turbine, but adapted to the offshore environment with marine-grade insulation, watertight protection and flexible cabling to withstand motion, humidity, and corrosion.
- **Mooring System and Anchor:** ensures the stability and positioning of the floating platform through tensioned lines connected to seabed anchors. The design depends on water depth, seabed type, and platform motion. Materials must resist fatigue, corrosion, and dynamic marine loads.

1.3.1. Conventional Wind Turbine

The upper section of a FOWT is basically identical to that of a conventional onshore wind turbine. It consists of:

- **Yaw system**: which rotates the nacelle to align the rotor with the wind direction, with the purpose of maximizing the captured energy. In FOWTs, it also work in function of platform movement, ensuring proper orientation even when the floating structure drifts slightly due to currents or wind-induced motion. It is vital for aerodynamic efficiency and stability.
- **Pitch system:** which adjusts the angle of the turbine blades to control rotor speed and optimize power output under different wind speed. In FOWTs, it also plays an important role in mitigating structural loads caused by platform motion, improving both performance and component lifetime in marine environments.
- **Rotor and blades**: three aerodynamic blades mounted to a central hub, designed to extract kinetic energy from the wind, but with larger size
- **Nacelle**: houses the main shaft, generator and auxiliary systems such as cooling and braking. The nacelle also includes the control systems and monitoring equipment.
- **Tower**: a tall, cylindrical structure that connects the nacelle to the floating platform and keeps the rotor to optimal wind heights. It is typically made of steel and must be engineered to withstand dynamic loading caused by waves and wind interaction.

1.3.2. Floating Platform

As mentioned in the state of art chapter, floating platform is a great work of engineering to allow the exploitation of wind power even farther off the coast. The platform must support the full weight of the tower and turbine while maintaining minimal motion to ensure efficient power generation and structural integrity. According to [18] there are:

- **Spar buoy**: a simple design vertical cylinder with ballast at the bottom to ensure stability. It requires at least 100 meters depth and turbine is needed to be assembled offshore.
- **Semi-submersible**: it requires the onshore assembled and it is a more flexible structure thanks to the ability to work in shallow water depth. However, it involves high structural mass to provide stability and presents complex fabrication with respect to other concepts.
- **Tension Leg Platform (TLP)**: which uses taut vertical mooring lines under tension, thanks to which there is a minimization of heave motion. Suitable for moderate depths but more complex to install.
- **Barge**: which presents a wide, shallow draft design, ideal for less severe sea conditions and easier port-side assembly. It provides good stability for small-to-medium turbines and is often used in early-stage demonstration projects. However, it is more sensitive to wave-induced motion compared to spar or semi-sub types.

1.3.3. Electrical System

FOWTs integrate a complex electrical system, largely similar to that of onshore turbines, but adapted for the offshore environment. It includes:

- **Generator**: typically a permanent magnet synchronous generator in direct-drive configurations, with the purpose to convert wind potential energy into electrical one.
- **Power converters** and **transformers** housed within the nacelle or at the tower base,
- **Cables**, which let the connection between the site and the land. In particular, there are:
  - **Array cables:** which transfer power from wind turbine to offshore substation [19]
  - **Export cables:** which connect the onshore and offshore substations to transmit power from wind farm to the shore [20]

These cables must withstand constant motion, bending, and marine exposure, making their design and installation a critical aspect of offshore wind projects.

1.3.4. Mooring System and Anchors

Unlike BFWTs, which are fixed to the seabed, FOWTs require a flexible and solid mooring system to keep position while allowing controlled motion. These systems typically include:

- **Catenary mooring lines**: heavy chains or synthetic ropes that sag to absorb tension.
- **Taut-leg systems** (used in TLPs): keep the platform vertically constrained.
- **Anchors**: types vary based on seabed conditions and include drag embedment anchors, suction piles, and vertical load anchors.

The design of the mooring and anchoring system must consider dynamic loads, fatigue life, and corrosion in a challenging offshore environment.

2. The maintenance function: key points and general aspects

The maintenance is one of the most essential activities in technological and engineering contexts, playing a key role in ensuring the proper operation and continuity of systems. The main goal is to assure that the technologies in operation maintain high levels of efficiency, reliability, and safety over time. To mention [13]:

"*Maintenance is the function responsible for overseeing all facilities involved in the production of goods and services. Its role is to design, organize, and carry out interventions aimed at ensuring the nominal performance and proper preservation of equipment during operational periods—in other words, to minimize downtime required to restore these conditions"*

Maintenance includes different tasks, including preserving the functional condition of equipment, restoring performance after failures, and improving the operational capabilities of assets. As a result, it supports not only the integrity of individual components but also the overall optimization of entire processes.

Nowadays, maintenance is intended as a strategic function not only in industrial field but also across a wide range of sectors. Its role is crucial to reduce the costs associated with unexpected equipment downtime, ensuring consistent product quality, and prolonging the service life of that technologies. As such, maintenance has become a key activity to manage resources efficiently and keeping operational expenditures (Opex) under control, thereby supporting the long-term technical and economic sustainability of production systems.

Considering the above, the maintenance function has become an integral part of the entire production process and a well-structured connection between production and maintenance is able to achieve optimal outcomes form an efficiency, cost and safety point of view. This management between these two functions is vital for maintaining high performance standards and minimizing unplanned interruptions.

In the specific case of floating offshore wind turbines (FOWTs), maintenance becomes even more critical due to the harsh and unpredictable environment. The need for maintenance arises primarily from the progressive deterioration of components subjected to external loads and environmental conditions. The main causes that lead to failures or performance degradation include extreme weather conditions, mechanical fatigue, corrosion, and accidental impacts.

Severe metocean conditions, such as high wind speeds, large wave heights, and turbulence, impose significant dynamic loads on turbines, blades, towers and mooring lines. These loads accelerate wear and can lead to structural damage if not properly monitored and managed. Storm events or rapid changes in sea state may trigger emergency shutdowns or force components to work under non-optimal conditions, increasing the likelihood of fault development.

Another major factor is material fatigue, which arises from the cyclic nature of the loads acting on the rotating and support components. Over time, the repetitive stress can initiate cracks or deformation in mechanical parts, such as drivetrain bearings, blades, or joints. Fatigue failures are often not immediately visible, making them particularly dangerous if left undetected.

Corrosion is a persistent threat in the offshore environment because of continuous exposure to saltwater, humidity, and temperature variations. Components such as the tower platform, electrical connections, and mooring lines are very exposed. If not adequately protected or periodically treated, corrosion can compromise structural integrity, increase electrical resistance in connections, and lead to complete component failure.

Additionally, extreme events such as lightning strikes can cause sudden and severe damage. Although these events are relatively rare, their consequences can be catastrophic in terms of turbine downtime, repair costs, and safety risks.

Maintenance, therefore, is not simply a reactive activity but a preventive and strategic need. It aims to identify early signs of failure, restore functionality before total breakdown and adapt systems to withstand the site-specific operational challenges. A properly implemented maintenance plan, whether corrective, preventive, or predictive, helps to minimize the occurrence and impact of these failure causes. It ensures higher system availability, reduces unscheduled events and maintains consistent energy production, which is essential for keeping the LCOE under control in floating offshore wind.

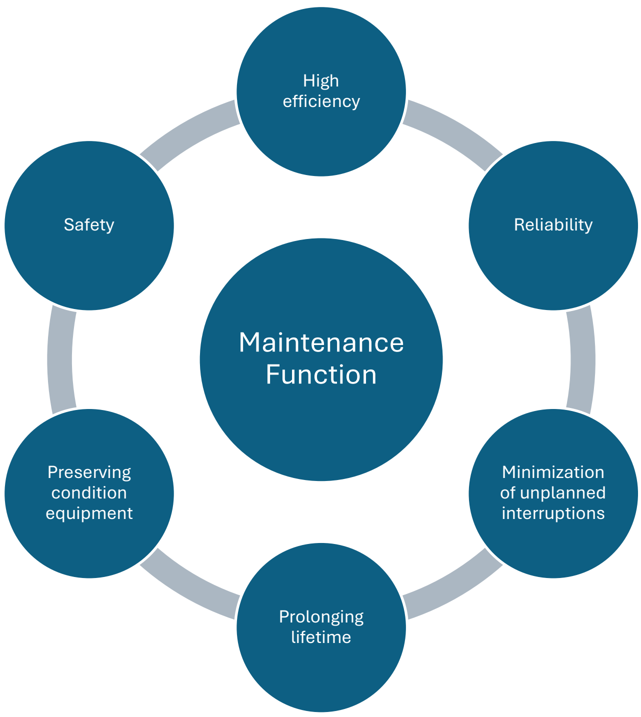


Figure 2. Maintenance function and main factors

Among the different types of maintenance, the main ones are corrective, preventive, and predictive:

- Corrective maintenance works just after a failure occurs, since it waits for the problem to manifest before starting the repair.
- Preventive maintenance aims to avoid failures through scheduled interventions at regular intervals, reducing sudden downtime and increasing plant reliability.

- Predictive maintenance, instead, works with advanced sensors, which constantly monitor plant performance and take action when anomalies or strange behaviour occur.

Additionally, according to [14] opportunistic maintenance gains traction in recent years. It involves performing additional interventions by exploiting opportunities due to ongoing downtime. This approach is particularly relevant offshore, where resources are limited and so the aim is to optimize as much as possible.

How these strategies interact each other is a key activity to develop an effective and efficient maintenance plan. For this reason, several analytical models and optimization techniques have been developed, each structured to specific objectives, but with a common goal: to continuously monitor system status, prevent potential downtime, and enhance overall performance from both technical and economic perspectives.

Preventive and predictive maintenance strategies are very important in the offshore wind sector. Difficulties in accessing leads to pre-empt the failure instead to fix it downstream. However, a corrective maintenance analysis is important to complete the maintenance overview and understand how to behave when an urgent action is needed. Literature and industrial practice concerning corrective maintenance (CM) in floating offshore wind remains relatively limited. This is largely because of novelty of the technology and the still-limited number of operational floating wind farms, which makes real-world data collection and empirical model validation more difficult.

Most existing research focuses on fault prediction models or digital twins for early anomaly detection. For instance, condition-based and AI-driven predictive approaches are well-documented in recent studies such as [43], which emphasize how vibration analysis, SCADA data, and sensor fusion can forecast failures in gearboxes, blades, or generators. However, these models are designed for fixed-bottom offshore wind and do not take into account the operational challenges related to floating platforms, like increased motion, complex mooring systems or restricted accessibility.

Instead, corrective maintenance, has often been treated in the literature as a procedure to avoid, useful only when all preventive and predictive mechanisms fail. Yet in floating offshore wind, the presence of unexpected events because of severe metocean conditions, platform dynamics, logistical limitations makes corrective interventions likely and inevitable.

Furthermore, the cost and time review of corrective maintenance are often oversimplified in LCOE estimations. In reality, the cost of a corrective intervention at sea can change rapidly basing on:

- The season (weather windows, wave height, wind speed)
- The location (distance from shore, water depth)
- The type of failure (small repair, full component replacement)
- The type of strategy employed

In this context, this thesis introduces a novel perspective. Rather than attempting to eliminate all failures through perfect forecasting, the present approach acknowledges the inevitability of unplanned breakdowns in floating offshore environments and provides a seasonal, cost- and time-based model to quantify their impact.

This model contributes on the research about the maintenance of FOWTs for several reasons:

1. It allows project developers to account for unplanned events in the early feasibility study and financial planning phases of the project itself. This could help not only the developers to account for corrective maintenance interventions, but also for a smoother authorization process.
2. It helps to provide a starting point for the Opex assessment estimation on a single turbine and then on wind farm level.
3. It provides insight into corrective maintenance strategies, such as vessel limits or equipment required.
4. It provides a model and a way of thinking that is not based on the entire "typical" year, but on individual seasons. Showing the variability of costs and intervention times season by season.
5. It allows a comparison between the Mediterranean Sea and the North Sea, highlighting how the distance from the nearest port and the resulting weather and sea conditions influence maintenance costs and times interventions.
6. It provides a review based on hindcast approach and therefore, it accounts metocean conditions related to historical data, something that has already happened. As result, if a maintenance strategy is not feasible in the previous years, it will not be feasible in the incoming future. In contrast, if a maintenance strategy was successfully completed, therefore is very likely that it will be successfully completed in the next future. For sure under specific circumstances. However, the cost-effectiveness without excessive computational load represents the main benefit of the model analysed in the present work.

The present work contributes to shifting the paradigm: from seeing corrective maintenance as a marginality to recognizing it as an integrated part of the O&M section, which should be optimized and forecasted. Unlike most of the existing literature, which focuses almost to forecast failure, the present review brings attention to managing failure when it does occur: time, costs and successfully interventions.

Moreover, the use of a seasonal modelling approach increases innovation to the research. Many offshore O&M models assume average conditions across the year, whereas present methodology adapts to monthly metocean variability. This allows for more accurate downtime forecasting and smarter scheduling of unplanned interventions.

In summary, while the broader literature keeps developing advanced forecasting tools aimed to reduce failure impacts, there is a less developed frameworks for quantifying the real-world impacts of corrective maintenance in the floating offshore sector. The present thesis addresses this gap by proposing a comprehensive, seasonal cost-time model to manage properly unplanned failure by estimating average costs and downtimes.

2.1. The importance of maintenance for renewable energy technologies

Concerning of what has been discussed in the previous paragraphs, continuous monitoring and in-depth analysis of technologies play a vital role in ensuring operational efficiency, functional reliability, plant safety, and long-term economic and environmental sustainability. The same is valid for renewable energy technologies.

According to [15] the maintenance of renewable energy systems provides benefits from different point of view: economic, social and occupational. In the specific case of offshore wind turbines, the marine environment presents particularly harsh conditions: the combined effects of wind, waves, salt spray, and corrosion can accelerate component deterioration, leading to mechanical or electrical failures to which turbines are constantly exposed. For this reason, technicians have to inspect the system's moving parts at least one each year and according to manufacturer recommendations [16]. As a result, it is essential to implement sophisticated monitoring systems and predictive maintenance strategies to prevent downtime and ensure the safety of personnel. In contrast, in the photovoltaic sector, the environment in which panels operate is generally less aggressive; although they are subject to dirt, dust, or temperature fluctuations, the risks to structural integrity and safety are lower compared to offshore installations, with typically lower maintenance costs and failure rates.

Furthermore, careful and scheduled maintenance management of these systems allows postponing the repowering intervention, avoiding premature execution. This helps to contain costs, increase return on investment, and prevent unnecessary marginal expenditures.

Although these measures require higher initial investments, they enable a significant reduction in operational costs over the following years of these technologies. Such expenses certainly include the hiring of specialized and properly trained technicians, as well as the deployment of advanced sensor systems to monitor the performance of these renewable solutions.

This kind of approach ensures a high availability rate and a strategic point for making renewable sources competitive with conventional ones. In addition, a well-structured maintenance program ensures greater operational safety for these systems, enhancing their efficiency, performance, and longevity over time.

2.2. Corrective Maintenance: technologies, equipment and vessels

Corrective maintenance (CM) is a critical aspect when it comes to floating wind turbines. The issue goes beyond the failure itself, what really complicates things is the planning of the intervention: choosing how and when to act involves major logistical and operational challenges. As [13] mentions CM is necessary when the productive system is unable to work due to a failure. Although this type of maintenance involves relatively low initial costs, it still leads to unplanned downtime and additional damage and costs due to secondary failures affecting other components. Unlike bottom-fixed turbines, floating wind systems present completely different conditions, making corrective maintenance one of the toughest challenges in the field.

This is because planning a maintenance operation is closely tied to weather and sea conditions, which directly affect turbine accessibility. There is little room for improvisation, interventions must be carefully timed around favourable weather windows. As a result, specialized technologies, highly trained technicians, and a dedicated fleet of vessels are essential to carry out the work safely and effectively in such challenging environments.

Corrective maintenance operations in offshore environments involve a wide range of vessels and technologies, each designed for specific purposes and characterized by defined operability limits from significant wave height (Hs) and wind speed point of view. Even though, for each required vessels is necessary also to include mobilization times, availability and charter costs [17]. Below there is a list of the most common used vessels, along with a brief description of each one. A summary table is given at the end of the list to highlight the main features and operational limits of each vessel type. Following this, the main equipment used in floating offshore operations is presented with the same structure of the vessel one.

- **Crew Transfer Vessels (CTV):**
  As shown in the picture above, these kinds of vessels can be either monohull or catamaran types and are designed to transport technicians and light tools at relatively high speeds. Their main purpose is to support replacement operations and provide minor repairs, and inspections. However, due to their limited size and small deck space, CTVs are not suitable for transporting large equipment or a large amount of personnel.

Figure 3. Crew Transfer Vessel (CTV) typologies

- **Service Operation Vessels (SOVs) / Multi-purpose Vessels:**
  Unlike CTVs, SOVs are larger, as showed in the above figure; more advanced vessels able to transport more personnel, medium-to-large spare parts, and lifting equipment such as cranes. They can be used for both minor repairs and major replacement operations. As shown in the table, they feature less restrictive operational limits compared to CTVs, particularly in terms

of Hs and wind speed. However, their higher cost and significantly lower transit speed are important trade-offs to consider.

Figure 4. Service Operation Vessel (SOV) – Multi - purpose vessel

- **Helicopters:**
  Air transport is the fastest for offshore wind turbines access, since it is not constrained by wave height but only by wind speed. Nevertheless, helicopters are associated with high operational costs and limited availability. They are mainly used for small repairs and for transporting a few technicians with very light equipment.
- **Heavy Lift Vessels (HLV):**
  This type of vessel is used exclusively for the replacement of heavy components, such as generators, gearboxes, or entire nacelles. They are typically equipped with cranes capable of lifting very large loads and can also carry multiple large spare parts, making them suitable for supporting several maintenance operations on different turbines. However, HLVs have extremely high charter costs and are relatively scarce. As a result, due to their limited availability, they often need to be booked in advance, which can significantly increase both the cost and duration of a corrective maintenance intervention.

Figure 5. High Lift Vessel (HLV)

As mentioned at the beginning of the chapter, a summary table is given to highlight the main features and limits of these offshore maintenance vessels.

Feature	CTV	SOV	Helicopter	HLV
Hs (m)	2.5	3	-	5
Wind Speed (m/s)	20	25	15	25
Crew capacity	12-14	50	4	-
Fuel consumption (l/h)	320	1000	537	900
Charter Cost (€/day)	2.500	30.000	1.090 [€/h]	150.000
Speed (km/h)	45-50	13	250	23
Reference	[17][45][49]	[17][49]	[47][48]	[45][50]

Table 1. Vessel features

In the following section, as previously done for the different types of vessels, an overview is provided of the most advanced technologies and devices used in the corrective maintenance of FOWTs. These technologies are crucial, as they not only speed up the intervention process but also significantly improve safety and control. Unlike bottom-fixed wind turbines, floating turbines are subject to dynamic motions such as heave, pitch, and roll. As a result, it is essential that the vessel remains as synchronized as possible with the turbine's movements, enabling safe and efficient maintenance operations.

- **Dynamic Positioning (DP):**
  This system allows a vessel to keep a fixed position with high precision, even in the presence of waves, currents, and wind. It is based on a series of GPS sensors, gyroscopes, anemometers, and motion sensors that continuously detect the vessel's position as well as wind, wave, and current forces in real time. These data are processed by a central computer that constantly controls the thrusters to adjust and maintain the vessel's position. Different levels of Dynamic Positioning exist (DP1, DP2, DP3), depending on the required safety level and system

redundancy with the main purpose to provide the necessary stability and ensures safe access to the turbine during maintenance operations. For sake of simplicity, DP system is included in the charter cost of the vessel itself.

- **Motion-Compensated Gangways:**
  These gangways are able to let the direct access to the turbine and can either be temporarily installed between the vessel and the turbine or exist as permanent systems mounted on the turbine platform. Permanent installations are particularly useful for quick access during frequent inspections. Thanks to their motion compensation capability, these gangways are suitable for safe technician transfer and the movement of light equipment.
- **Offshore Cranes:**
  Offshore cranes are essential when heavy component replacement is required. They can be mounted on the vessel, on the turbine platform, or even temporarily installed on the nacelle to enable in-situ replacement operations, by avoiding the need for Tow-to-Port (T2P) strategies.

Feature	Offshore crane	Gangway
Rental Cost (€/day)	10.000	6.000
Reference	[53]	[54]

Table 2. Equipment features

2.3. Main failure types

Due to the factors discussed in the previous paragraphs, floating wind turbines are constantly exposed to harsh metocean conditions, which significantly increase the likelihood of failures and the need for planned corrective maintenance interventions. These failures can generally be classified into three main categories: mechanical, electrical, and structural.

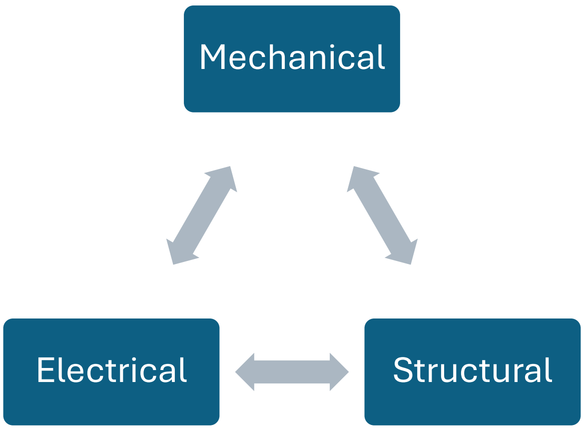


Figure 6. Main failure types

- **Mechanical failures:**
  These occur because of issues involving two or more moving parts in contact. They mainly affect drivetrain components such as gearboxes, bearings, and shafts. Common causes include

wear, lubrication problems, or misalignment. Particularly within the generator, potentially leading to overheating or, in more severe cases, a complete shutdown of the rotating machinery. Additionally, hydraulic leaks and actuator malfunctions are among the most frequent issues affecting the turbine's pitch system.

- **Electrical failures:**
  These are among the most common types of failures when dealing with technologies exposed to humid and salty environments, which cause degradation and corrosion, reducing the efficiency of the affected components. Moisture and salt particularly affect sensors, leading to malfunctions and communication losses that can result in unexpected shutdowns and false alarms. If not properly managed, such issues can lead to significant operational costs.
- **Structural failures:**
  Although less frequent, structural failures must not be underestimated, as they can lead to critical problems. The floating platform is constantly subjected to stress and fatigue caused by continuous wave motion. As a result, cracks or hull corrosion may compromise the structural integrity of the platform, potentially leading to a major failure.

Understanding these failure modes is very important to develop effective maintenance strategies, improving reliability, and minimizing downtime. For these reasons, communication and monitoring systems must always be regularly checked and fully operational, in order to avoid being caught off guard and to ensure timely and effective intervention when needed.

2.4. Current corrective maintenance strategies

Stated that FOWTs operate in harsh environments and are constantly subjected to stress and loads, the next paragraph analyzes the most recent strategies used to access the turbines in the context of corrective maintenance. As previously mentioned, traditional corrective maintenance strategies must be adapted to operate in deeper waters. However, also sea and wind conditions have to be involved to assess the turbine accessibility. Therefore, planning such interventions requires a careful balance between technical feasibility, safety, and cost-effectiveness.

Unlike bottom-fixed wind turbines, where the use of a jack-up vessel for major corrective maintenance operations is often convenient and safe, in the case of FOWTs it is necessary to account higher costs and extended intervention times. As operations move into deeper waters, the use of jack-up vessels becomes unfeasible. Consequently, traditional maintenance strategies must be adapted by incorporating the technologies mentioned in the previous paragraph. Therefore, the main approaches can generally be grouped into two categories: *In-Situ Strategies* and *Tow-to-Port*.

However, the choice between these two categories depends on several factors: the severity of the failure, the available weather window, vessel availability, and the distance from shore. For this reason, a hybrid approach is sometimes adopted. Minor repairs are handled through in-situ strategies, while major component replacements require a tow-to-port operation. Nonetheless, the latter is generally avoided whenever possible due to its high costs and extended time requirements.

2.4.1. In-Situ

In-Situ strategies involve all methods that allow maintenance interventions to be performed directly at the turbine's location. Specifically, access to the turbine can be achieved through three main approaches [21]:

- **the boat landing**, where technicians reach the platform ladders directly from the vessel at sea level;
- **the platform**, reached by an advanced motion compensated gangway and where technicians are to able to enter directly into the turbine tower;
- **the hosting platform**, which provides direct access to the nacelle.

In addition to aerial access, these strategies rely on the technologies previously described: dynamic positioning (DP), motion-compensated gangways, and offshore cranes. While the use of such technologies may introduce higher costs, in-situ strategies remain highly advantageous, especially in terms of reducing intervention time. For this reason, the methodological section of this work will focus primarily on this category.

These strategies are mainly used for minor repairs, but recent technological advancements have enabled their application in the replacement of larger components. One of the most notable in-situ interventions was carried out at the Kincardine project, where an entire generator was replaced in just under a month [22]. The main benefit of this approach lies in avoiding the need to disconnect and tow the turbine over long distances and significantly reduces both downtime and repair costs. However, this strategy is heavily dependent on metocean conditions and the size of the component to be replaced. Therefore, careful and well-controlled planning is essential to ensure successful execution.

2.4.2. Tow to Port

[23] This article deals with the main challenges posed by the Tow-to-Port (T2P) approach, leading to the core dilemma: *"Tow or not to Tow?"*. Tow-to-Port (T2P) strategy involves disconnecting the FOWT from its moorings and electrical cables, followed by towing it to the closest port for repair operation. This approach is preferred when dealing with the replacement of large components, where in-situ operations may be unsafe or technically unfeasible. It is typically applied in failures involving generators, gearboxes, or structural damage to the turbine.

A report published by ORE Catapult in 2024 [24] analyzes the feasibility of the T2P approach, using the Kincardine site as a reference. As shown in the corresponding figure, the process is divided into five main phases:

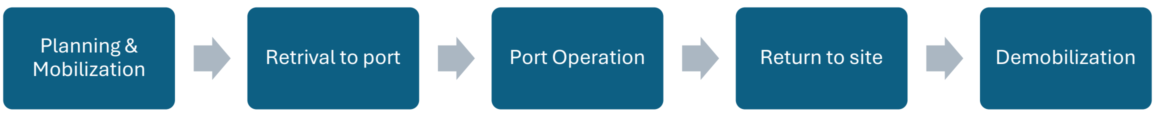


Figure 7. Tow to Port phases

After the Planning & Mobilization phase, the T2P operation begins with disconnecting the turbine from its electrical cables and mooring lines. The turbine is then towed to port using tugboats and CTV with specialized procedures, where it is berthed at a quay for maintenance and replacement activities. Once completed, the turbine is towed back to its offshore site and reconnected.

Although this method can be safer than in-situ operations, it presents significant challenges in terms of cost and downtime. A suitable weather window is still required both for the disconnection and reconnection phases, therefore it always depends on the metocean conditions. According to the report [24], the full T2P operation (excluding planning) may last just over one week; however, the Planning & Mobilization phase alone can extend up to 12 months, resulting in very long downtimes and high associated costs.

Therefore, while T2P remains a feasible and safe solution for the replacement of major components, it is not the most cost-effective or time-efficient option.

2.5. Existing Models for Maintenance Costs and Downtime Evaluations

This chapter will address the main and most recent O&M models related to the offshore wind sector. As floating wind technology progresses at a commercial scale, the need for increasingly accurate and reliable O&M models becomes more pressing. These models are designed to integrate various factors: environmental, economic, and technical, in order to provide realistic forecasts of performance and operational costs. The main question to answer is whether these existing and validated models should be adapted for FOW use or a new model should be created to include additional complexities of FOW [25].

The floating wind sector introduces significantly more complex and rigid variables compared to traditional bottom-fixed systems. In addition to requiring specialized vessels, it is essential to account for much harsher wind and sea conditions than those typically encountered nearshore. Moreover, the dynamic behaviour and loads experienced by floating turbines add further complexity. As a result, state-of-the-art models incorporate a wide range of parameters and simulation techniques to accurately reflect real-world conditions and achieve the highest possible levels of precision and reliability.

Among the main models and simulation methods, there are:

- **Petri Nets-based model:**
  These models can analyse complex dynamic processes by using graphical-mathematical tools such as Petri Nets. Thanks to their ability to represent failures, favourable weather windows, and resource availability as discrete events, they can effectively describe the sequence of activities. As a result, they help optimize the planning of maintenance interventions, aiming to minimize downtime and reduce bottlenecks. [44] is an application of the PN-based model in the offshore wind sector. Where through PN approach applied on 4 scenarios: no monitoring, SCADA, CMS, CMS & SCADA; a resulting economic analysis about the impact

of CMS on the cost of availability and on the availability of an Off-shore Wind Turbine is provided.

- **Monte Carlo simulations:**
  This approach is particularly useful for understanding the behaviour of failures and corresponding repair actions. Through stochastic simulations, it enables the analysis of highly complex scenarios, including failure probabilities, weather windows, and intervention times. As a result, it becomes possible to estimate operational costs, downtime, turbine reliability, and availability. These outputs are especially valuable for supporting maintenance strategies and for detailed planning of intervention activities. [45] is a demonstration of usefulness linked to Monte Carlo approach. Specifically, it defines a variability review on LCOE as a function of the AEP, Opex and both together, applied to two reference case studies: Hywind and Kincardine. In addition, for each case of study it provides a downtime study caused by the turbine component failures.
- **Markov Chain model:**
  This model is used to describe the evolution of the operational states of FOWTs over time. It enables the quantification of key O&M indicators such as availability and reliability. The model is based on the possible operational states of the turbine and the probabilistic transitions between them. When integrated with metocean conditions and available resources, it can support and optimize O&M strategies and allow for detailed planning of maintenance interventions. Alan Turnbull and James Carroll explore this approach in greater depth in their work [46]. Combined with the Monte Carlo method, their study provides an analysis of predictive and condition-based maintenance (CBM) strategies and their impact on operational expenditures (Opex). It examines four distinct scenarios, each featuring a different number of turbines and varying distances from the shore. The study also defines a baseline for O&M costs based on reactive maintenance and analyses deviations resulting from the implementation of predictive and CBM strategies. Finally, a sensitivity analysis is carried out on both Opex and lost production as a function of the distance from the coast.

Among the main tools used for planning O&M interventions, **hindcast models** are also included. This type of model will be described in greater detail in the following paragraph and will be the one adopted in the methodological chapter of this work.

In general terms, these models are based on several factors and their interconnection, as outlined in the figure below:

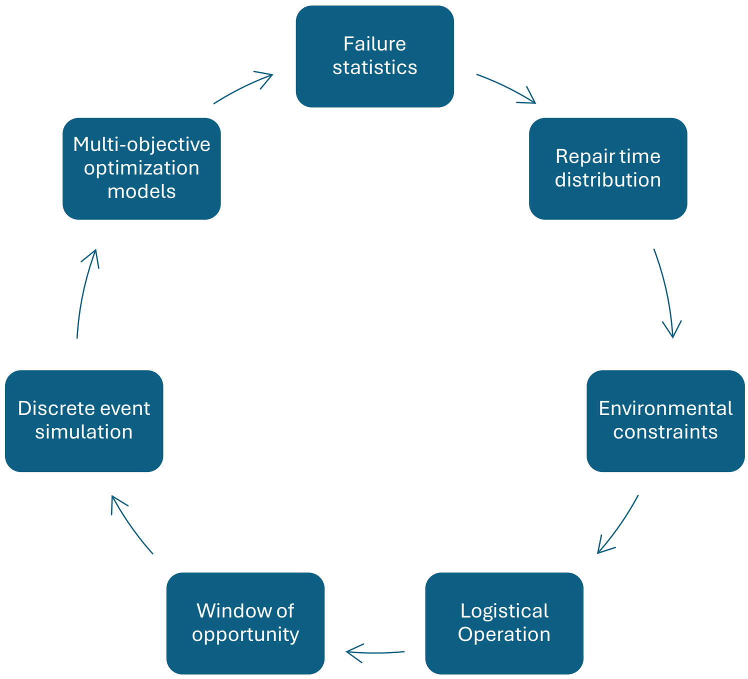


Figure 8. Hindcast model factors

2.5.1. Hindcast Model

As previously mentioned, the hindcast approach is one of the simplest yet most effective methods for modelling potential corrective maintenance scenarios in the floating offshore wind sector. The main steps defined by this model are summarized in the following steps:

Data acquisition: long-term metocean data, such as wind speed, wave height, current velocity; is collected from historical records or reanalysis datasets. These data build the model foundation.

Threshold definition: thresholds for vessels, access operation, and turbine components are defined based on safety and technical limits (e.g., maximum significant wave height or wind speed for safe access) to complete the maintenance interventions.

Availability window calculation: the model identifies time intervals, or weather windows, during which maintenance operations can be safely and effectively performed according to the predefined thresholds.

Failure simulation: based on failure rates, component reliability data, and probabilistic distributions, turbine faults are randomly generated within the simulation period.

Intervention modelling: for each simulated failure, the model selects the first available weather window for access and estimates intervention time based on vessel type, repair complexity, and resource constraints.

Cost and time evaluation: finally, the model calculates downtime, logistics duration, and total costs associated with each scenario, providing key performance indicators such as turbine availability, OPEX estimation, and maintenance efficiency.

By assuming a possible maintenance strategy with defined operational limits and adapting it to the metocean conditions of the specific site, it becomes possible to assess the effectiveness of the strategy in terms of both economic impact and technical feasibility.

This is particularly important for supporting key decisions related to the O&M of FOWTs. More broadly, as this technology becomes increasingly commercialized, there will be a growing need for realistic models capable of enhancing its competitiveness and reliability.

2.6. Operational Expenditure (Opex) in Floating offshore wind

In the context of the global energy transition, floating offshore wind energy represents one of the most promising technologies for large-scale renewable power generation. However, despite growing industrial and institutional interest, one of the main barriers to the full maturation of this technology lies in the operational costs. Operational Expenditure (Opex) includes all expenses related to the operational phase of a floating wind farm's lifecycle, including maintenance. These costs play a critical role in the economic assessment of projects and directly impact the profitability and competitiveness of the technology in interest.

Floating wind turbines are built in deep waters, where metocean conditions can be harsher and accessibility more challenging. This results in greater uncertainty and variability in operating costs, making accurate planning and optimized maintenance strategies essential. In particular, corrective maintenance can lead to significant unplanned expenses, both in terms of technical intervention and revenue losses due to turbine downtime.

In recent years, increasing focus has been directed toward analysing and optimizing Opex to improve system reliability and reduce the Levelized Cost of Energy (LCOE). In this context, the integration of digital technologies such as condition monitoring, predictive diagnostics and frequent inspections is playing an increasingly important role. Nevertheless, effective Opex management also requires a deep understanding of contractual frameworks and the availability of vessels skilled personnel.

In summary, the management of Opex is a critical component in the development and operation of floating offshore wind farms. An accurate approach to its analysis can significantly contribute to the technical and economic sustainability of the sector, supporting the scalability of the technology and its integration into the future energy mix.

The present paragraph discusses the main drivers that mainly affect Opex of the floating offshore wind farm. In particular, details are given about metocean conditions, vessel availability and port facilities and maintenance strategies manly adopted. In this way, the impact on the overall LCOE will be showed.

2.6.1. Main Opex drivers in Floating Offshore Wind

Operational expenditure (Opex) in floating offshore wind systems is influenced by a wide range of interconnected factors: technical, logistical, environmental. As this emerging technology keep evolving and scale, understanding the economic dynamics that work underneath its operational phase becomes increasingly critical, not only for developers and operators but also for investors, policymakers, and other stakeholders involved in the renewable energy transition.

Unlike, traditional offshore wind farms based on fixed-bottom foundations, floating offshore wind systems are typically installed in deeper waters, further away from shore and in regions where metocean conditions are more severe and changeable. These features, while opening access to vast wind resources, previously inaccessible, also introduce a unique set of challenges that have an important impact on the overall cost structure of the project. In particular, during the operations and maintenance (O&M) phase. The increased distance from shore complicates logistics, while exposure to severe sea and wind state increase technical risk and affects accessibility for maintenance interventions. As result, floating wind farms tend to show Opex profiles that differ significantly, both in magnitude and variability, from their fixed-bottom counterparts.

Operational expenditure represents all ongoing costs related to lifetime operation of a wind farm, without including capital expenditure (Capex) required for installation and commissioning. These operational costs include, but are not limited to, routine and corrective maintenance, vessel chartering, spare parts management, insurance, environmental monitoring, personnel and remote diagnostics. Given the long-term nature of wind farm operation, the cumulative effect of Opex on the project's financial viability is remarkable. Therefore, identifying and thoroughly understanding the main drivers that influence these operational costs is essential in both the design and strategic planning phases of floating wind developments.

A detailed evaluation of Opex drivers is not only important for financial modelling but also for resource planning and supply chain management. These drivers can affect the frequency and cost of interventions, the downtime of individual turbines and the long-term reliability and lifetime of critical components. Moreover, they influence the overall Levelized Cost of Energy (LCOE) and by reducing the LCOE is a major goal across the renewable sector and in floating offshore wind, it cannot be achieved without optimizing installation costs, but also Opex. This highlights the relevance of a dedicated analysis focused on operational drivers.

This section introduces the first three categories of factors that have an impact in shaping the operational expenditure of floating offshore wind: metocean conditions, vessel availability and port facilities, and maintenance strategies. The first driver, **metocean conditions**, involves the sea and wind state parameters that characterize the environment in which the wind farm works. These include wave height, wind speed, sea state, current profiles and temperature variations. For the purposes of this study, particular emphasis has been placed on significant wave height (Hs) and wind speed at 100 meters, since these variables are commonly used to evaluate site accessibility and operational limits. The severity and variability of metocean conditions can directly affect the frequency and feasibility of offshore access, thus playing a central role in determining both planned and unplanned maintenance costs.

The second category of influence, referred to as **vessel availability and port facilities**. Maintenance activities, whether scheduled or corrective, require reliable access to specialized vessels capable of operating safely in challenging offshore environments. In addition, the proximity and capabilities of onshore port infrastructure significantly affect operations from technical and economic point of view. In this analysis, a simplifying assumption has been made that vessels, spare components, and qualified personnel are always available when needed.

The third and final driver introduced here is related to **maintenance strategies**, which define the operational procedures guided by intervention planning, asset monitoring, and fault management. Whether relying primarily on corrective actions, preventive scheduling, or advanced predictive systems, the chosen strategy direct impact on operational costs. In the context of floating wind, where system complexity is higher and access is more limited, selecting an appropriate maintenance approach is vital for achieving cost control and long-term asset integrity.

These factors do not act in isolation; instead, they are often interdependent. For instance, severe metocean conditions can limit vessel availability, while an optimized maintenance strategy may help to mitigate the impact of logistical delays. Therefore, a comprehensive understanding of these drivers, and their interaction, is an important step toward improving the economic sustainability of floating offshore wind technology.

In conclusion, as floating offshore wind keeps growing, managing operational expenditure becomes a key enabler of commercial viability. By identifying and analysing the main cost drivers, project developers and operators can enhance their decision-making processes, reduce uncertainty, and build more resilient, cost-effective offshore energy systems.

2.6.2. Metocean Conditions

One of the most critical drivers of operational expenditure (Opex) in floating offshore wind is the combination of wind and sea state at the site, commonly referred to as metocean conditions. These environmental parameters not only influence the energy yield of the wind farm but also have a direct and significant impact on the feasibility, downtime and cost of operations and maintenance (O&M) activities. As floating offshore wind farms are typically located in deeper waters and more remote marine environments, often subject to severe weather conditions, the role of metocean factors becomes even more relevant in shaping the overall operational strategy.

Metocean conditions involve a broad set of parameters that describe the physical state of the ocean and the atmosphere at a given location. The most considered are significant wave height (Hs), wind speed, wave period, wave direction, current speed and direction, air and sea surface temperature, and visibility conditions. Although these parameters affect turbine performance, are also responsible for offshore accessibility which is a key factor in the scheduling and execution of corrective maintenance interventions.

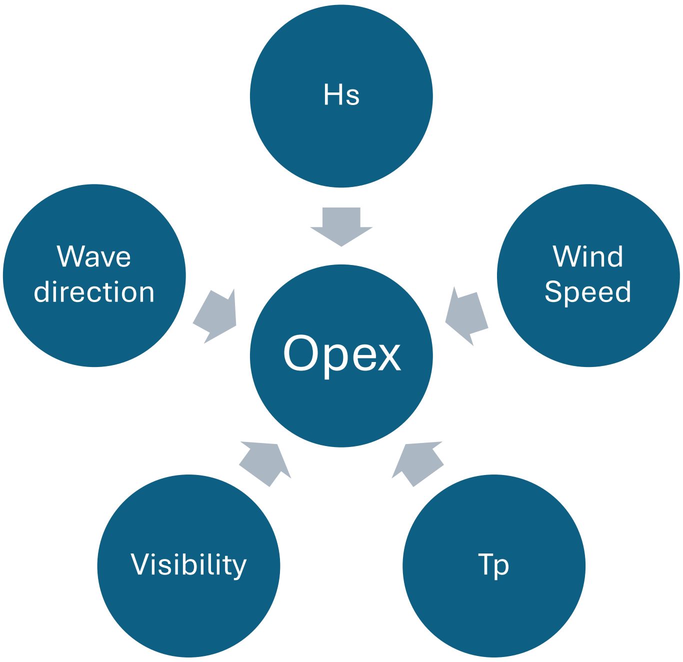


Figure 9. Opex Metocean Coditions factors

Even short periods of adverse metocean conditions can result in delayed vessel deployment, extended downtime, and increased costs due to rescheduling, charters, or lost production. For this reason, access windows are often defined based on strict metocean thresholds, and understanding the statistical distribution of these variables is essential to model Opex accurately.

In this study, particular attention is given to two metocean parameters that are widely recognized in the literature: significant wave height (Hs) and wind speed at 100 meters above sea level. Even thought more attention is given to visibility conditions as reported in [12], where limited visibility is shown to be highly relevant with a reduction of up to 60% in accessibility.

Significant wave height (Hs) represents the average height of the highest one-third of waves over a specific time period and is a crucial parameter in assessing sea state severity. High Hs values limit the ability of maintenance vessels, for this reason, including in this review, every vessels present a threshold. When wave heights exceed predefined operational limits (typically ranging from 1.5 to 4 meters depending on vessel type), offshore access is either delayed or cancelled, which can lead to prolonged turbine downtime. Moreover, excessive wave motion can compromise the stability of floating platforms and introduce additional safety risks for personnel during transfer or on-board operations.

Wind speed at 100 meters, which corresponds to the hub height of most offshore wind turbines. While wind is the primary source of energy generation, excessive wind speeds can make helicopter operations unsafe and increase the difficulty of performing certain maintenance tasks at height. Additionally, wind gusts have to be considered, which can exacerbate dynamic loading on turbine components, complicating the repair window. Many maintenance protocols define a maximum wind speed threshold—often around 15–20 m/s—above which operations are postponed for safety reasons.

Although other parameters such as wave direction, current speed, or visibility conditions can also influence offshore interventions, Hs and wind speed at hub height remain the most influential when it comes to defining safe and operable weather windows. For floating offshore wind, where platform motion is more pronounced and operations are more sensitive to dynamic sea states, these two variables are particularly important in determining when, how, and at what cost corrective maintenance can be performed.

2.6.3. Vessel availability and port facilities

A second major factor influencing Opex is the availability of suitable vessels and the supporting port infrastructure. Due to the complexity and scale of floating offshore wind turbines, maintenance operations often require specialized vessels, such as heavy-lift ships and dynamic positioning (DP) vessels, like CTV and SOV, able to operate safely in open sea conditions. The availability of these vessels, in terms of both quantity and scheduling, can highly influence the reactivity and efficiency of corrective interventions.

In this study, a simplifying assumption is adopted: vessels, spare components, and technical personnel are always available when needed. Although, this assumption removes a layer of uncertainty from the model, it is important to recognize that in real-world scenarios, logistical constraints often lead to significant delays and increased costs.

Port facilities also play a fundamental role in supporting offshore operations. Deep-water ports with adequate cranage capacity and storage space are relevant for efficient component handling and pre-assembly work. Their distance from the wind farm site is another critical variable, as it directly affects transit times and fuel consumption, all of which contribute to Opex. In particular, distance from the closest port is a crucial variable which is included in the sensitivity analysis in the methodology chapters. Therefore, even though availability factor is treated as ideal in this analysis, its critical role as an Opex driver is recognized and further discussed in the dedicated section of the thesis.

2.6.4. Maintenance strategies

The third main driver of Opex in floating offshore wind is about maintenance strategies adopted to make intervention among the FOWTs. Corrective maintenance is the focus of this thesis, involves unscheduled interventions following the detection of faults or failures. It is often associated with high costs due to its reactive nature, the urgency of interventions, and the potential for prolonged downtime before repairs are executed. The selection of a maintenance strategy influences not only the frequency and type of interventions but also the organizational structure: spare parts inventory and data infrastructure needed to support operations. In the context of floating offshore wind, corrective maintenance includes additional challenges because of increased motion of the platform and higher exposure to environmental loads. Therefore, maintenance strategies must be designed to account every single possible factor which can make more complex and riskier. A poorly planned maintenance strategy can significantly increase Opex, reduce accessibility and negatively impact asset lifetime. On the other hand, a well-planned corrective approach, supported by rapid fault detection and swift response mechanisms, can involve costs and improve operational efficiency; specifically, when coupled with favourable metocean conditions and effective logistical support.

Since floating wind turbines are often located far from shore, every maintenance activity involves extensive logistical coordination and weather window planning. As a result, any delay in response or inefficiency in the maintenance approach can result in days or even weeks of lost production, which turns directly into increased Opex.

In addition, one of the most relevant aspects which is influenced by maintenance strategies is accessibility. For instance, if a failure occurs and the strategy in place does not allow for quick diagnosis or pre-positioned spares and vessels, the lost production window could be significantly longer, even if the metocean conditions are favourable. Conversely, if the strategy is robust, efficient and well-planned then the same accessibility window could be used more efficiently, reducing downtime and ultimately lowering Opex.

The cascading effect of an inefficient maintenance strategy should not be underestimated. For example, a failure to respond promptly to a small issue, like an abnormal vibration in a generator, could lead to a critical failure, requiring a full generator replacement. This type of escalation not only increases direct repair costs but can also monopolize vessel and crew time, creating a bottleneck for other planned interventions. Such compounding effects are a key contributor to rising Opex in floating wind, and a clear indicator of the importance of integrated and pre-emptive maintenance planning.

Moreover, the operational constraints in floating offshore environments, such as dynamic platform motions, more complex anchoring systems, and greater exposure to corrosion and fatigue, demand higher attention to the timing, coordination, and risk assessment of maintenance tasks. Strategies that do not take these realities into account can lead to repeated interventions, inefficiencies, and safety issues, all of which contribute to increased operational costs and decreased turbine availability.

It is also important to consider that in floating wind, the scale of the project and the fleet size influence how much flexibility an operator has in maintenance planning. In small-scale demonstration projects, corrective strategies might be tolerable. However, in utility-scale floating wind farms with dozens of turbines, corrective-only approaches can lead to unmanageable levels of downtime and exponential increases in Opex.

In conclusion, while corrective maintenance remains the focus of this thesis, the broader implications of maintenance strategy selection are central to understanding and controlling Opex in floating offshore wind. A reactive approach that is not supported by adequate planning, logistics, and monitoring capabilities can severely limit turbine accessibility and increase operational costs. Conversely, a well-structured corrective maintenance strategy, aligned with reliable metocean forecasting, flexible resource allocation, and robust response protocols, can mitigate these impacts and improve the long-term economic sustainability of floating wind farms.

2.6.5. Impact on the overall LCOE

The Levelized Cost of Energy (LCOE) is a widely adopted metric used to assess the average cost of electricity generation over the full operational life of an energy-producing technology. According to the following general equation, it represents the ratio between the total costs (Capex, Opex, decommissioning) and the total energy output delivered to the grid, typically expressed in €/MWh.

$$LCOE = \frac{Capex + Opex + Decommissioning\ Costs}{Total\ Energy\ Produced}$$

In the context of floating offshore wind, which is still an emerging and capital-intensive technology, controlling the LCOE is crucial for ensuring competitiveness against both traditional fossil fuels and other renewable energy sources. In particular, according to [36] LCOE decreases with a higher number of turbines with increased rated power. In addition, the same paper shows how LCOE changs according to geographic location: Canary Islands 100 – 135 €/MWh, Galicia and Cataluña 105 – 160 €/MWh, Andalucia 135 – 140 €/MWh. Instead, according to [37], lowest LCOE correspond to the areas where the wind resource is most abundant: off Great Britain, Ireland and in the North Sea. Specifically, in the North Sea LCOE reaches 95-135 €/MWh and the distance to shore is found to be the main variable affecting the LCOE [37].

Although recent floating offshore wind projects have been characterized by high capital expenditure (Capex), the contribution of Operational Expenditure (Opex) to the overall LCOE becomes increasingly relevant over time. As the technology matures, Capex is expected to decrease due to standardization, but in this scenario, Opex remains a critical variable.

Opex includes all recurring costs related to operations, maintenance, logistics, asset monitoring, personnel, and insurance throughout the 20–25 year lifecycle of a typical floating wind farm. Even relatively small inefficiencies in the operational phase can accumulate and significantly raise the total cost of energy produced. Moreover, due to the remoteness and environmental complexity of floating wind installations, Opex in this sector tends to be higher than in fixed-bottom offshore wind and much more sensitive to site-specific conditions.

The long operational life of floating wind farms influenced the cumulative effect of Opex on LCOE. Unlike Capex, which is a cost concentrated at the beginning of the project, Opex is incurred every year, meaning that inefficiencies or unexpected cost can progressively damage the financial performance of a project. In some scenarios, especially in severe offshore environments, Opex can account for up to 25–35% of the total LCOE [35], making its management a priority for project developers and investors.

Corrective maintenance, vessel chartering, downtime-related energy losses, and insurances are some of the largest contributors to Opex. Each of these is influenced by external drivers and by internal choices, such as maintenance strategy and asset design. In particular, unscheduled interventions can lead to extensive turbine downtimes, during which no energy is produced, but costs for repairs are always present. This results in a double negative effect on the LCOE: increasing the numerator (costs) while simultaneously decreasing the denominator (energy produced).

In addition, floating offshore wind turbines are subject to higher dynamic loads due to wave-induced motions and more complex mooring systems, which can increase the likelihood of component fatigue or failure over time. This translates into more frequent and costly maintenance needs, particularly when strategies rely on corrective rather than predictive or preventive approaches.

An important dimension of Opex's impact on LCOE is also its variability and uncertainty. While Capex can often be estimated with a high degree of accuracy, Opex is more difficult to predict, especially in floating wind where operational experience is still limited. This uncertainty leads to higher perceived project risk, which can result in higher financing costs.

Therefore, proactive Opex management is essential for achieving long-term cost reduction targets. This involves improving accessibility through smarter vessel planning, integrating digital condition monitoring to enable earlier fault detection and designing wind farm layouts and logistics around realistic metocean windows.

3. Methodology: purpose and structure

The following chapter introduces the methodological framework adopted in this study, aiming to provide a comprehensive understanding of the approach used to evaluate the seasonal impact of corrective maintenance strategies. The methodological process is structured to understand the sequence of technical and analytical assumptions made during the development of the review, by starting from the problem definition to end up with full comprehension of the results.

Given the increasing interest in floating wind energy as a correct solution for deep-water wind exploitation, the need for an established model of maintenance-related operational expenditures has become vital. Although, some models are available for the Opex estimation, they often involve high computational costs and require several input parameters. In fact, corrective maintenance represents one of the most critical and cost-intensive aspects of offshore operations. The difficulty in accessing turbines, the seasonal variability of metocean conditions and the lack of standards for floating structures introduce additional challenges that must be accounted in the planning maintenance interventions and in the resulting economic assessment.

This chapter highlights the main objectives of the work, with a specific focus on developing a simplified and basis methodology able to estimate the seasonal average costs and times related to corrective interventions. In addition, a post-processing analysis is carried out to estimate the annual Opex related to the corrective maintenance and In-Situ approach employed to the chosen components.

This study proposes a pragmatic solution to predict the seasonal costs and times based on hindcast model of metocean data and component-specific in-situ strategies. The model is designed to be replicable to the other turbine components as long as they are characterized by the same corrective maintenance strategy. Moreover, it can be adapted to different case of studies and different turbine types.

In this review the methodology is presented specifically for two critical components: **generator** and **pitch system**. In particular, as shown in the figure below the first paragraphs are focused on three different but connected layers: component, maintenance and strategy.

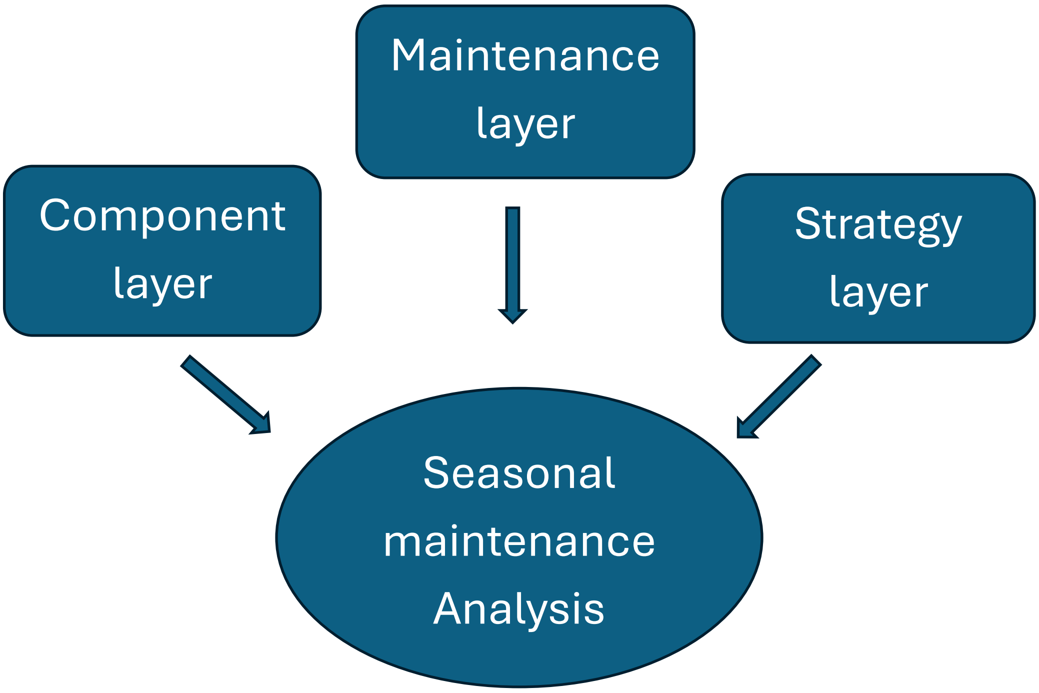


Figure 10. Seasonal maintenance analysis structure

Once the starting points are defined, the core description of the analysis is described, highlighting the assumptions made, the model input and the expected results. Furthermore, the review is tested to three different wind farm sites: two in the North Sea, one in the Mediterranean Sea to perform a sensitivity analysis and to evaluate the metocean condition influence.

Finally, a starting point approach to estimate the annual Opex related to corrective maintenance is presented by post-processing the results obtained by the hindcast-based model.

3.1. Component layer

The component layer focuses on the analysis of the specific components selected for this study. As illustrated, it explains the reasons behind the Pitch System and Generator selection with the failure categorization into small repairs and replacements.

Figure 11. Component layer structure

Specifically, this starting layer was particularly challenging, as it involves the specific collection of data for the various components of the turbine. This data collection was carried out by reviewing multiple databases and scientific papers reporting the annual failure rate by component. However, since floating wind is still an emerging technology, the amount of publicly available data remains limited. Furthermore, many companies that hold such information tend to keep it confidential, making this phase of the analysis particularly challenging and hard-working.

As a first step, the turbine was divided into functional modules, each containing multiple components. This modular breakdown helped to provide a clearer picture of the system and allowed the identification of most critical elements. In particular, the following table shows the modules, the components associated and the annual failure rate basing on several papers and databases.

Component	Failure Rates										
	[29]	[30]		[31]	[32]	[33]		[34]			
		HyWind	Kincardine			SPARTA	Strathclyde	Strath Off	Huadian	LWK	CIRCE DD
Converter	-	3%	2%	3%	3%	6%	2%	2%	17%	0%	14%
Generator	13%	13%	11%	18%	3%	3%	9%	9%	11%	6%	5%
Pitch System	14%	15%	12%	20%	9%	7%	10%	10%	9%	4%	1%
Blades	5%	7%	5%	9%	1%	7%	5%	5%	2%	8%	2%
Yaw System	3%	3%	2%	3%	20%	4%	2%	2%	2%	5%	6%
Gearbox	4%	-	7%	12%	7%	5%	6%	6%	7%	10%	-
Electrical components	14%	24%	19%	31%	39%	17%	15%	14%	32%	23%	40%
Mooring System	34%	12%	13%	-	-	-	-	-	-	-	-
Floating Foundation	30%	1%	11%	-	-	-	-	-	-	-	-

Table 3. Failure rate statistics

As shown in the table above, the selected components are those with the highest annual failure rates. In addition to the Generator and Pitch System, electrical components also exhibit a high failure frequency. However, their analysis was excluded from the corrective maintenance assessment, as they involve significantly different intervention strategies and procedures compared to the other two systems.
Moreover, due to the still emerging nature of the technology, maintenance practices for electrical components are still less consolidated. Instead, for what concerning the Underwater Module (Mooring system and Floating foundation), the available data turned out to be too less and scattered to carry out a reliable analysis.

As the second step and based on [26], failures were classified into two main categories: small repair and replacement. In addition, [26] introduces a further distinction between Small Replacement (less than 2000 kg) and Large Replacement (more than 2000 kg). However, since the corrective maintenance strategies for both types are basically the same, this study chose to treat replacement in a general sense, while keeping the same category of small repairs.

3.2. Maintenance layer

The maintenance layer covers all aspects related to the type of maintenance adopted in this work. In particular, it focuses on the selected maintenance approach and the choice of corrective strategies, providing a complete description of each one. This section also highlights the reasons behind these decisions and the assumptions made throughout the development of the analysis.

Figure 12. Maintenance layer structure

As discussed in the previous chapters, the current literature still lacks extensive data and consolidated insights regarding corrective maintenance in the sector of Floating Offshore. This is likely because such interventions are generally avoided whenever is possible, with a preference for preventive or predictive strategies. However, when not properly managed, corrective maintenance can lead to significant downtime and high operational costs, especially regarding the offshore environment.

3.2.1. In-Situ strategy definition: small repair and replacement

In this work, the focus is on the In-Situ approach, meaning that maintenance interventions are performed directly at sea. This decision is based on two key points: the aim to estimate costs and downtimes related to FOWTs intervention and on the other hand, the limited logistical feasibility of T2P, especially for sites located far from shore. In fact, Tow-to-Port involves fully disconnecting the turbine, towing it to port, performing the intervention onshore, and re-deploying it at sea; often resulting in higher costs and downtimes compared to on-site operations.

In addition, the In-Situ approach allows maintenance to be carried out directly at the installation site by using specialized equipment such as DP (Dynamic Positioning) vessels, motion-compensated gangways, and other offshore access technologies. Although, this approach requires a stable operational window, characterized by favourable weather conditions, it is able to minimize costs and particularly downtimes.

The maintenance strategies adopted in this study are classified according to the type of failure analysed, but are the same for both components under investigation. These strategies include vessels and equipment that are realistically employed in major offshore operations, ensuring a practical and feasible maintenance scenario. The following table presents the selected strategies, identified also based on operational experience, which will be employed for the upcoming seasonal analysis.

Generator & Pitch System CM strategy	
Small Repairs	**Replacements**
CTV + Gangway	HLV + Crane
SOV/Multipurpose vessel + Gangway	SOV + Crane + Support CTV
Helicopter	

Table 4. Generator & Pitch System CM strategy

The selected strategies are the result of a combination of sources: analysis of real offshore case studies, review of currently used technologies, and engineering assumptions based on realistic and replicable scenarios.

For Small Repair strategies, in addition to sea-based access, the helicopter option was also considered. This choice is supported by several reasons: first, the speed of intervention, which significantly reduces waiting times, especially when dealing with narrow weather windows. Moreover, helicopters are particularly effective for the quick transport of technicians and light tools, especially in the case of localized failures that do not require heavy lifting equipment.

As for the Replacement strategies, they include the use of both SOV (Service Operation Vessel) and CTV (Crew Transfer Vessel). This combination reflects a real operation successfully carried out for Kincardine site, as mentioned in the article [27]. Additionally, a HLV (Heavy Lift Vessel) is considered, a large ship typically used in the oil & gas industry, ideal for replacing large components thanks to its stability and high lifting capacity in open sea conditions.

3.3. Strategy layer

The Strategy Layer represents the third and final level of the methodological framework adopted in this work. Once the strategies have been defined and justified, this section focuses on their detailed analysis. Each strategy is broken down into several operational phases, with a description and a specific cost and estimated duration.

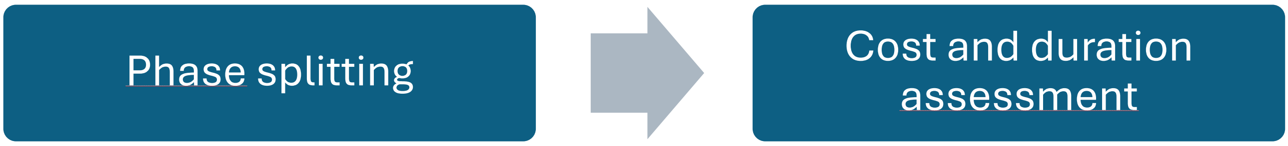


Figure 13. Strategy layer structure

This step allows for a realistic modelling of the maintenance intervention, providing a more accurate representation of seasonal analysis.

3.3.1. Phase splitting: cost and duration

The operational phases considered are the same among all strategies. However, what may differ from one strategy to another is the specific description of each phase, as well as its duration and associated cost.
These variations become especially significant when distinguishing between Small Repair and Replacement, since both the vessels used and the equipment required for the intervention change.

Based on the considerations above, each strategy is divided into four main phases provided by a readaptation of [24]:

- Failure reception,
- Mobilization,
- Repair window,
- Commissioning.

An additional return phase is also considered, which account the return of vessels back to port, but only for cost evaluations. From time point of view, it is assumed that the turbine is already back online once the commissioning phase is completed.

The operational phases of each maintenance strategy are derived from real-world offshore experience and assumption, which reflect the typical sequence of a corrective intervention. Below there is a description of the four main phases with a summary table at the end of each phase to resume their description and cost typology.

1. Failure Reception

This phase involves fault detection through the SCADA system, followed by communication with the O&M team and scheduling of the repair/replacement intervention. It also includes vessels charter and required equipment, as well as the overall logistical preparation. Moreover, this phase includes also all the installations at port like crane installation, especially for replacement. This step is important to coordinate a timely response and aligning the intervention with suitable weather windows.

Phase	Description
Failure Reception	SCADA alarm, communications, repair/replacement scheduling, vessel charters, equipment charter, crane installation, gangway installation

Table 5. Failure reception phase

2. Mobilization

This refers to the transfer of the vessel(s) from the closest port to the turbine site. The distance to the site, metocean conditions, and vessel speed all affect the total mobilization time. Even though this phase involves the higher fuel consumption with a resulting impact on costs as well.

Phase	Description
Mobilization	From closest port to site location

Table 6. Mobilization phase

3. Repair Window

This is the most operationally intensive phase. It includes:

- Gangway installation for safe offshore access,
- Transfer of personnel from the vessel to the floating platform,
- Ascent to the turbine nacelle,
- The actual repair time (based on technical literature and field data),
- The return process from nacelle to vessel,
- Gangway deinstallation.

Instead, regarding replacement actions, this phase involves lifting and lowering damaged/new components from nacelle to the HLV's (or SOV) deck and viceversa. This phase is highly sensitive to metocean conditions and must be planned within an appropriate operational window. In addition to the costs related to charters and technicians' salary, this phase includes also a rate of fuel consumption. This percentage is given in order to account the fact that vessel during operation keep consuming fuel because of DP and to maintain the position.

Phase	Description
Repair/Replacement window	Offshore gangway/crane installation, vessel to platform transfer, platform to nacelle transfer, effective repair/replacement time, turbine exit procedure, return to vessel, gangway/crane deinstallation

Table 7. Repair/Replacement Window phase

4. Commissioning

Once the repair is completed, the commissioning phase begins, involving the restarting of the turbine and a series of functional tests to check the repair or the replacement action. Just following these testes the turbine is considered back online.

As mentioned before, there is a 5^{th} phase which describes the return of vessels back to port. This phase is not included from a time point of view, since turbine is back online. However, it is considered from a cost point of view, to evaluate consumed fuel and relative cost to go back to the port.

Each of these phases is modelled through Matlab software and are specifically characterized by a proper limit on Hs and wind speed (at 100 m). Moreover, the definition of this layer is essential to get an accurate simulation of the real world.

Phase	Description
Commissioning	Testing

Table 8. Commissioning phase

3.4. Seasonal corrective maintenance analysis

Following the way to select the components under investigation and the definition of maintenance strategies, now the treatment focuses on the core of the work. This paragraph discusses the seasonal corrective maintenance analysis, specifying every single steps, choices and assumptions made.

The decision to perform a seasonal-based review starts from the analysis of a representative "typical year." This typical year was defined by calculating the monthly averages of hourly metocean data, specifically significant wave height (Hs) and wind speed at 100 meters above sea level. In more detail, data are provided by website LAUTEC | ESOX [51] for Mediterranean Sea at coordinates 37°32'36.6"N 11°57'20.1"E, where 7SeasMed project is located and referred to years 1990 – 2019.

As illustrated in the corresponding figure, there is a clear and marked variation in environmental conditions across the different months and seasons.

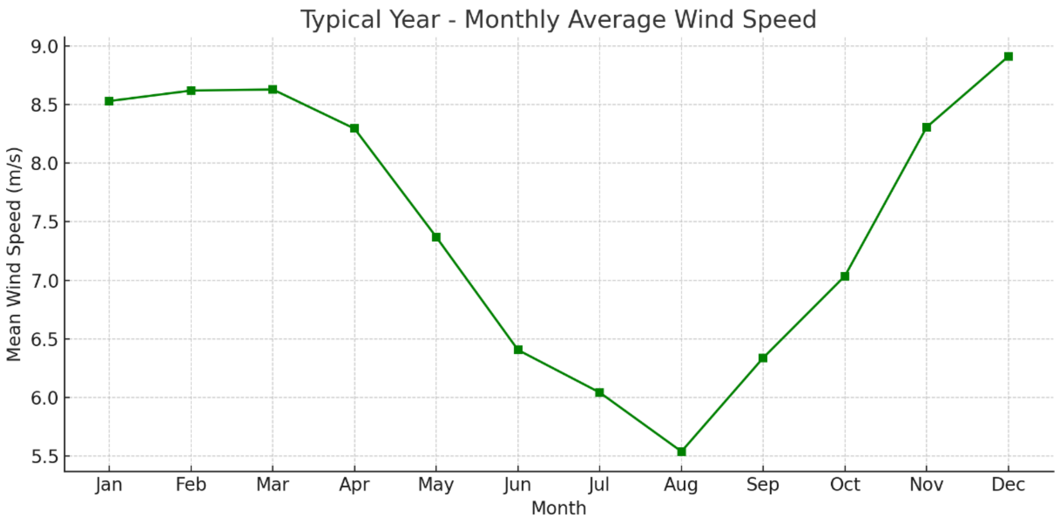


Figure 14. Monthly average wind speed - Typical Year

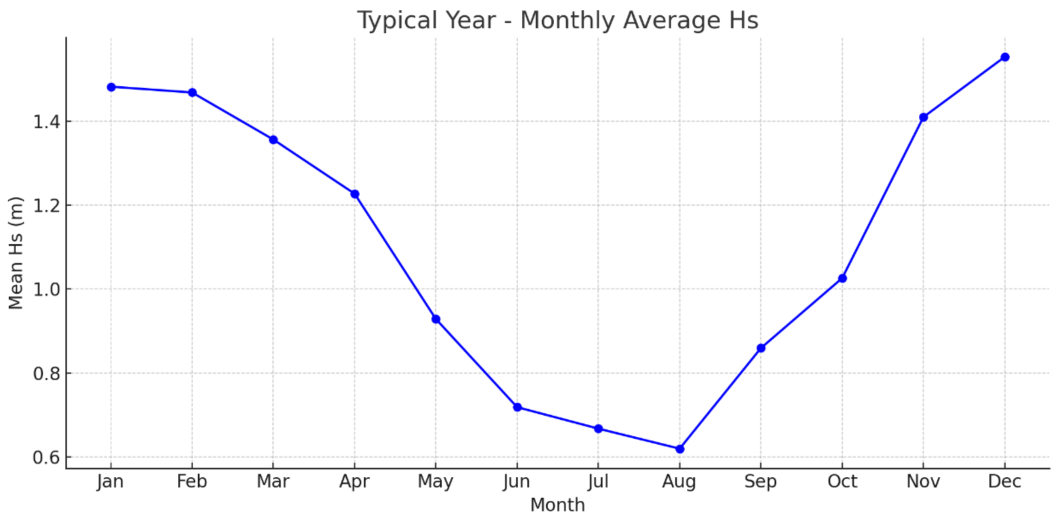


Figure 15. Monthly average Hs - Typical Year

Winter consistently presents the most severe metocean conditions, often limiting access to offshore sites and increasing the likelihood of component failures. In contrast, summer is characterized by milder conditions, which are more favourable for planned maintenance or installation activities. Spring and autumn tend to show intermediate trends, depending on their proximity to the winter or summer terms.

This approach allows for a reliable seasonal categorization of data, providing a solid basis for the development of seasonal corrective maintenance models. As evidenced by the data trends shown in the figures, such seasonal segmentation enables not only a more detailed operational analysis, but also forms the foundation for aggregating results into a comprehensive annual assessment.

Moreover, this trend becomes even more pronounced when analysing offshore sites located in the North Sea, where environmental conditions are much harsher and more changeable.

The main goal of this section is to describe the replicable model able to assess the seasonal impact of corrective interventions in terms of costs, intervention times and success rate, based on historical metocean data.

The starting point of the analysis is that offshore environmental conditions — specifically significant wave height (Hs) and wind speed at 100 meters — directly affect the operational feasibility of each strategy.
For this reason, the model is built on ERA5 historical data from three different offshore sites, aiming to evaluate how downtimes and costs varies across different seasons. In addition, there is the estimation of costs and downtimes related to each season and how they vary across the different sites. In this way a comparison among the different sites gives a general overview on how costs and downtimes differ between North Sea and Mediterranean Sea. This is a sort of sensitivity analysis based on the variation of metocean conditions and on the distance site-port according to the site selected.

The analysis is not limited to estimate the seasonal costs and downtimes of a single component. Instead, it aims to extend the methodology to the entire rest of the turbine components characterized by the same corrective maintenance strategies and therefore the entire wind farm. As result, despite its simplified structure, the proposed approach provides valuable insights to support Opex forecasting, resource planning, and optimization of corrective maintenance operations in the floating offshore wind sector.

The following paragraphs will discuss about the description of the model itself, empathizing inputs, assumptions and outputs.

3.4.1. MATLAB model description

The entire analysis presented in this review is developed by using MATLAB programming language. In this way, it was possible to calculate the main outputs of interest: average costs, average intervention times, average waiting times, and number of successfully completed operations.

This section focuses on explaining how the analysis was implemented in MATLAB. In the following, there is an illustrative diagram of the model with the description of the three main functions in which model is structured with a conclusion summary table to resume the inputs and outputs for each function.

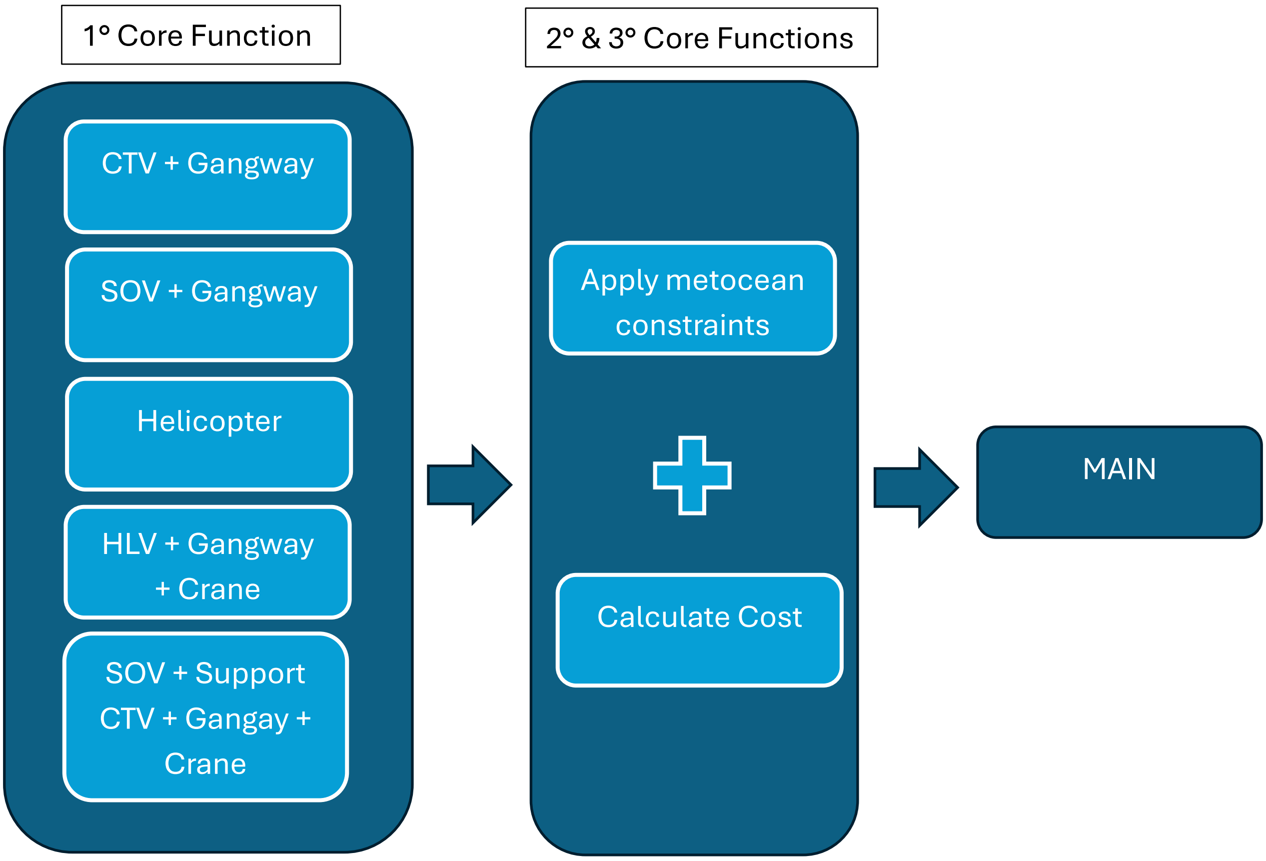


Figure 16. MATLAB model illustrative diagram

The first core function is implemented to define the corrective maintenance strategy. It includes all the parameters associated with the selected strategy. This function receives as input the distance between the offshore site and the closest port, along with the repair time (from the literature), and returns as output:

- the sequence of maintenance steps,
- their Hs and wind speed operational limits,
- the fixed costs and fixed parameters of the strategy.

In detail, this function incorporates:

- vessel speed,
- fuel consumption,
- number of technicians involved,
- fixed costs such as vessel, gangway and crane charter.

A key innovative element of the strategy function is the inclusion of an efficiency index that adjusts the intervention time according to the number of technicians deployed. The logic behind it is simple: the more technicians are available, then faster is the intervention; up to a physical limit. Beyond a certain threshold, adding more technicians does not improve the speed because of physical operational constraints.

This index is calculated by using a reference number of technicians, derived from literature and adjusted according to the type of vessel used, along with the actual number of technicians deployed. In this case a strategic specific assumption is made on the number of technicians basing on [26], [31], [35], [36] and according to the type of vessel. In particular, 5 reference technicians are employed for small repairs and 20 reference technicians for replacements. Therefore, the ratio is multiplied by the base repair time to get the adjusted intervention time. This up to 30% of the original repair time, accounting the physical restriction involved in the intervention.

Additionally, a fixed failure reception time is defined:

- 15 hours for Small Repairs,
- 50 hours for Replacements.

These durations are based on real-world experience, assuming that the necessary vessels and equipment are immediately available at port.

Finally, the strategy function includes the four main operational phases previously described (Failure Reception, Mobilization, Repair Window, Commissioning), along with operational thresholds (Hs and wind speed) for each phase, derived from literature.

INPUT	OUTPUT
• Distance between offshore site and closest port • Repair/Replacement time	• the sequence of maintenance steps, • their Hs and wind speed operational limits, • the fixed costs and fixed parameters of the strategy.

Figure 17. I&O first core function

The second core function of the MATLAB model applies the site-specific metocean conditions to the selected corrective maintenance strategy.

This function receives as input:

- the duration of each operational phase,
- the corresponding Hs and wind speed thresholds (previously defined in the strategy function),
- the hourly time series of Hs and wind speed for the offshore site under analysis with an Excel file downloaded from ERA5 [1].

Based on this input, the function returns:

- the total intervention time,
- the total waiting time,
- the number of successfully completed operations.

More specifically, the function performs a check for each phase of the operation, to verify whether the metocean conditions remain within the acceptable limits for the entire duration. During the mobilization, if conditions get worse after vessel departure, and this results in a waiting time exceeding 1 hour, the intervention is cancelled. This represents a realistic scenario in which the vessel does not wait offshore, but rather returns to port when operational conditions are no longer safe.

Similarly, during the Repair/Replacement Window, if the waiting time exceeds 168 hours (1 week) due to persistent unfavourable conditions, the entire intervention is considered cancelled. This threshold reflects the operational and economic limits of prolonged offshore standby.

Additionally, the function assumes that technicians work in two alternating teams, allowing for 24-hour operations. This is a strict assumption to let that corrective operation ends up as fast as possible.

INPUT	OUTPUT
• The duration of each operational phase • The corresponding Hs and wind speed thresholds (previously defined in the strategy function) • The hourly time series of Hs and wind speed for the offshore site under analysis with an Excel file downloaded from ERA5 [1].	• The total intervention time, • The total waiting time, • The number of successfully completed operations.

Figure 18. I&O second core function

The third and final core function of the seasonal model is focused on the cost evaluation of the corrective maintenance strategy.

This function receives as input:

- the total operation time,
- the net repair time,
- the distance from the port,
- the fixed costs,
- and all the characteristic parameters defined in the strategy function.

Its output is the total cost associated with the selected corrective strategy.

Beyond fixed elements, this function also includes variable costs, such as:

- the fuel cost per liter,
- the technician hourly wage,
- and a correction factor that accounts for fuel consumption during the repair window, where the vessel remains on standby but still consumes energy.

A special case is considered for the strategy involving the use of a helicopter. This scenario is treated separately within the model, with the assumption that the helicopter:

- drops off the technicians,
- then returns to port,
- and flies back to retrieve them once the repair is completed.

This approach reflects realistic logistical behaviour and cost implications of aviation-based maintenance in offshore operations.

INPUT	OUTPUT
• The total operation time • The net repair time • The distance from the port • The fixed costs • All the characteristic parameters defined in the strategy function	• Total cost associated with the CM strategy in question

Figure 19. I&O third core function

The main script of the MATLAB model is the central point that executes all the predefined strategy functions.

Within this script:

- the selected maintenance strategy function is called,
- the distance from the nearest port is defined,
- and the repair or replacement duration, based on literature data and specific to each component under analysis, is set.

In addition, the script calls the functions described before:

- applying the site-specific metocean conditions,
- and calculating the associated operational costs.

Once the outputs of each function are available, the script proceeds to compute the average values for:

- total intervention time,
- waiting time,
- total cost of successfully completed operations,
- number of successfully completed operations

All results are then automatically exported into four Excel files (one for each season), which provides a clear and organized dataset for further analysis and post processing.

3.4.1.1. Input

This section classifies and well-describes the input parameters included in the model just mentioned. To improve the clarity and organization of the model, the main inputs used in this work have been grouped into three categories: generic, site specific, and strategy specific.

The generic inputs include all parameters that remain constant throughout the analysis and are not influenced by the specific location or the type of strategy adopted. These are essential values used in the cost calculation and operational modelling.

- the fuel cost per liter, which directly affects the operating expenses associated with vessel mobilization and standby time offshore [52];
- the hourly cost of technicians is key factor in determining expenditures during both Small Repair and Replacement operations (assumed);

- a percentage factor, set at 30% of total fuel cost, which is used to model the fuel consumption during the Repair Window. This assumption is provided to account for the fact that vessels do not shut down their engines while waiting or during on-site repair activities, but remain operational (e.g., to stabilize position, support the crew, or operate auxiliary systems), consuming energy continuously.

The site-specific inputs refer to all the key parameters that are directly related to the geographical features of the selected offshore location. These inputs vary from site to site, and their inclusion in the model enables a sort of sensitivity analysis, showing how different site conditions affect maintenance feasibility and costs.

The two main site-specific parameters are:

- The distance from the closest port to the offshore site:
  this value is critical for calculating mobilization times and fuel consumption. It differs for each of the three case studies considered (two in the North Sea and one in the Mediterranean Sea), reflecting real-world logistical constraints.
- Metocean conditions (significant wave height and wind speed):
  these are provided through an Excel input file derived from the ERA5 database, which includes hourly data from 1990 to 2022. The metocean dataset is used to determine how the different phases are affected by sea and wind state; but also how costs, times and successfully completing maintenance activities change in each seasons

The strategy-specific inputs complete the definition of the selected corrective maintenance strategy. These parameters are directly connected to the operational and logistical characteristics of each strategy and, although they may vary from one strategy to another, they are not necessarily unique for every case.

The main strategy-specific inputs are:

- Number of technicians (actual and reference):
  both values are derived from technical literature [26], [31], [35], [36], but were also selected based on real-world experience and the type of vessel involved in the operation. The reference number is used in the efficiency index to adjust the actual repair time according to technicians employed.
- Repair/Replacement time:
  these two parameters are kept constant across all strategies by distinguishing Small Repair actions and Replacements ones. In addition, they are derived from literature [26], [31] by differing from the component under investigation. They represent the effective time required to perform the actual repair or replacement, excluding waiting periods or logistical delays.
- Vessel characteristics:
  for each strategy, details regarding the daily charter cost, fuel consumption and average operating speed of the vessels involved are specified. These values are essential for estimating total operational costs during mobilization and repair phases and are already reported in table 1.

- Equipment costs:
  this refers to the costs of specialized tools and systems required for the intervention. In particular, the motion-compensated gangway and the crane are considered, with their respective daily rental costs provided as input and reported in table 2.

- Operational limits for Hs and wind speed at 100 meters:
  each phase of the maintenance process (mobilization, repair window, commissioning) is characterized by specific thresholds for significant wave height and wind speed, according to a combination of literature values and practical experience. Some of these limits have been already reported in table 1; however, an assumption is made for HLV threshold on Hs set to 5 (m), according to technical specification and dimensions of the vessel. In addition, because of the variability of wind speed limit at 100 meters hight for technicians, it has been set to 15 (m/s) by assumption. These limits are crucial for determining whether an operation can be successfully completed under given environmental conditions.

Altogether, these inputs allow for a realistic, flexible, and strategy-aware simulation of offshore corrective maintenance scenarios. Specifically, some of these have been already detailed in the table 1; instead, the missing ones are resumed in the following table:

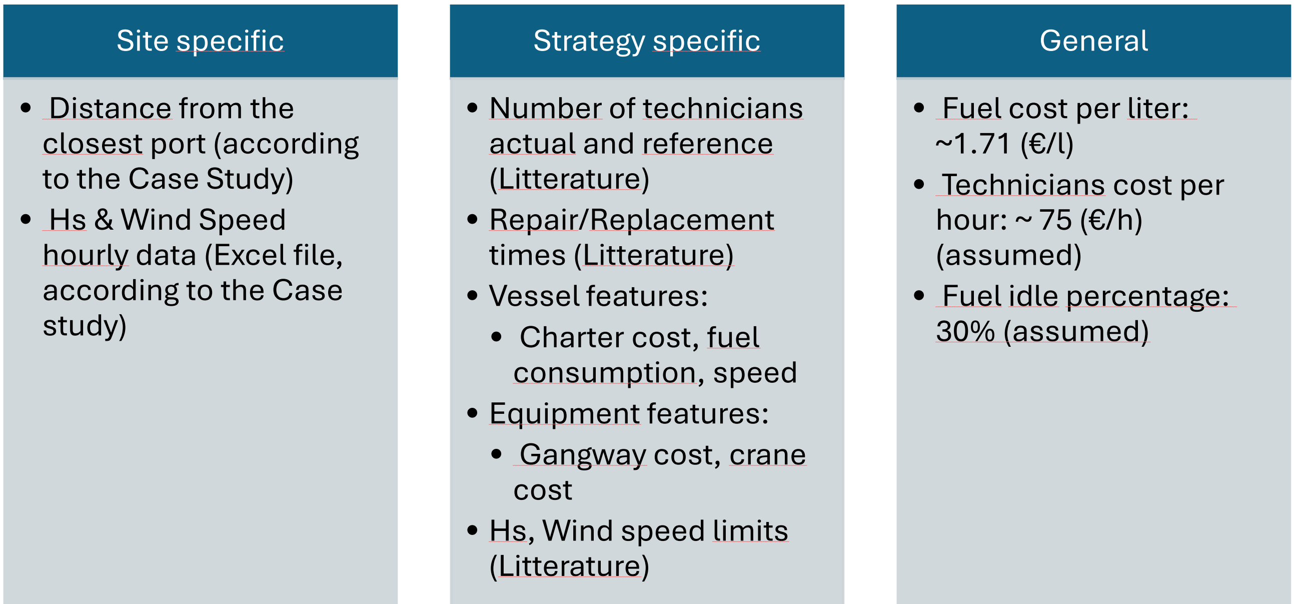


Figure 20. Input definition

3.4.1.2. Assumptions

This section outlines the main assumptions made in the present work. It serves as a conceptual bridge between the input parameters just described and the outputs that will be discussed in the following paragraphs.

For clarity and consistency with the input classification, the assumptions have also been grouped into three categories: site-specific, strategy-specific and general. In addition, a conclusion summary table is reported to resume the assumptions made, by following the same structured of input description.

Site-Specific Assumptions

Among the site-specific assumptions, a key hypothesis is the full availability of spare parts, vessels, and crew at the port. For the sake of simplification and to keep the model computationally light, it was assumed that these resources are 100% available at all times. The most critical assumption in this group concerns the availability of vessels. While this assumption is relatively acceptable for smaller vessels like CTVs (Crew Transfer Vessels) and SOVs (Service Operation Vessels), it becomes much stricter for larger vessels, such as HLVs (Heavy Lift Vessels). HLVs are fewer in number and are often engaged in operations across different locations. Considering the actual time needed for such vessels to arrive at port could significantly extend the downtimes, which is not accounted in this preliminary model.

Strategy-Specific Assumptions

As mentioned in previous sections, strategy-specific assumptions include:

- The use of two alternating teams of technicians, working in shifts to maximize the operational window and reduce overall intervention time.
- A fixed failure reception time, based on full port availability and operational experience:
    - 15 hours for small repairs
    - 50 hours for component replacements.
- A reference number of technicians, chosen based on literature and adapted to the type of vessel used:
    - 5 technicians for small repairs [26], [31], [35], [36]
    - 20 technicians for replacements.
- Effective repair/replacement durations, given totally from literature sources and dependent on the component:
    - Replacement time: 19 hours for the pitch system, 21 hours for the generator [26], [31].
    - Small repair time: 9 hours for the pitch system, 6 hours for the generator [26], [31].

General Assumptions

Finally, among the general assumptions is the turbine size, which is assumed to be of the same typology (Semi-submersible) and in the range between 10 and 15 MW. This choice is meant to standardize the weight and typology of the components involved in maintenance activities, ensuring consistent modelling regardless of the specific turbine type. In addition, it is assumed the technician cost per hour, which is very variable across the geographic location and the idle percentage used to quantify fuel consumption during the repair window.

Site specific

- Full spare parts availability
- Full vessel availability
- Full crew and technician availability

Strategy specific

- Two technician teams
- HLV Hs threshold
- Technician wind speed threshold at 100 (m) hight
- Fixed failure reception time:
  - 15 h (Small Repair)
  - 50 h (Replacement)
- Ref. Numb. Of technicians:
  - 5 (Small Repair)
  - 20 (Replacement)
  - Effective repair/replacement times:
    - Replacement time: 19 h for Pitch System, 21 h for generator
    - Small repair time: 9 h for Pitch System, 6 h for generator

General

- 10 – 15 MW turbine
- Semi-submersible floating offshore wind turbine
- Technicians cost per hour
- Fuel idle percentage

Figure 21. Assumption definition

3.4.1.3. Case-studies and site features

Before analysing the model outputs, it is essential to identify and describe the sites selected for the application of the methodology. This step is particularly relevant, as it helps to highlight how average costs, intervention times, and successful maintenance operations can vary significantly based on site-specific metocean conditions.

In this study, three offshore locations were selected: two in the North Sea and one in the Mediterranean Sea. Each of these sites provides a different environmental context and logistical configuration.

- The Mediterranean site corresponds to the recently authorized 7SeasMed project. This floating wind farm includes 21 turbines with a rate power of 12 MW each. Its technical characteristics and operational setup are summarized in the table below. The site represents a relatively calmer weather window, typical of Mediterranean conditions, and offers insight into lower downtime potential and cost-effective maintenance scenarios.

7SeasMed			
Location	37°32'36.6"N 11°57'20.1"E	Turbine type	Vestas V236-15 MW
Country	Italy	Numb. of turbines	21
Sea	Mediterranean Sea	Turbine power	12 (MW)
Bathymetry	200 (m)	Platform type	Semi-Submersible
Distance from coast	50 (km)	Rotor diameter	250 (m)
Average Wind Speed	7,7 (m/s)	Hub hight	155 (m)
Average Hs	1,11 (m)		
Closest port	Porto di Mazara del Vallo		
Distance from closest port	60 (km)		
T2P port	Porto di Augusta		

Table 9. 7SeasMed features

- The first North Sea site is the Kincardine project, currently operational and composed of five 9.5 MW turbines and one 2 MW turbine. Having been in service for several years, Kincardine has undergone both In-Situ and Tow-to-Port maintenance operations, making it an ideal benchmark for real-world corrective maintenance strategies in harsher marine conditions.

Kincardine			
Location	57°00'00.0"N 1°51'00.0"W	Turbine type	V164-9,5 Vestas
Country	UK	Numb. of turbines	5 (+1)
Sea	North Sea	Turbine power	9,5 [MW] (+2 [MW])
Bathymetry	60-80 [m]	Platform type	Semi-Submersible
Distance from coast	15 [km]	Rotor diameter	164 [m]
Average Wind Speed	9,3 [m/s]	Hub hight	100 [m]
Average Hs	1,3 [m]		
Closest port	Aberdeen		
Distance from closest port	20 [km]		
T2P port	Rotterdam		

Table 10. Kincardine features

- The second North Sea site refers to the planned GreenVolt project, which, although not yet approved, is expected to deploy 35 turbines with rated capacities ranging from 14 to 16 MW. The site's configuration and turbine capacity offer an outlook on future large-scale developments in floating wind technology.

GreenVolt			
Location	57°52'36.3"N 0°36'53.5"W	Turbine type	Vestas V236 15 MW
Country	UK	Numb. of turbines	35
Sea	North Sea	Turbine power	14-16 [MW]
Bathymetry	100-115 [m]	Platform type	Semi-Submersible
Distance from coast	80 [km]	Rotor diameter	220-242 [m]
Average Wind Speed	10,3 [m/s]	Hub hight	132-143 [m]
Average Hs	1,95 [m]		
Closest port	Peterhead		
Distance from closest port	80 [km]		
T2P port	Rotterdam (Assumption)		

Table 11. GreenVolt features

Together, these three locations reflect a range of real-world offshore environments, from relatively mild Mediterranean seas to the more severe and operationally constrained North Sea. This allows the methodology to assess how the key model outputs: intervention time, total cost, and success rate, change in response to different sea conditions and distances from shore.

3.4.1.4. Output

This section introduces and describes in greater detail the outputs returned by the seasonal simulation model. These outputs are essential for the post-processing analysis carried out in the following chapter, where they will be used to estimate the operational expenditures (Opex) associated with corrective maintenance.

The MATLAB model generates four Excel files for each maintenance strategy and for each component analysed, with each file corresponding to one of the four seasons of the year. In total, the analysis produces 40 Excel files, allowing for a structured and seasonal-based comparison.

Each Excel file involved yearly parameters, including:

- the year,
- the number of successfully completed interventions in that year,

- the average total time required,
- the average waiting time due to metocean conditions,
- the average cost associated with the successfully completed operations.

The structure of the output files is illustrated in the figure below to get an idea on how data are structured. This by following always the purpose discussed at the charter's beginning: beside it is not possible to predict when a failure will occur, this approach allows for a seasonal estimation of the expected cost, intervention time, and number of successful operations.

Year	Num_Repairs	Avg_Cost_Euro	Avg_Total_Time_h	Avg_Waiting_Time_h
1990	42	60681,65	47,12	13,52
1991	41	67052,86	53,22	19,39
1992	34	78258,89	62,97	29,65
1993	33	78377,24	63,42	29,94
1994	32	73190,48	58,59	25,13
…..	…..	……	……	……

Table 12. Excel exemple - Seasonal analysis output

Once data has been collected across all simulation years (from 1990 to 2022), a first average is performed over the years for every output parameters. Subsequently, a second average is applied across all strategies for each season, by keeping the distinction between small repairs and replacements, resulting in seasonal estimations of:

- average total intervention time,
- average waiting time,
- average maintenance cost,
- average number of completed interventions.

Finally, all results have been visualized through a series of bar charts, first by site, comparing how costs, times change according to the season and then by season, comparing the performance of different sites. This dual approach provides a comprehensive overview of how maintenance corrective performance varies under different geographical and seasonal conditions.

3.5. Post – processing

The following section describes the post-processing analysis performed after the core model execution. This step focuses on estimating the annual operational expenditures (Opex) associated with corrective maintenance. Starting from the outputs obtained from the seasonal simulation, the data are reprocessed to define an annual maintenance cost, which can then be scaled up to represent the entire wind farm.

Before detailing the process, it is important to clarify that the post-processing analysis in this work is applied specifically to the generator and the pitch system. However, the methodology can be extended to other components of the turbine although the corrective maintenance strategies are different. It is possible to categorize floating wind turbines into three main component groups:

- **Turbine subsystem** (e.g. generator and pitch),
- **Floating Platform Subsystem**,
- **Cables, mooring, and anchoring subsystem**.

This classification mainly arises from the different maintenance approaches required by each subsystem.

Among the key parameters used in the post-processing phase is the average seasonal cost, which expresses the mean cost per season for each failure category: small repair and replacement. Another fundamental variable is the annual failure rate. This obtained from literature and previously used for component selection. For calculation purposes, the annual failure rate is split by intervention type: 80% of failures are assumed to result in small repairs, and 20% in replacements.

In addition, for each season has been assigned a failure distribution according to the severity of metocean conditions. This is an important assumption that accounts for the varying failure probability of components based on seasonal metocean conditions. Specifically, during winter, the likelihood of failure is assumed to be higher due to harsher metocean conditions. In contrast, in summer, with more stable and milder conditions, the failure probability is expected to be lower. Autumn and spring have been assigned the same failure probability, as their metocean characteristics are considered to be relatively similar.

Spring	Summer	Autumn	Winter
22,5 %	5 %	22,5 %	50 %

Table 13. Seasonal failure distribution

Based on this structure, the annual corrective maintenance OPEX is estimated by using the following formula:

$$Opex = \sum_{1}^{4} [\mathbf{N\_events\_SR} \times \mathbf{C\_SR} + \mathbf{N\_events\_R} \times \mathbf{C\_R}]$$

Where:

- *N_events_SR* = number of small repair events per season
- *C_SR* = corresponds to average cost per small repair
- *N_events_R* = number of replacement events per season
- *C_R* = corresponds to average cost per replacement

This framework enables a scalable and component-based estimation of annual corrective maintenance costs for floating offshore wind turbines, forming the basis for future OPEX modelling across entire floating wind farm

4. Results and discussion

This chapter aims to highlight the main results obtained from the previously described seasonal corrective maintenance analysis. It is important to recall that the study was applied to three different offshore wind sites: one located in the Mediterranean Sea (7SeasMed project), and two in the North Sea (Kincardine and GreenVolt). For sake of simplicity, in the following, the analysis is developed and described just for Generator for both small repair and replacement failures. However, the bar charts for Pitch System small repair and replacement failures are reported for completeness in appendix A, although results are almost similar to generator case.

The discussion will begin by presenting the results related to the 7SeasMed site in the Mediterranean, followed by those from the North Sea sites. For each location, a comparison between the four seasons is carried out, focusing on key performance indicators such as: the number of successfully completed interventions, average cost, total average operation time, and average waiting time, all reported separately for *small repairs* and *replacements*.

Following the seasonal analysis, the focus will shift to site comparison, where the same indicators are compared for each season across the three sites. These two comparisons enable a better understanding of how the results vary not only seasonally, but also geographically.

In particular, this dual analysis acts as a kind of sensitivity study, taking into account both the impact of metocean conditions, by comparing the severe environment of the North Sea with the milder Mediterranean and the influence of distance from the nearest port, which directly affects operational times and costs.

4.1. 7SeasMed

7SeasMed is one of the three sites analysed, located in the Mediterranean Sea. Unlike the North Sea, this basin is generally characterized by more favourable metocean conditions, although they can still be limiting during certain seasons or for complex operations. According to the EIA (Environmental Impact Analysis) [28], the site already includes a section dedicated to maintenance management, particularly focused on the Tow-to-Port (T2P) strategy. However, a detailed and quantitative analysis of corrective maintenance is missing, especially one that considers key parameters such as average costs, total intervention time, and waiting time. This is exactly the purpose of the present work: to estimate and describe these aspects season by season, focusing on successfully completed operations. In fact, this allows for the quantification and prediction of the economic and operational impact associated with corrective maintenance, offering a solid foundation for more informed and efficient planning.

Before diving into the detailed analysis of the results, it is important to note that, once the outputs were obtained for each season and for every maintenance strategy, they were processed by calculating average values. This allowed the creation of two summary tables: one focused on Small Repair interventions and the other on Replacements, both supported by explanatory bar charts. Below is the bar chart referring to Small Repairs on the generator.

- **Small repair**

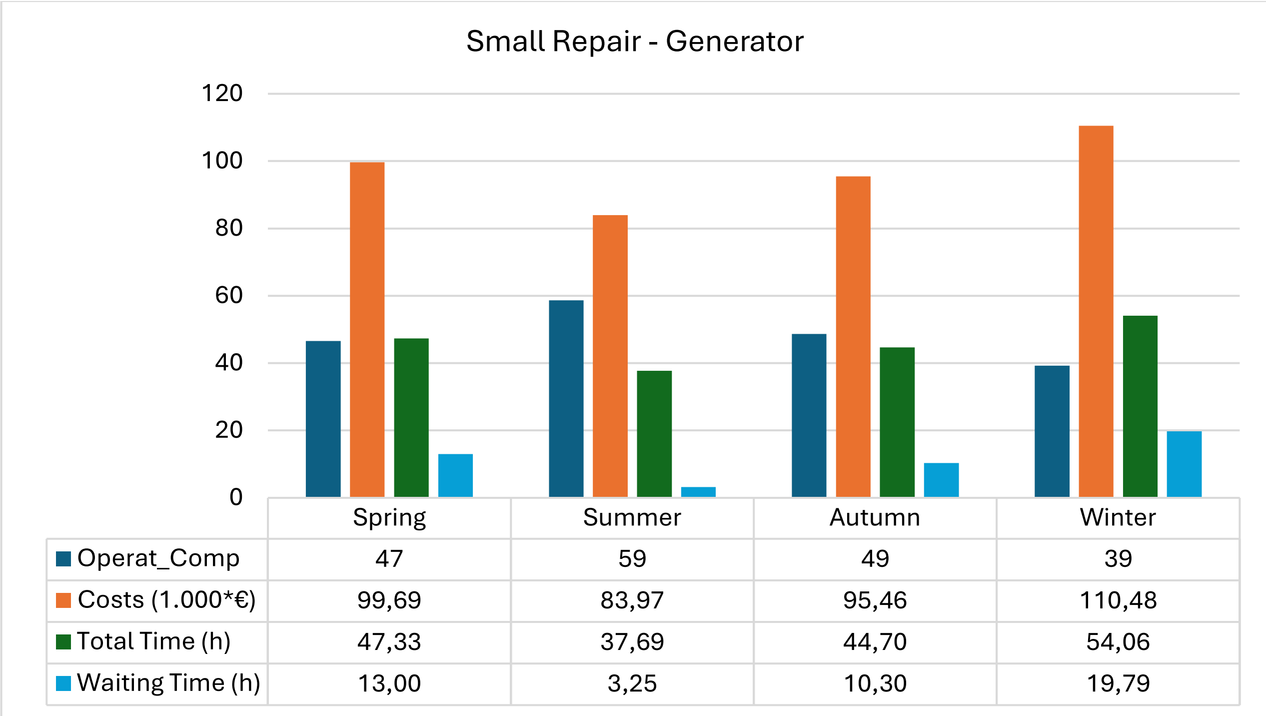


Figure 22. 7SeasMed - Small Repair - Generator case

The seasonal analysis of corrective maintenance operations on floating offshore wind turbines highlights significant trends related to the temporal distribution of interventions, the time required to complete operations, waiting times, and associated costs. It is interesting to observe how the number of completed operations varies across the different seasons. Although the variation is not particularly significant, it is worth noting that the analysis refers exclusively to small repairs, involving interventions that do not require extended execution times. In particular, summer is the season with the highest number of successful operations. During this season, weather and sea conditions are generally more favourable, allowing easier and safer access to the turbines. Instead, winter is the season with the fewest successful maintenance operations, primarily because of severe weather conditions, such as strong winds and cold temperatures, which make intervention difficult and risky. The intermediate seasons, spring and autumn, represent an intermediate way, with the number of completed operations falling between the extremes of summer and winter.

In general, winter season, with its severe weather conditions, represents the most challenging period for maintenance of floating offshore wind turbines across the seasons. Even though this issue is less pronounced in the Mediterranean Sea, where are present a high number of successfully completed interventions even during the winter months. However, difficulties in accessing turbines and the increased risks during winter require more complex operations and greater time. As result, the number of operations completed during this season is significantly reduced, and the time required to complete maintenance activities is longer.

In summer, however, more favourable conditions allow for a reduction in the average time for completing operations. The analysis of average total times for successfully completed interventions confirms this trend. Intervention times in winter are significantly longer than in summer, with operations requiring more time and resources. This can be attributed to the difficulty of accessing turbines and the challenging conditions, which force maintenance teams to work in riskier and more complex environments.

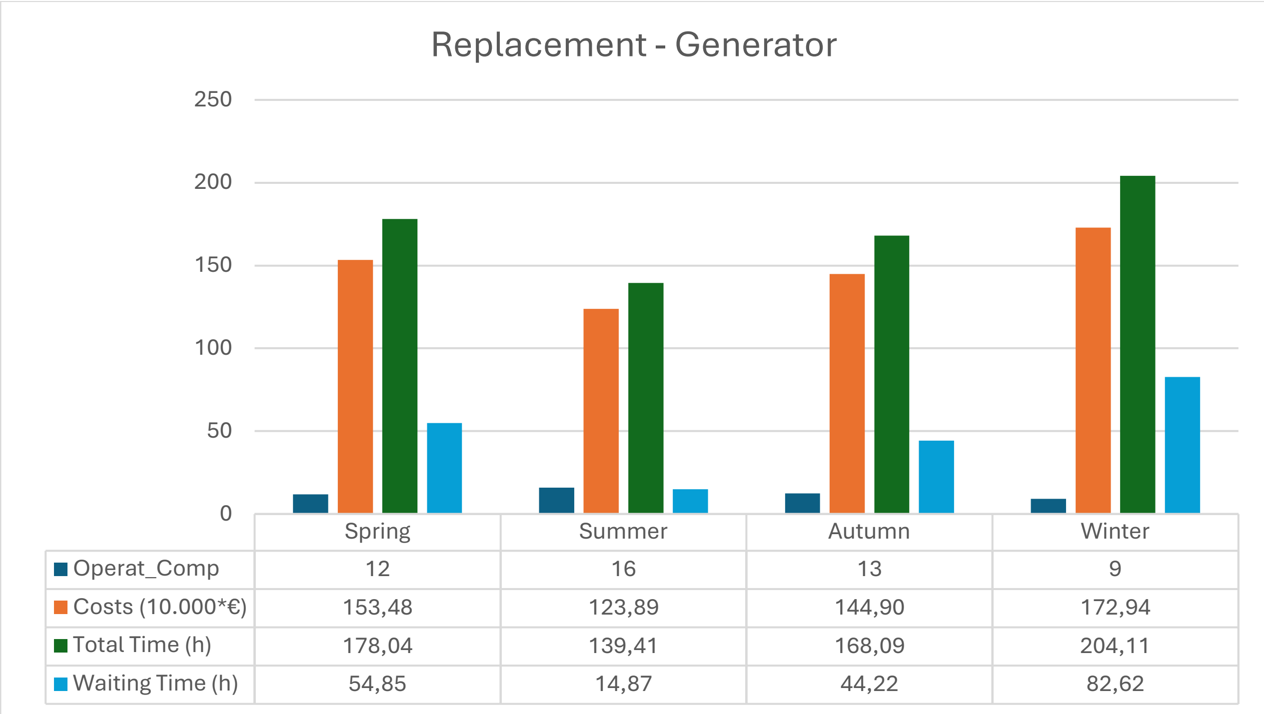
In addition, in winter, waiting times are higher, especially for challenging metocean conditions, which make the turbine access very complex. In summer, on the other hand, waiting times decrease significantly, thanks to more favourable operational conditions.

Finally, the economic aspect plays a crucial role in the seasonal analysis of offshore turbine maintenance. Operational costs are higher during the winter months, with an average cost of around €110.480 per intervention. This increase in costs is closely linked to the greater complexity and duration of operations, as well as the need to use specialized equipment and additional resources to bear seasonal challenges. In contrast, the summer months are when the lowest average costs are recorded, thanks to reduced intervention times and lower operational risks, which allow for better resource optimization and cost containment.

This type of analysis shows that, despite the difficulties in accessing the turbines and the more severe weather and sea conditions, several Small Repair interventions are still completed.

Even during the winter months, an average of 39 operations were completed, with an average total time of 54 hours and an average waiting time of about 20 hours. This highlights that even in the case of minor issues with the generator during winter, intervention is still possible. The same reasoning is applied to the other seasons. In particular, summer, as expected, is the season when the most interventions are completed, with an average of 59 successful operations. During this period, the average waiting time is about 3 hours, and the average total time is just over a day and a half, demonstrating that the favourable conditions allow for greater efficiency in carrying out the interventions.

- **Replacement**



	Spring	Summer	Autumn	Winter
Operat_Comp	12	16	13	9
Costs (10.000*€)	153,48	123,89	144,90	172,94
Total Time (h)	178,04	139,41	168,09	204,11
Waiting Time (h)	54,85	14,87	44,22	82,62

Figure 23. 7SeasMed - Replacement - Generator case

Corrective maintenance operations related to replacements, particularly those referring to the 7SeasMed site in the Mediterranean Sea and the associated generator, present distinct characteristics compared to Small Repair operations. One key aspect is that the number of successfully completed operations concerning replacement is significantly lower compared to repair operations. This is mainly because of greater complexity of replacement operations, which require longer intervention times compared to small repairs, leading to a greater impact from a costs point of view. In addition, it can be observed that the number of successfully completed operations tends to decrease to the point of becoming nearly uniform across seasons. However, the real difference lies in the average costs and intervention times, which are considerably lower during the summer months compared to the winter season.

Replacement operations involve several phases that require more time, specialized equipment, and coordination. This is reflected not only in the time required to complete the operations but also in cost management. The replacement of critical components, such as generators, requires the use of highly specialized equipment like Heavy Lift Vessels (HLV), which are necessary to transport and install the new parts. While these vessels are essential for the operation, they include high costs, both in terms of charter and fuel consumption, leading to an overall higher expenditure compared to repair operations.

Another aspect that emerges in the analysis of replacement operations is that, because of their complexity, many of these operations may have been postponed or even cancelled. This could happen manly because of metocean conditions and therefore logistical challenges. Moreover, the overall duration of the operation can lead to an increase in waiting times, resulting in delays during maintenance operations, which in turn can lead to a loss of operational efficiency.

Despite these difficulties, the analysis of average times for each season shows a similar trend to the one observed in small repairs: winter is the season with the longest average intervention times, while summer is the season with the shortest intervention times. However, it is important to emphasize that, unlike in small repair case, in replacement operations the average times are significantly longer. The need for specialized equipment, such as cranes for lifting heavy pieces and HLV vessels provides an impact on planning but also into a significant increase in operational costs.

The analysis of average costs related to replacement operations reveals a much higher expenditure compared to other types of intervention. The use of HLV vessels, which have a very high daily rental cost, along with fuel consumption costs, leads to a total expense that can reach millions of euros for each operation, especially during the winter months. During this season, difficult metocean conditions require additional times to complete the operation safely and therefore higher costs. In contrast to the summer months, when operational conditions are more favourable and costs are lower.

Nonetheless, despite the high cost and extended time required for replacement operations, it is important to note that these operations are still feasible even though at a slower pace compared to small repairs. In the winter months, for example, an average of about 9 replacement operations were successfully completed, which proves that process is still possible. Therefore, this proves that effectiveness of the maintenance system shows that replacement operations can be completed even in severe conditions. This represents an interesting alternative to traditional replacement operations carried out by T2P approach, which involves longer downtime and higher costs.

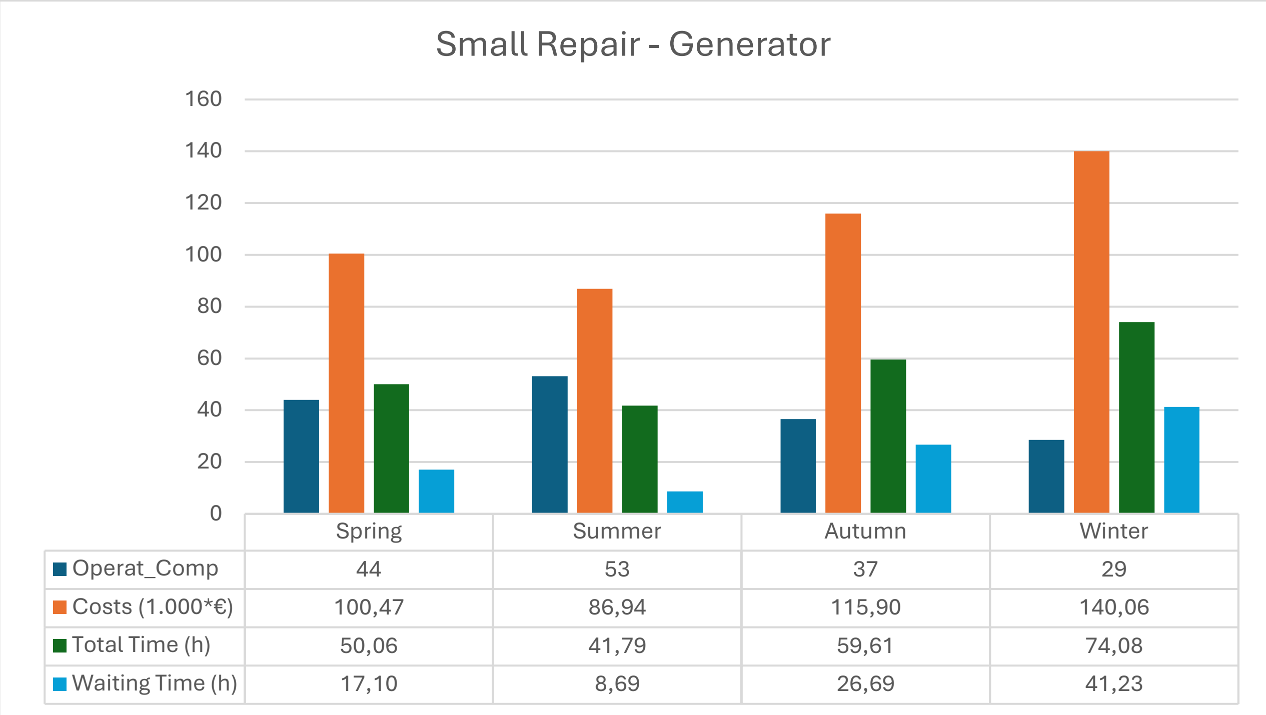
Data clearly shows that situation improves as the winter months recede. In fact, during the summer, an average of 16 maintenance interventions are completed, with an average time of about 140 hours and average waiting times of about 15 hours. This demonstrates that In-Situ approach is not only feasible but also effective, even for replacement operations that require more attention and precision. Furthermore, as the data shows, the situation keep improving with the passing of the seasons, making the option of In-Situ corrective maintenance even more valid and practical.

4.2. Kincardine

The next section will discuss the results for the Kincardine site, located in the North Sea about 20 km from the nearest port, Aberdeen. In this case, the meteorological and sea conditions are significantly more severe compared to those of the Mediterranean Sea. In particular, the average significant wave height (Hs) is 1.3 m, and the average wind speed at 100 m is 9.3 m/s. Despite these more challenging conditions, several maintenance operations have already been carried out at the Kincardine site. A generator replacement was performed using an In-Situ approach [27], as well as a traditional T2P approach [24] has been already tested on this site.

According to the report [27], the generator replacement operation lasted just under a month and was completed using a GenHook™ up-tower crane, temporarily installed above the turbine. In the case of Major Component Exchanges (MCE), the T2P approach was used, as described in the report [24]. Although the operation was successfully completed, the report highlights that this type of intervention involves significantly longer downtimes and higher costs.

- **Small repair**



	Spring	Summer	Autumn	Winter
Operat_Comp	44	53	37	29
Costs (1.000*€)	100,47	86,94	115,90	140,06
Total Time (h)	50,06	41,79	59,61	74,08
Waiting Time (h)	17,10	8,69	26,69	41,23

Figure 24. Kincardine - Small Repair - Generator case

Small repairs, which involve minor interventions to resolve non-critical issues and keep turbines in good condition, are a significant part of maintenance activities. The Kincardine site, located in the North Sea, experiences significantly severe weather, which directly impacts on frequency, duration, and costs of maintenance operations. The analysis of small repairs at this site highlights how seasonal parameters, such as wind intensity and wave height, have a direct impact on the efficiency and costs of maintenance activities.

At the Kincardine site, small repair operations follow a well-defined seasonal trend. In winter, weather conditions are particularly challenging, with strong winds and high waves making access to the turbines difficult, which affects the effectiveness of interventions. During this season, an average of 29 small repair interventions are completed successfully, but the costs are significantly higher compared to more favourable seasons. The average cost in winter is around €140.060, with an average total time of 74 hours to complete each operation. In addition, the average waiting time is 41 hours because of adverse conditions. These prolonged waiting times, combined with the longer overall duration of interventions, significantly increase operational costs during the winter.

The combination of these factors, longer intervention times and higher operational costs, proves the significant impact that winter conditions have on operational efficiency. In particular, the challenges in organizing and carrying out interventions under such conditions result in longer waiting times, which in turn hinder overall operational performance.

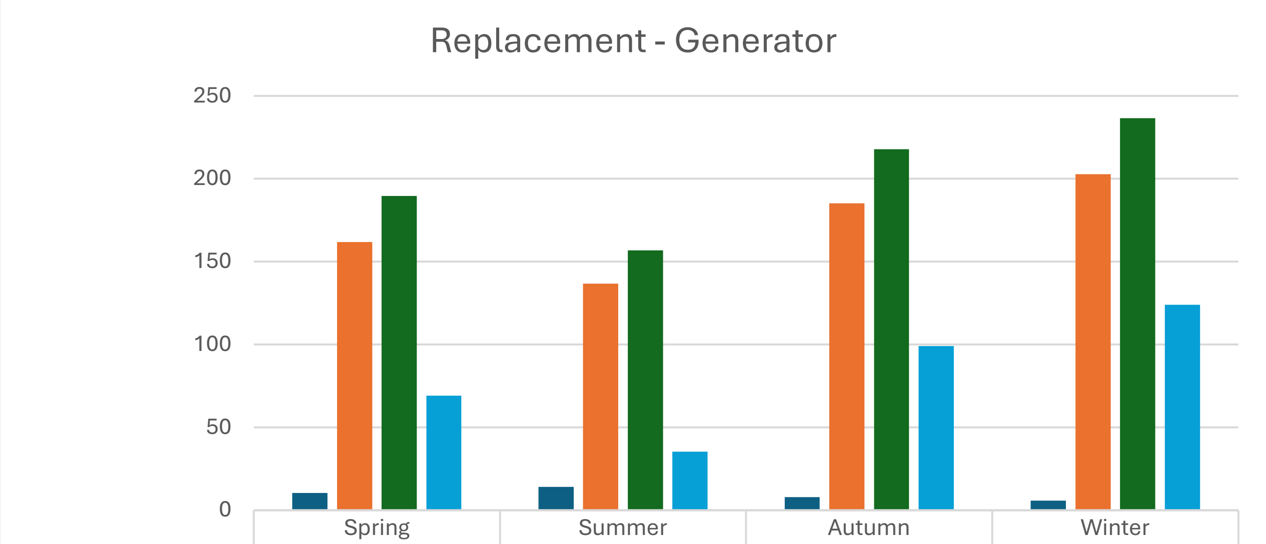
In contrast, during the summer months, metocean conditions are much more favourable. With weaker winds and lower waves, access to turbines and intervention timing improve significantly. In summer, an average of 53 small repair interventions are completed successfully, with an average cost of €86,940 per intervention. The average total time for each intervention is about 40 hours, with an average waiting time of just 3 hours. These numbers clearly show how summer represents the most favourable period for maintenance operations, with lower costs and significantly shorter intervention times compared to the winter months. Favourable weather conditions allow maintenance teams to complete interventions more quickly and with fewer risks, optimizing overall costs.

Intermediate seasons, such as spring and autumn, have weather parameters that fall between the extremes of summer and winter. During spring, as the season progresses towards summer, conditions improve. As a result, intervention times are shorter compared to winter, but do not reach the efficiency levels seen in summer. Costs, while lower than in winter, are still higher than in summer, but operations are quicker and less costly compared to the colder months.

In autumn, however, a worsening in weather conditions is observed, with an increase in wind speed and stronger waves, which slow down interventions and increase waiting times and the resulting costs. Although autumn does not reach the extreme levels of winter, weather parameters progressively worse, leading to longer intervention times and higher costs compared to spring and summer. The difficulty in planning and completing interventions increases as the winter months approach.

This analysis highlights how, despite being in the North Sea, corrective maintenance operations related to small repairs can still be completed even during periods with the severe weather and sea conditions, such as in winter. However, it is clear that during these periods, many operations may be cancelled and the completion times will inevitably be longer. Nevertheless, as shown in the graph, it is still possible to intervene despite the severe weather and sea conditions.

- **Replacement**



	Spring	Summer	Autumn	Winter
Operat_Comp	11	14	8	6
Costs (10.000*€)	161,89	136,74	185,19	202,81
Total Time (h)	189,62	156,90	217,75	236,51
Waiting Time (h)	69,19	35,30	99,11	123,90

Figure 25. Kincardine - Replacement - Generator case

Corrective maintenance operations related to the replacement of medium and large-sized components, such as parts of the generator or the entire generator, are totally more complex and costly than small repairs. At the Kincardine site, located in the North Sea, it is evident that the number of successfully completed replacement operations is significantly lower than that of small repairs. This mainly because of the much higher average time required for each replacement intervention. These operations require the use of highly specialized equipment, such as cranes and heavy-lift vessels, and are characterized by longer execution times and higher operational difficulty, especially under unfavourable weather and sea conditions.

During the summer months, despite more favourable weather and sea conditions compared to other periods of the year, an average of only 14 replacement operations were completed. This number is considerably lower than the small repairs, even though summer conditions allow for higher operational efficiency. However, the average time to complete each replacement intervention is nearly four times greater than for small repairs. This increase in time is mainly due to the complexity of the operation and the specialized equipment required. As result, the costs associated with replacement operations are significantly higher. Despite better conditions, the reduced number of replacement operations during summer highlights how the nature of these interventions limits their frequency.

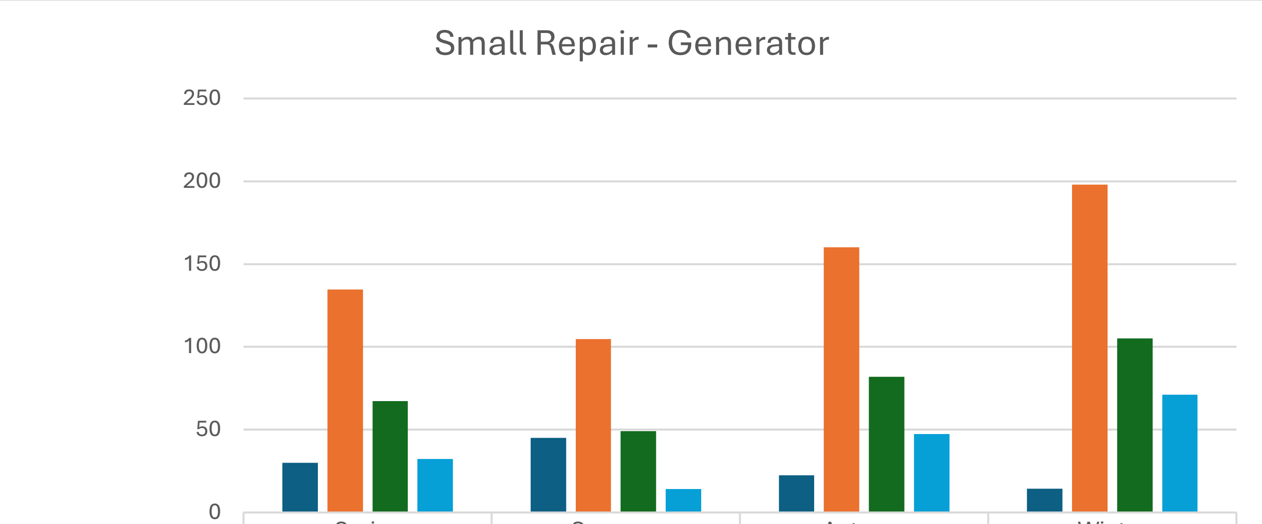
In winter, the weather and sea conditions worsen further, with strong winds and high waves, making it even more risky and costly to face replacement interventions. During the winter season, an average of only 6 replacement operations were completed. Winter replacement operations require an average completion time of 236 hours, a considerably long duration for each intervention. Additionally, the average waiting time is approximately 124 hours due to the operational difficulties arising from the severe conditions. These extended waiting times and prolonged operation durations significantly increase costs, which are about ten times higher than those for small repairs. This increase in costs is primarily due to the use of specialized vessels for lifting heavy pieces and the use of expensive equipment.

In addition, it is important to note that, as with small repairs, replacement operations also show a seasonal trend. As the summer season approaches, weather and sea conditions improve, allowing for increased efficiency and a reduction in waiting times and costs. This seasonal trend is also evident for replacement operations, where, although the number of interventions remains lower compared to small repairs, efficiency improves significantly when conditions become more favourable.

In conclusion, the analysis of replacement operations at the Kincardine site clearly highlights how these operations are complex and costly, regardless of the season, but particularly in winter, when difficult weather and sea conditions significantly increase times and costs. While summer offers the most favourable conditions, replacement operations remain costly because of the duration of the work and the specialized equipment required.

4.3. GreenVolt

- **Small Repair**



	Spring	Summer	Autumn	Winter
Operat_Comp	30	45	22	14
Costs (1.000*€)	134,64	104,75	160,17	198,01
Total Time (h)	67,21	49,17	82,01	105,08
Waiting Time (h)	32,35	14,15	47,40	71,04

Figure 26. GreenVolt - Small Repair - Generator case

The last site analysed is GreenVolt, a floating wind project located in the North Sea, roughly 80 km offshore from the Scottish east coast, where Peterhead represents the closest port. Compared to the previously discussed sites, GreenVolt is very far from shore in a considerably more remote and challenging environment in terms of accessibility for corrective maintenance operations. In addition, discrepancy between summer and winter seasons becomes increasingly evident as the distance from the coast increases and more severe metocean conditions are met. Although the sea is the same, remarkable differences also begin to emerge when compared to the performance observed at Kincardine, which will be further discussed in the following section.

This offshore distance significantly affects logistical complexity, even though such limitations are less critical in the case of small repair operations, which typically involve less intensive procedures and shorter execution times. Despite the exposure of the site and the depth of the waters in this region of the North Sea, the data reveals that it keeps feasible to complete a consistent number of corrective interventions, beside their effectiveness varies seasonally.

The seasonal trend observed at GreenVolt is consistent with that identified at the other sites: during winter, there is a remarkable decrease in the number of successful interventions, along with longer average completion times and higher associated costs. These increases are mostly driven by delays due to severe weather conditions, which complicate access to the turbines, prolong waiting times, and limit operational windows.

More specifically, the winter period is characterized by fewer interventions completed, and significantly higher costs per operation, mainly because of the extended duration of tasks. Waiting for suitable weather conditions to access the site can cause delays that impact operational schedules and increase overall costs. Even relatively minor repair tasks can become challenging to carry out during winter months.

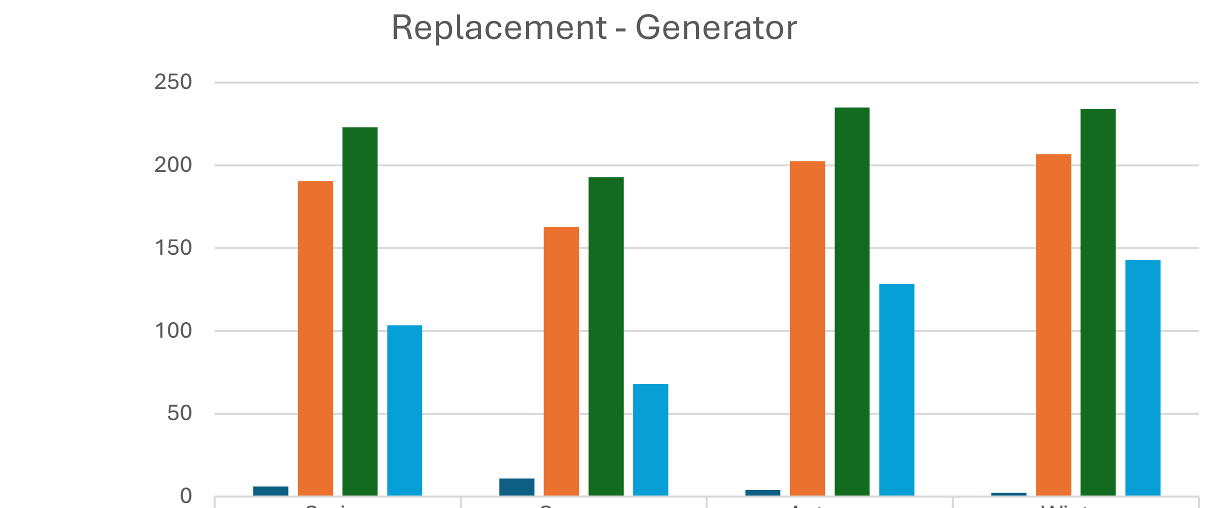
Nonetheless conditions improve moving into summer and the operational outlook becomes much more favourable. In this season, the site records an average of 45 successfully completed small repair interventions, with average completion times of around 50 hours and average costs of approximately €104.750 per intervention. These figures clearly indicate that summer is the optimal window for conducting maintenance activities, thanks to calmer seas, more predictable weather, and longer usable operational windows.

The overall analysis confirms an important insight: corrective maintenance involving small repairs is technically and logistically feasible in all four seasons. While execution times and costs vary substantially throughout the year, the probability of success remains consistently high. With proper planning, appropriate equipment, and well-coordinated resources, successful interventions are achievable even in harsh seasonal conditions.

This result is especially relevant for future Operation & Maintenance (O&M) strategies in the floating offshore wind sector. For remote deepwater sites like GreenVolt, maintaining year-round intervention capability is a strategic asset. Even under challenging conditions, operators can retain a certain level of responsiveness, minimizing turbine downtime and preserving system reliability.

GreenVolt also provides a useful benchmark for the future evolution of maintenance protocols in floating wind farms. Its offshore location and exposure make it a testing ground for assessing the robustness of current intervention In-Situ approach. The performance data across seasons confirms that with solid planning and the right tools, it is possible to keeps strong operational performance, even in extreme offshore environments.

- **Replacements**



	Spring	Summer	Autumn	Winter
Operat_Comp	6	11	4	2
Costs (10.000*€)	190,60	162,96	202,60	206,81
Total Time (h)	222,89	192,94	234,90	234,24
Waiting Time (h)	103,49	67,89	128,51	142,98

Figure 27. GreenVolt - Replacement - Generator case

To conclude this study, we examine the performance of corrective maintenance operations related to generator replacements at the GreenVolt site, located roughly 80 km off the eastern coast of Scotland, in the North Sea. Unlike small repairs, which can often be carried out with moderate cost and time even in less favourable conditions, replacement operations involve much higher levels of complexity and operational risks. This complexity is clearly reflected in the data, which reveal a significant impact of marine weather conditions on the feasibility and success of such interventions.

At a first glance, it becomes evident that the site's distance from shore and its exposure to the severe environment of the North Sea represent a serious operational constraint, even during the typically more favourable seasons. Unlike other previously analysed sites, where the summer season allows for a reasonable number of successful replacements, the data from GreenVolt provides a structural limitation.

In particular, during the winter months, harsh weather conditions significantly restrict operational capability: on average, only 2 replacement operations are completed successfully, with an average total intervention time of about 235 hours. This already high value is further worsened by waiting times, which are caused by the unpredictability of weather windows and compromised accessibility.

The average cost per intervention exceeds €1.9 million, alerting a level of financial and operational risk that is extremely high for corrective maintenance.

Even in the summer, which theoretically offers the best weather and sea conditions, the numbers remains modest as well. The average is only 11 successful replacement operations, which is still a low value compared to other sites. Costs during this season also remain elevated due to prolonged execution times and the use of specialized vessels, such as heavy-lift ships (HLVs) and up-tower cranes. The site's distance from shore further complicates logistics, adding to both duration and expense.

In addition, unlike at other sites, critical operational conditions are not limited only to winter. In fact, similar challenges are observed in other transitional seasons as well. For instance, during autumn, the average completion time reaches the same level as winter, around 235 hours. This suggests that even outside of the coldest months, conditions can be just as severe, especially in a site as exposed as GreenVolt. It confirms that seasonality alone is no longer the sole limiting factor: geographical and environmental characteristics play a dominant role in operational feasibility.

This pattern highlights how, at GreenVolt, seasonal variation is no longer enough to explain the limits of intervention. The site's remote location, depth and overall metocean conditions instability provide logistical challenges and increase risk levels. These factors, taken together, severely limit the effectiveness and cost-efficiency of generator replacement operations—even in seasons typically considered favourable.

The data also suggest that In-Situ replacement operations are becoming increasingly impractical and, in some cases unfeasible under these conditions. Although the In-Situ approach remains a valid strategy in accessible sites or during optimal weather windows, it quickly loses its operational and financial efficiency. This is especially true for high-complexity tasks such as generator replacements, which demand heavy equipment, experienced personnel, and especially long, stable weather windows.

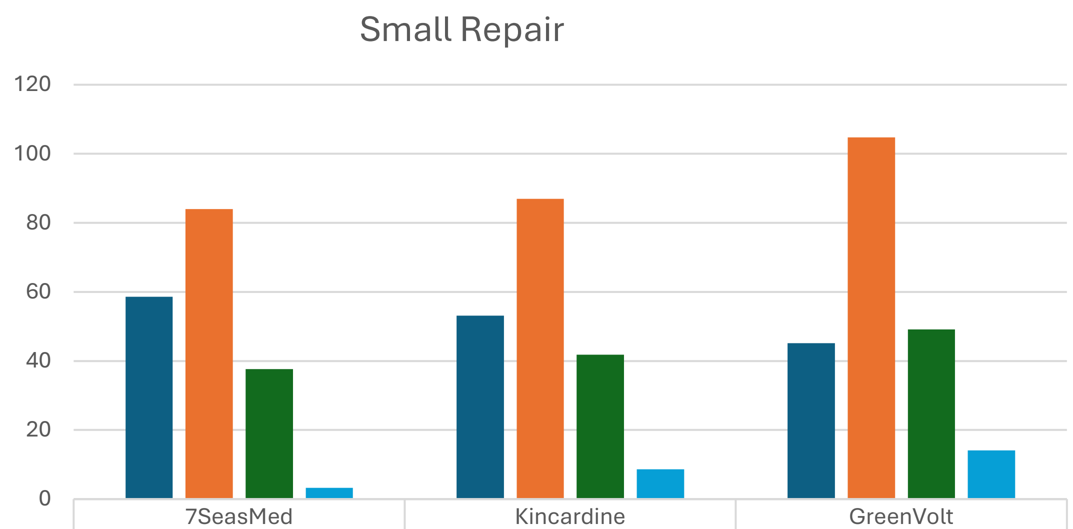
The fact that only two interventions were successfully completed during winter serves as a clear warning: the operational risk is approaching unsustainable levels, and the chances of delays, failure, or uncontrolled cost increases are high. In such a scenario, gaining access to the turbine becomes a high-risk activity. This raises serious concerns about current O&M strategies in remote, high-risk environments such as GreenVolt and calls for a reassessment of how and when to plan critical interventions.

Given these findings, maintenance planning for deep offshore wind farms must shift toward a multi-factor evaluation model, incorporating not only seasonality but also distance, water depth, access constraints, and weather predictability. This shift is essential for managing complex replacement operations effectively in harsh marine environments and for ensuring operational reliability in the face of increasing logistical challenges. As mentioned at the beginning of the chapter, the seasonal analysis results carried out for Pitch System small repair and replacement are almost similar to the generator ones. However, it is worth noticing how an increase of replacement window and a reduction of the repair window provide different results with respect to generator case. Results concerning the Pitch system case are available in the appendix A.

4.4. Site comparison

After carrying out the seasonal analysis for each site, highlighting how average costs, total repair times, and the number of successfully completed operations vary across the seasons, this section shows a direct comparison between the different sites. Specifically, it explores how these indicators change from site to site, according to season and type of the failure. The aim of this comparison is to provide a sensitivity analysis focused on two main factors: the ***distance from the closest port*** and the difference about **metocean conditions** between the Mediterranean Sea and the North Sea. Although the comparison focuses on the generator, the results are the same for the Pitch System, given the consistency observed in the seasonal analysis. In addition, since the main differences are very significant in summer and winter months, the spring and autumn seasons are reported in the appendix B.

- **Summer**



	7SeasMed	Kincardine	GreenVolt
Operat_Comp	59	53	45
Costs (1.000*€)	83,97	86,94	104,75
Total Time (h)	37,69	41,79	49,17
Waiting Time (h)	3,25	8,69	14,15

Figure 28. Site comparison - Summer – Small repair – Generator case

Summer is the most favourable period for all three sites, although the performance differences persist. For Small Repairs, 7SeasMed again leads with 59 completed interventions, average completion time of 37.7 hours, and costs around €84.000. The average waiting time is minimal at 3 hours, confirming that the Mediterranean is ideal for fast and reliable maintenance, especially during summer months.

Kincardine follows with 53 interventions, about 42 hours of total time, and average costs of €87.000, offering a strong balance due to its closer proximity to port. GreenVolt improves compared to spring but still lags behind: 45 interventions, 50 hours of total time, and average costs of €104.000, with waiting time around 14 hours.

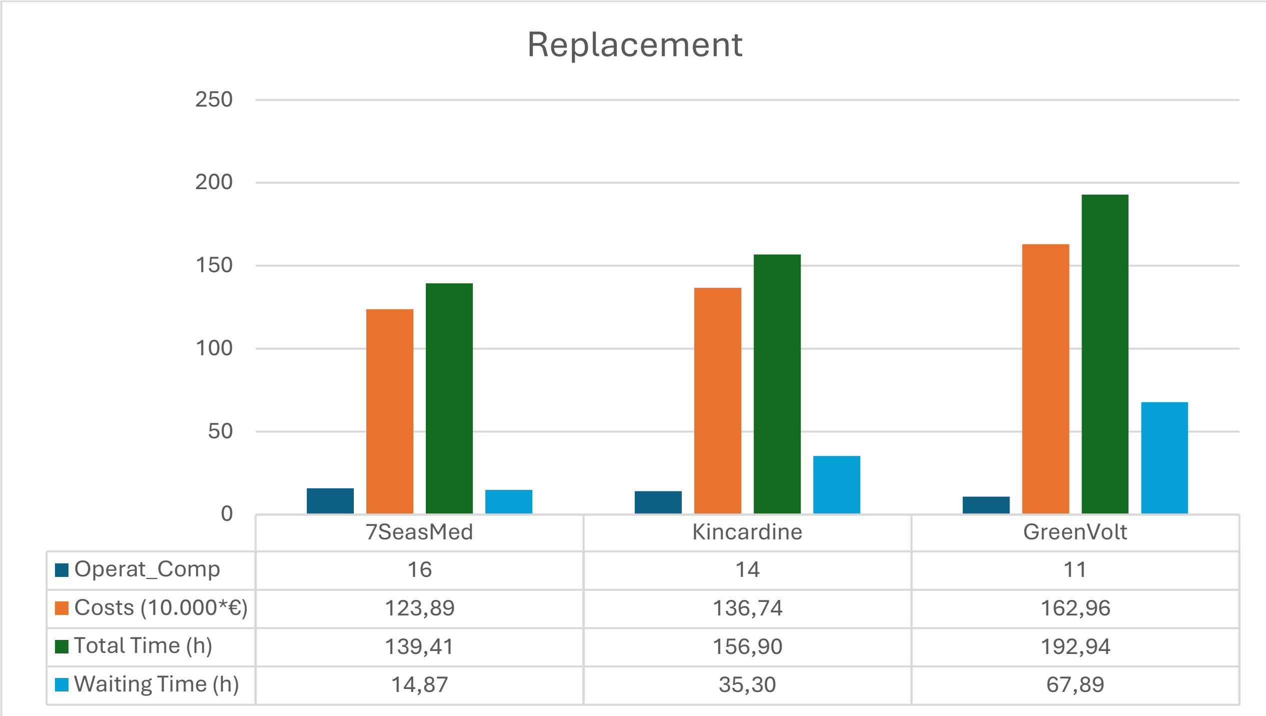
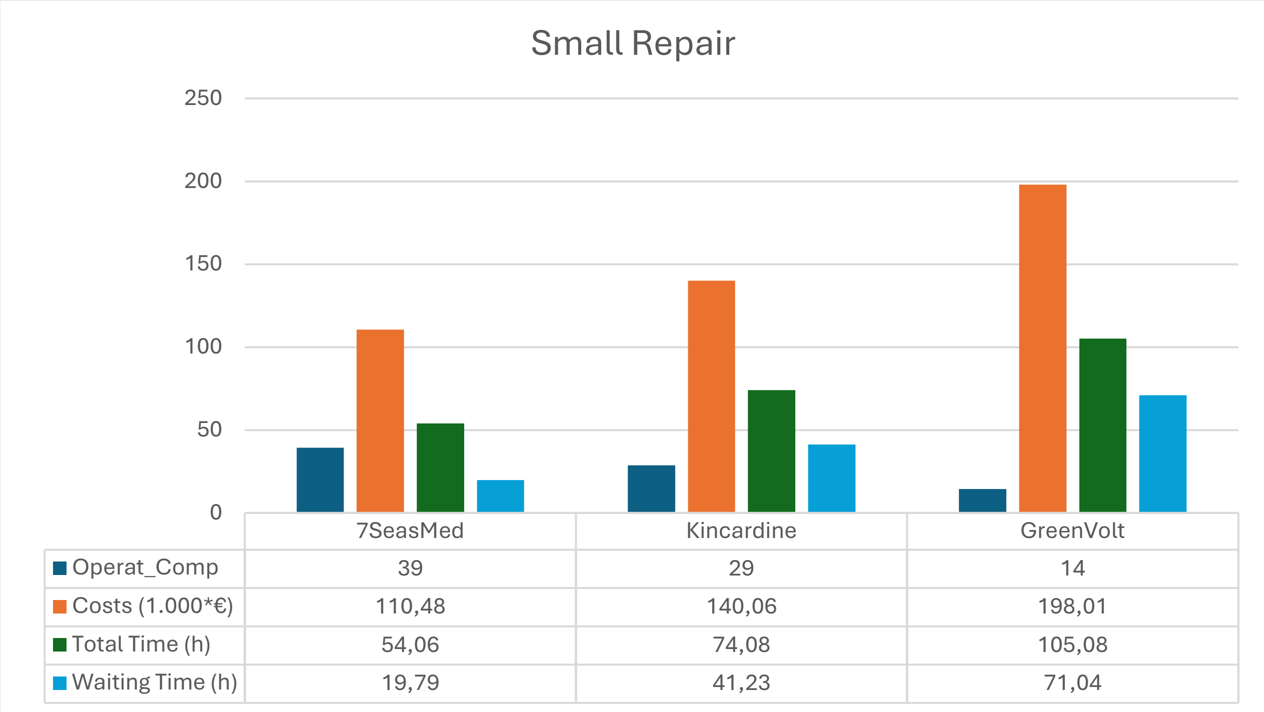


Figure 29. Site comparison - Summer - Replacement - Generator case

In terms of **replacements**, 7SeasMed still performs best: 16 replacements completed, average cost of €123.900, and completion time under 160 hours. Kincardine follows with 14 operations and slightly higher time and cost values. GreenVolt completes just 11 replacements, with average time exceeding 185 hours and costs around €190.000. Even in summer, the North Sea's remoteness and harsher environment limit productivity.

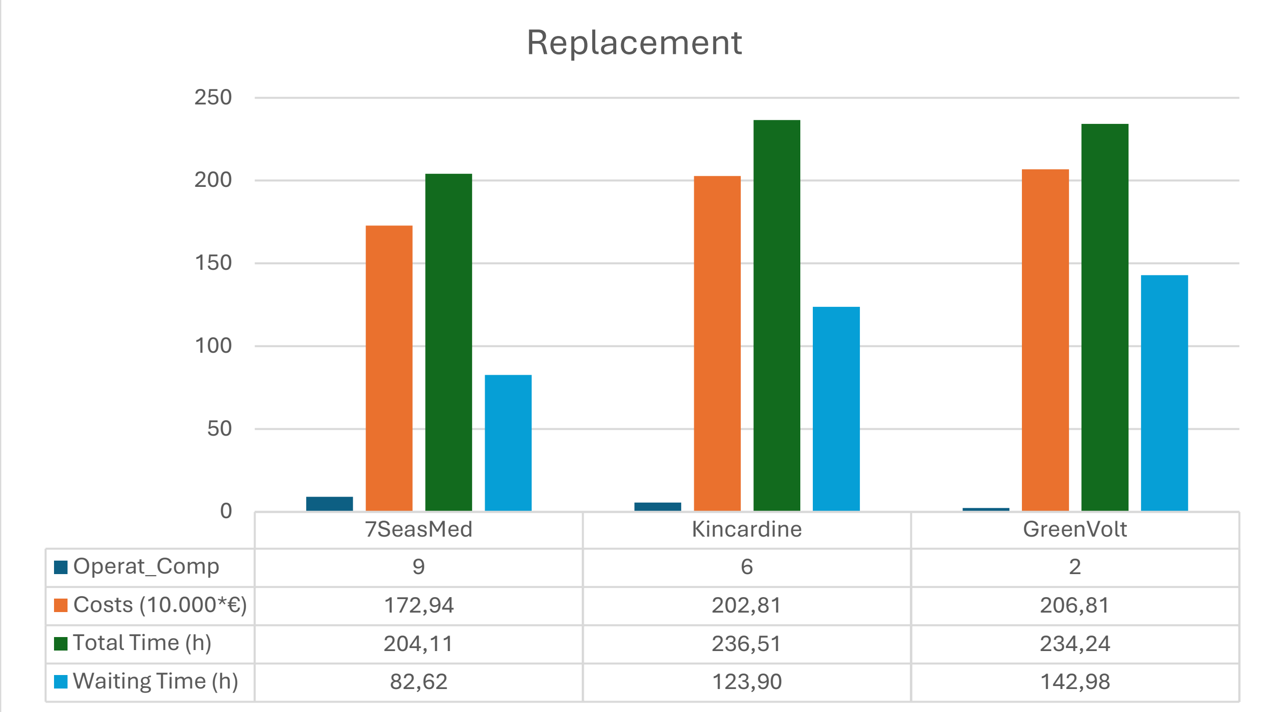
- **Winter**



	7SeasMed	Kincardine	GreenVolt
Operat_Comp	39	29	14
Costs (1.000*€)	110,48	140,06	198,01
Total Time (h)	54,06	74,08	105,08
Waiting Time (h)	19,79	41,23	71,04

Figure 30. Site comparison - Winter - Small repair - Generator case

Winter represents the operational limit for all sites, with the impact most severe in the North Sea. For **Small Repairs**, 7SeasMed still averages 39 interventions, with costs around €110.480, completion times of 54 hours, and minimal waiting delays. Kincardine decreases to 29 interventions, costs of €140.060, and waiting times around 41 hours. GreenVolt performs the worst: only 14 successful repairs, 105 hours of total time, and average costs around €198.000, with waiting time reaching 71 hours.



	7SeasMed	Kincardine	GreenVolt
Operat_Comp	9	6	2
Costs (10.000*€)	172,94	202,81	206,81
Total Time (h)	204,11	236,51	234,24
Waiting Time (h)	82,62	123,90	142,98

Figure 31. Site comparison - Winter - Replacement - Generator case

Replacements during winter are the most problematic. 7SeasMed completes 9 replacements, with 204 hours total time and costs around €173.000. Kincardine drops to 6 operations, while GreenVolt reaches the lowest point: only 2 interventions, 235 hours of total time, and costs approaching €2 million. In this season, the combination of severe weather and long distance from shore renders In-Situ maintenance nearly unfeasible.

The comparison across the different sites highlights how metocean conditions and distance from shore significantly affect the performance of corrective maintenance operations. In particular, when it comes to Small Repairs, these interventions are generally feasible throughout all seasons. Although winter shows a decreasing in the number of successfully completed operations, such activities remain, in most cases, achievable even during the most challenging months.

However, a key point is that: greater the distance from shore and poorer will be the operational performance, regardless of the season. GreenVolt, being the farthest offshore among the sites analysed, consistently showed the worst performance in terms of fewer successful operations, longer waiting times, and significantly higher average costs, reinforcing the impact of remoteness on maintenance feasibility.

The differences become even more evident when analysing replacement operations. Because of their higher complexity and considerably longer duration compared to small repairs, replacements are much more sensitive to both sea conditions and distance. During winter, in particular, such interventions become unfeasible, making turbine access extremely difficult. Under these conditions, an In-Situ approach would not only be inefficient but also potentially unsafe, making a Tow-to-Port (T2P) strategy a more viable option.

Moreover, the analysis showed that proximity to port plays a decisive role: sites located closer to shore, such as Kincardine, reported lower costs and greater operational efficiency, even if subjected to North Sea metocean conditions. On the other hand, when both distance and severe sea conditions come into play, like GreenVolt case, corrective maintenance operations, particularly complex ones, become almost entirely impractical.

4.5. Post – Processing and Opex estimation

This section presents the results obtained through a post-processing phase of the seasonal model described in Section 8.2. In particular, the focus is on the estimation of Operational Expenditures (Opex) associated with corrective maintenance activities carried out through an In-Situ approach, applied to both Small Repairs and Replacements of the generator and pitch system.

The analysis will mainly focus on the generator, using data from the three previously studied offshore sites: 7SeasMed, Kincardine, and GreenVolt. As for the pitch system, only the final results will be presented as they closely align with those of the generator.

The first step in the Opex estimation process involves collecting and organizing the average cost values related to both small repair and replacement operations. These costs have been calculated for each season of the year (spring, summer, autumn, winter), while also maintaining site-specific differentiation. The following tables summarizes the average costs per season and for the three sites.

- Small Repair

	7SeasMed	Kincardine	GreenVolt
Spring (€)	99.690	100.470	134.640
Summer (€)	83.970	86.940	104.750
Autumn (€)	95.460	115.900	160.170
Winter (€)	110.480	140.060	198.010

Table 14. Small Repair seasonal average costs

- Replacement

	7SeasMed	Kincardine	GreenVolt
Spring (€)	1.534.800	1.618.900	1.906.000
Summer (€)	1.238.900	1.367.400	1.629.600
Autumn (€)	1.449.000	1.851.900	2.026.000
Winter (€)	1.729.400	2.028.100	2.068.100

Table 15. Replacement seasonal average costs

After describing the average costs associated with each operation type, the next step involves integrating these data with the Annual Failure Rate (AFR) previously introduced in the Component Layer section. Based on values reported from the literature [29], [30], [31], [32], [33], [34] the AFR is set at 0.09 failures per year, meaning each component analysed has a 9% probability of failure annually.

However, for the purposes of Opex analysis, it is essential to distinguish between failures that can be addressed through small repairs and those that require a full component replacement. It is well known that minor repairable failures occur more frequently than those requiring replacement.

As result, an assumption has been established with 80% of failures attributed to small repairs, and the remaining 20% to replacements. Applying this distribution to the annual failure rate it is possible to get the following values:

- **Small repairs**: 0.09 × 0.80 = 0.072 failures/year
- **Replacements**: 0.09 × 0.20 = 0.018 failures/year

These values represent the expected annual frequency of each type of corrective intervention on the considered component.

However, in order to achieve a more accurate Opex estimation, it is essential to consider that each season carries a different probability of intervention, because of different metocean conditions. As discussed in previous chapters, and particularly in Section 8.3, winter is the most critical period of the year, marked by harsh environmental conditions that severely limit access to turbines and the feasibility of performing corrective maintenance.

Following this reason, and in line with the data presented in the table from Section 8.3, it is possible to adjust the previously estimated Annual Failure Rates (AFR, by applying seasonal correction factors. This allows for a more realistic distribution of failures that can actually be addressed throughout the year.

- **Small repair: 0,072 failure/year**

Season	% failure	N. of events
Spring	22,5 %	0,0162
Summer	5%	0,0036
Autumn	22,5 %	0,0162
Winter	50%	0,036

Table 16. Small repair seasonal failure rate

- **Replacement: 0,018 failure/year**

Season	% failure	N. of events
Spring	22,5 %	0,00405
Summer	5%	0,0009
Autumn	22,5 %	0,00405
Winter	50%	0,009

Table 17. Replacement seasonal failure rate

Finally, a comprehensive Opex estimation for the generator has been carried out based on the formula previously introduced in Section 8.3:

$$Opex = \sum_{1}^{4} [\mathbf{N\_events\_SR} \times \mathbf{C\_SR} + \mathbf{N\_events\_R} \times \mathbf{C\_R}]$$

This expression enables a preliminary quantification of the annual operational costs associated with corrective maintenance activities performed through an In-Situ approach.

By applying this methodology, which combines the seasonally adjusted failure frequency with the corresponding average costs, it was possible to get a first estimation of the generator-specific Opex for each site analysed. This approach serves as a basic tool for assessing the economic viability of a corrective maintenance - In-situ approach. The following table shows the results obtained for the three different site and for the components analysed.

- **Generator**

	7SeasMed	Kincardine	GreenVolt
Opex – single turbine (€/year)	36.205	42.400	48.285
Opex – wind farm (€/year)	760.350	254.403	1.689.993
Opex – wind farm (€/MW)	3.017,26	5.139,45	3.219,03

Table 18. Opex estimate - Generator case

- **Pitch System**

	7SeasMed	Kincardine	GreenVolt
Opex – single turbine (€/year)	36.363	42.966	48.813
Opex – wind farm (€/year)	763.636	257.800	1.708.458
Opex – wind farm (€/MW)	3.030,30	5.208,08	3.254,21

Table 19. Opex estimate - Pitch case

It is important to note that the estimated values do not include the cost of the component being repaired or replaced, nor the costs related to turbine downtime during the intervention. In addition, this estimation does not account for preventive maintenance costs or for potential long-term economic variations, such as inflation or future cost escalation.

These aspects represent critical variables for a comprehensive Opex evaluation and should be considered in more advanced and detailed analyses. However, the purpose of this review is to provide a preliminary reference post-processing model for estimating the Opex associated with corrective maintenance activities carried out through an In-Situ approach in offshore wind farms. As a result, it is quite difficult to find studies in the existing literature to provide a direct comparison with the results of the present analysis. For this reason, the proposed work establishes a methodological foundation upon which further and more advanced research on corrective maintenance in floating wind farms can be built.

Although it is not straightforward to find studies in the literature that allow for a direct comparison with the present results, a rough reference can still be derived from existing data. Specifically, [55] reports that the annual Opex associated to corrective maintenance ranges between €73,000 and €77,000 per MW per year. In addition, [56] estimates approximately €108,000 per MW per year for general maintenance activities, while [57] proposes values between €58,000 and €71,000 per MW per year under conservative assumptions.

As these examples demonstrate, Opex values can vary significantly depending on the geographic location and technological configuration of the wind farm. In this study, the Opex estimation focuses specifically on the generator and pitch system. Assuming same Opex contribution for each major turbine component mentioned in section 1.3. and taking Kincardine, as operational site, as a reference, the resulting value is approximately €62,500 per MW per year, which is in close alignment with the range reported in the literature.

It should be noted, however, that this estimate does not account for component-specific maintenance strategies. As a result, the actual OPEX values would likely be higher in a more detailed and component-targeted analysis.

The model developed can nonetheless be replicated and adapted for other turbine components, making it a flexible and scalable tool for broader system-level economic assessments.

5. Conclusions

This study has developed and described a seasonal analysis model for corrective maintenance in the context of floating offshore wind technology. Although still in its early stages, this technology shows great promise while facing several operational challenges, maintenance being one of the most critical. Once installed, an offshore wind farm must be kept in optimal condition not only to extend its lifetime but also to ensure peak performance. However, the emerging nature of this sector means that no robust and consolidated models yet exist for forecasting and optimizing maintenance strategies.

In this context, the work presented offers a first structured framework for estimating costs, average intervention times, and the mean number of corrective maintenance operations, distinguishing between Small Repairs and Replacements, while incorporating seasonal variability. Rather than predicting the exact moment of failure, the model estimates, for each season, the average expected cost, duration, and number of interventions that could be carried out if a failure were to occur.

Beyond the seasonal performance analysis, the study also includes a post-processing phase to estimate preliminary OPEX. In particular, for the generator and the pitch system, based on an In-Situ approach. The methodology developed is replicable for any wind turbine component, including floating platforms and subsea structures, provided that appropriate maintenance strategies are applied.

The seasonal model was integrated into a MATLAB-based simulation and applied to three sites: 7SeasMed (Mediterranean Sea), Kincardine, and GreenVolt (North Sea). The use of seasonal values for significant wave height (Hs) and 100 meter wind speed allowed for detailed comparisons across different locations. A comprehensive analysis was carried out, assessing average costs, total maintenance durations, and waiting times for each component and for each season.

This comparison made it possible to evaluate not only the differences between small repairs and replacements point of view among the seasons, but also the site-specific operational challenges. On one hand, it was observed that increasing distance from shore leads to higher costs and longer durations due to greater fuel consumption and increased vessel and equipment rental costs. On the other hand, the more severe marine conditions in the North Sea make turbine access significantly more complex, particularly for replacements.

Overall, a clear seasonal trend emerged across all sites and failure types, with more favourable conditions in summer and more critical scenarios in winter. This work thus provides a solid foundation for future O&M optimization studies and represents a preliminary tool for building more advanced models that may include preventive maintenance, downtime estimation, inflation, and long-term planning.

As a potential future development, this work could be further improved by extending the seasonal analysis, both technical and economic, to include other turbine components. This would allow for a more comprehensive and accurate estimation of the annual Opex related to corrective maintenance performed by an In-Situ approach, not only at single-turbine scale, and eventually across the entire wind farm.

To make the model even more representative of real-world operations, an additional improvement could involve pausing maintenance activities overnight, simulating the possibility for the team to sleep on board the vessel and start working the following day. In addition, another improvement could be the introduction of a threshold on the wave period (Tp), in order to increase the reliability and robustness of the analysis, particularly under severe marine conditions. Moreover, for a more comprehensive analysis, an evaluation of the availability of ports and vessels should be taken into account. This assessment would inevitably extend the intervention timeline, with a corresponding increase in costs. A clear example is the T2S operation carried out for Kincardine [], where factoring in both the vessel availability and the port's readiness to allocate quay space could result in waiting times of up to 12 months.

Additionally, the same report highlights that the most significant cost factor is the rental of vessels and equipment. This cost carries considerable weight, as both vessels and equipment remain rented for the entire duration of the operation, leading to substantially higher expenses.

Finally, to make the analysis even more realistic, it would be necessary to include the availability of spare parts and personnel, both of which would further extend the intervention timeline.

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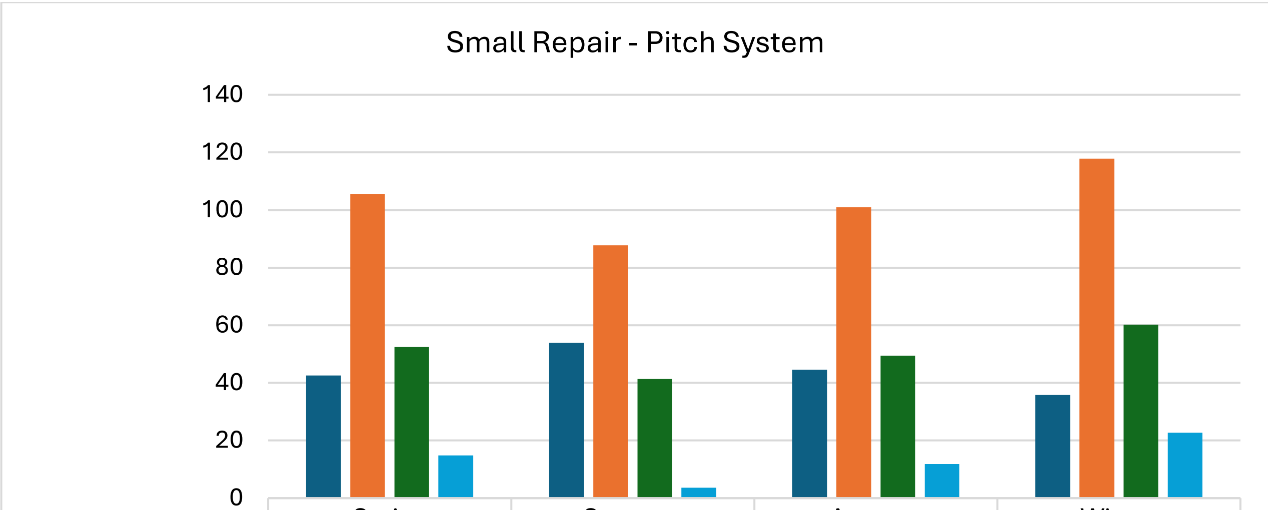
Appendix A

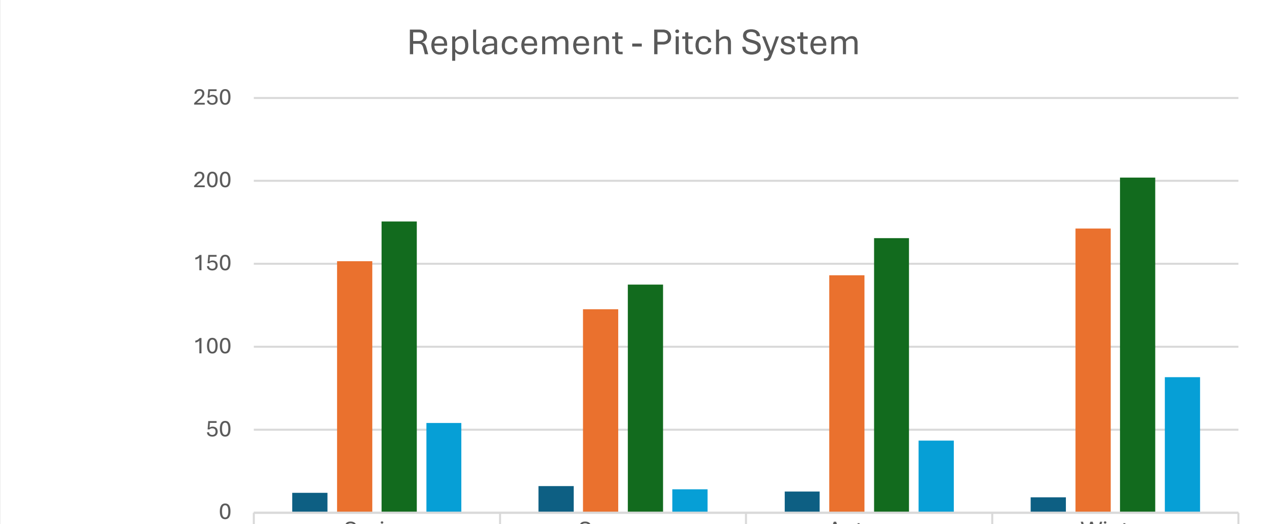
This appendix presents the detailed results and visual outputs related to the Pitch System, focusing on both *Small Repair* and *Replacement* cases. The analysis was carried out across the three reference sites: 7SeasMed, Kincardine and GreenVolt. Results are shown through bar charts that illustrate both average maintenance cost, intervention time (hours) and waiting times, along with average o successfully completed operations for each season.

- **7SeasMed**



	Spring	Summer	Autumn	Winter
Operat_Comp	43	54	45	36
Costs (1.000*€)	105,64	87,74	100,92	117,79
Total Time (h)	52,45	41,32	49,44	60,21
Waiting Time (h)	14,87	3,63	11,83	22,67

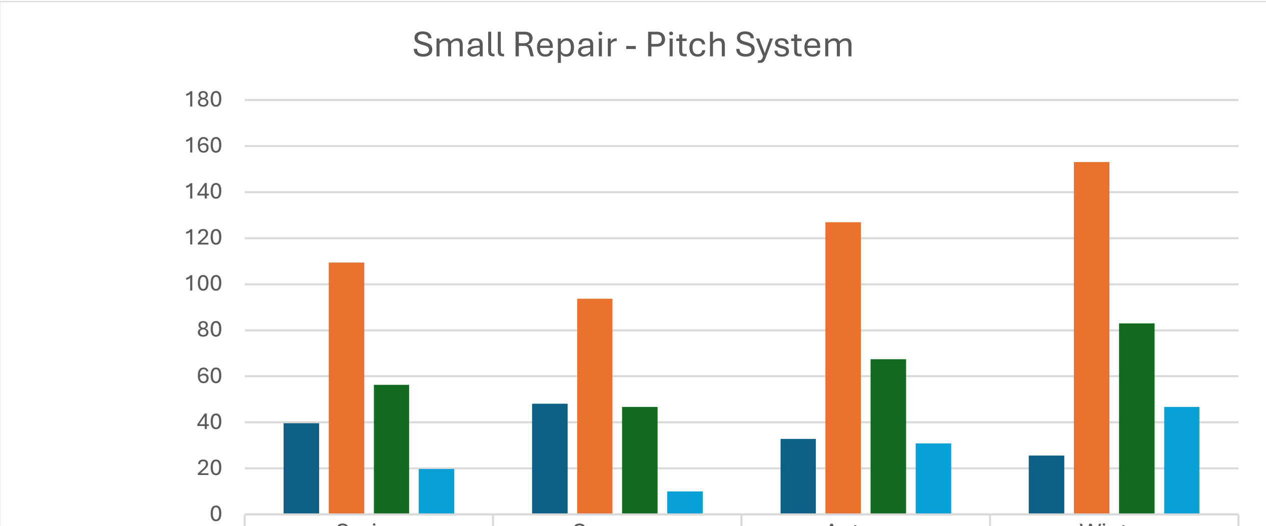
Figure 32. 7SeasMed - Small repair - Pitch case



	Spring	Summer	Autumn	Winter
Operat_Comp	12	16	13	9
Costs (10.000*€)	151,68	122,60	143,17	171,29
Total Time (h)	175,58	137,47	165,53	201,98
Waiting Time (h)	54,20	14,10	43,40	81,75

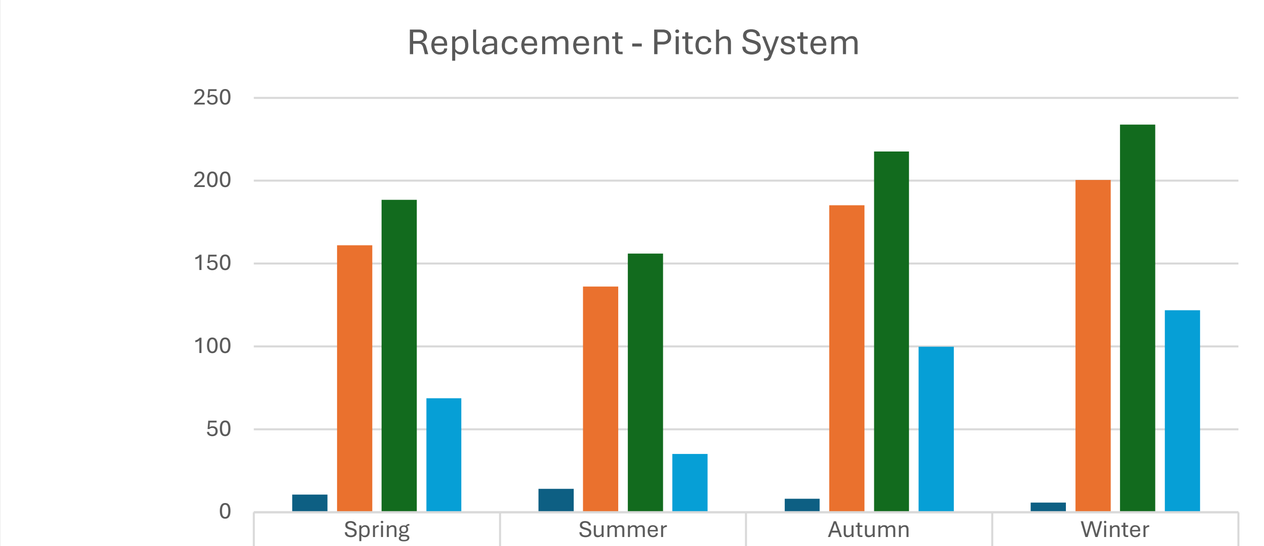
Figure 33. 7SeasMed - Replacement - Pitch case

- **Kincardine**



	Spring	Summer	Autumn	Winter
Operat_Comp	40	48	33	26
Costs (1.000*€)	109,34	93,68	126,90	153,03
Total Time (h)	56,28	46,68	67,36	83,06
Waiting Time (h)	19,73	10,04	30,88	46,76

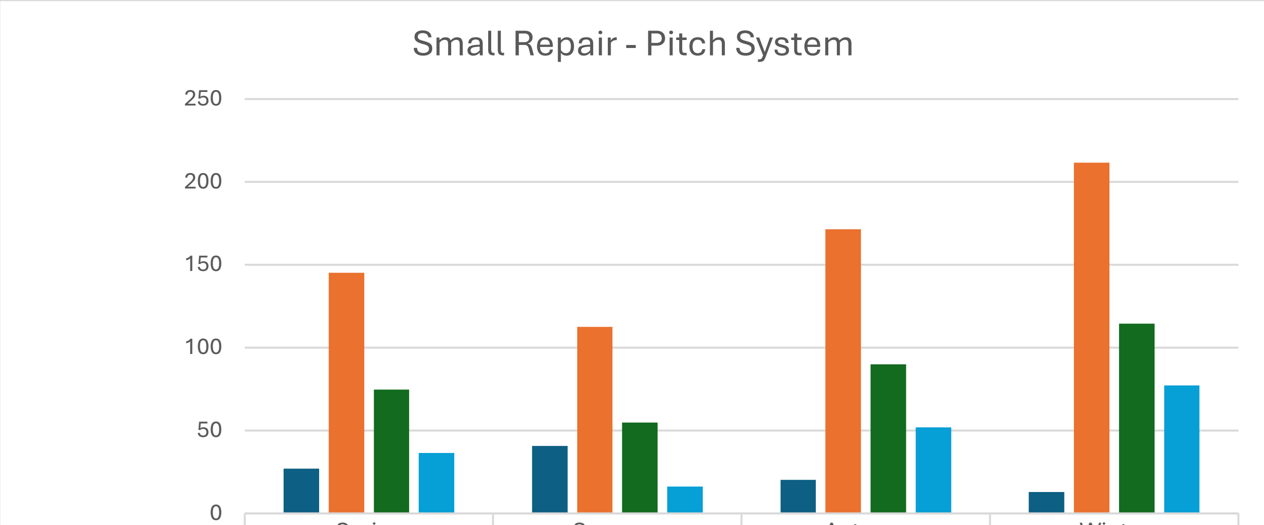
Figure 34. Kincardine - Small repair - Pitch case



	Spring	Summer	Autumn	Winter
Operat_Comp	11	14	8	6
Costs (10.000*€)	161,08	136,15	185,13	200,51
Total Time (h)	188,56	155,99	217,73	233,90
Waiting Time (h)	68,88	35,15	99,84	121,91

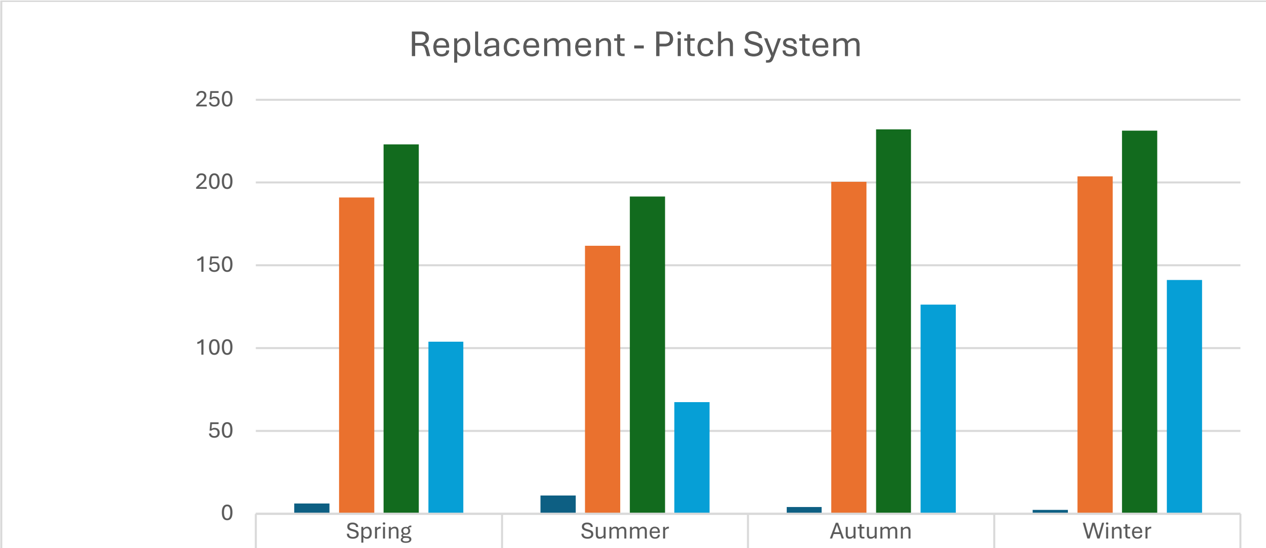
Figure 35. Kincardine - Replacement - Pitch case

- **GreenVolt**



	Spring	Summer	Autumn	Winter
Operat_Comp	27	41	20	13
Costs (1.000*€)	145,21	112,56	171,50	211,67
Total Time (h)	74,77	54,81	89,99	114,42
Waiting Time (h)	36,40	16,24	51,94	77,28

Figure 36. GreenVolt - Small repair - Pitch case



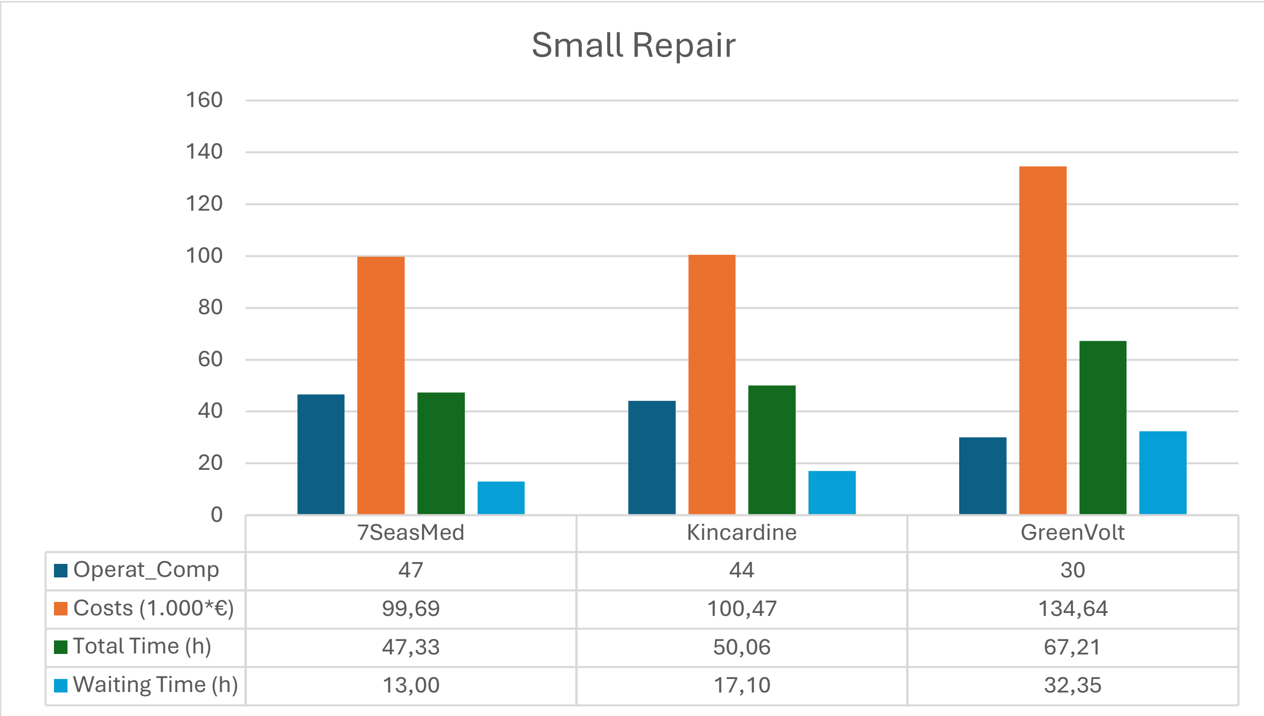
	Spring	Summer	Autumn	Winter
Operat_Comp	6	11	4	2
Costs (10.000*€)	190,99	161,80	200,56	203,81
Total Time (h)	223,03	191,64	232,11	231,40
Waiting Time (h)	103,91	67,41	126,42	141,11

Figure 37. GreenVolt - Replacement - Pitch case

Appendix B

The following appendix presents a comparative analysis across the three sites: 7SeasMed, Kincardine and GreenVolt; specifically focusing on the spring and autumn seasons. This data has been included to complete the seasonal comparison between locations. Bar charts and summary tables are provided below to illustrate and consolidate the results obtained.

- **Spring**

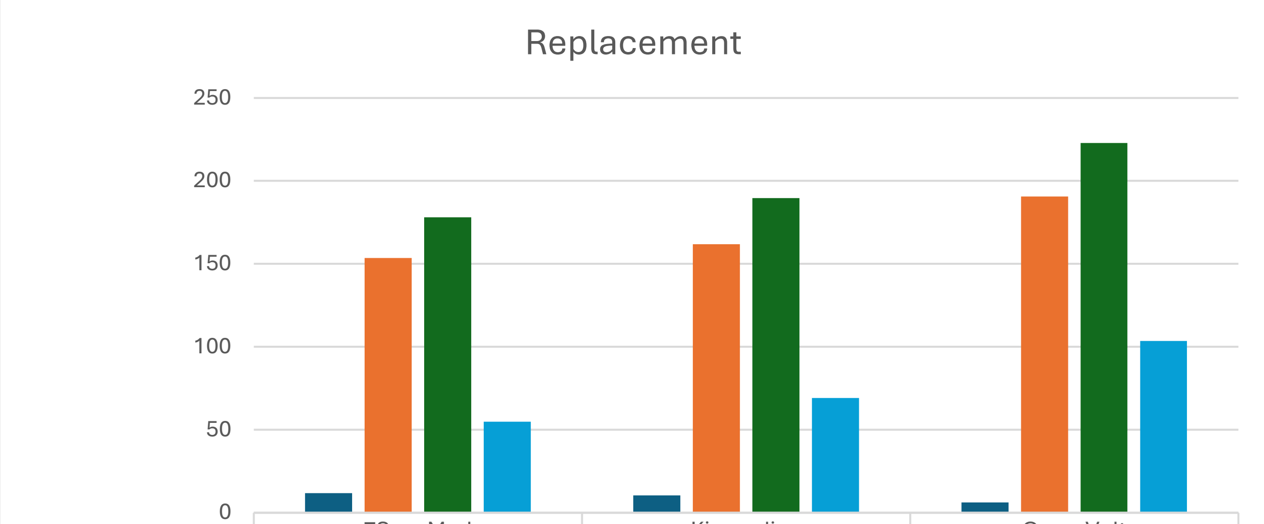


	7SeasMed	Kincardine	GreenVolt
Operat_Comp	47	44	30
Costs (1.000*€)	99,69	100,47	134,64
Total Time (h)	47,33	50,06	67,21
Waiting Time (h)	13,00	17,10	32,35

Figure 38. Site comparison - Spring - Small repair - Generator case

During the spring season and as shown in the figures, the performance differences among the three sites start to emerge clearly. Regarding **Small Repairs**, the 7SeasMed site in the Mediterranean Sea shows significantly better operational results: an average of 47 successful interventions, an average cost of approximately €99.690, average total repair time of 47.3 hours, and average waiting time of just 13 hours. These values reflect the more favourable weather conditions of the Mediterranean, which allow for more consistent turbine access.

Instead, GreenVolt, located in the North Sea 80 km from the closest port, already reveals access limitations in spring, with only 30 completed operations, average costs exceeding €134.600, completion times above 67 hours, and waiting times around 32 hours. Kincardine, although also in the North Sea but much closer to shore (20 km), shows intermediate results: 44 interventions, average cost of €100.470, and waiting times near 17 hours.

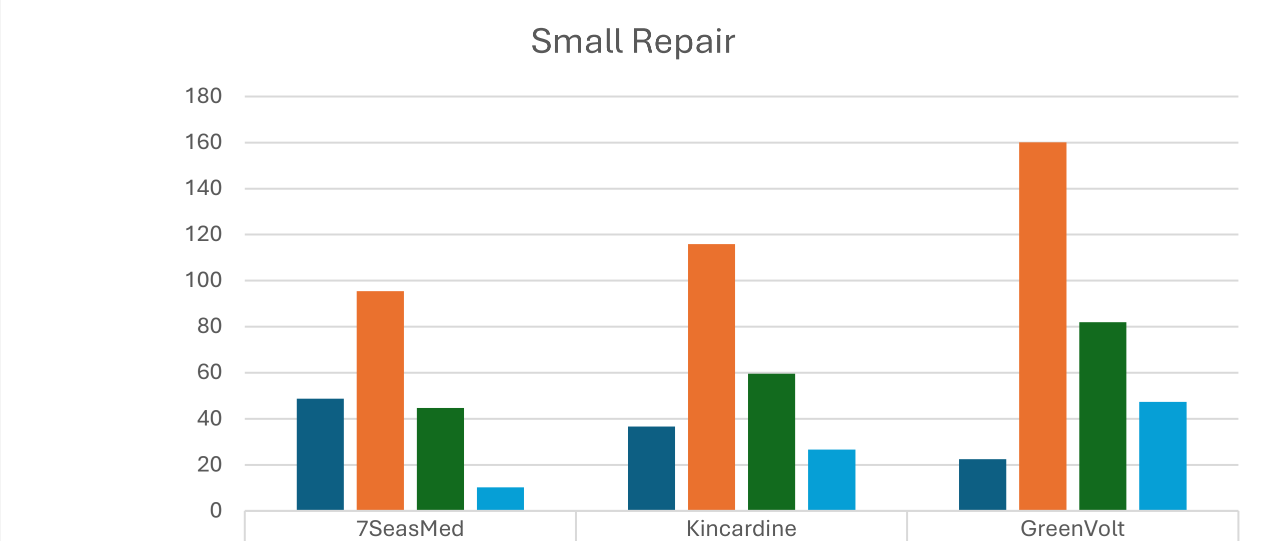


	7SeasMed	Kincardine	GreenVolt
Operat_Comp	12	11	6
Costs (10.000*€)	153,48	161,89	190,60
Total Time (h)	178,04	189,62	222,89
Waiting Time (h)	54,85	69,19	103,49

Figure 39. Site comparison - Spring - Replacement - Generator case

By looking at **replacements**, the gap between sites is even wider. 7SeasMed maintains a satisfactory level of 12 successful replacements, average total time of 178 hours, and waiting time around 55 hours. GreenVolt performs far worse, with only 6 replacements completed, over 222 hours of completion time, and more than 103 hours of waiting. These figures confirm that both distance and unstable sea conditions in the North Sea severely limit the feasibility of complex maintenance interventions, even during a moderate season like spring.

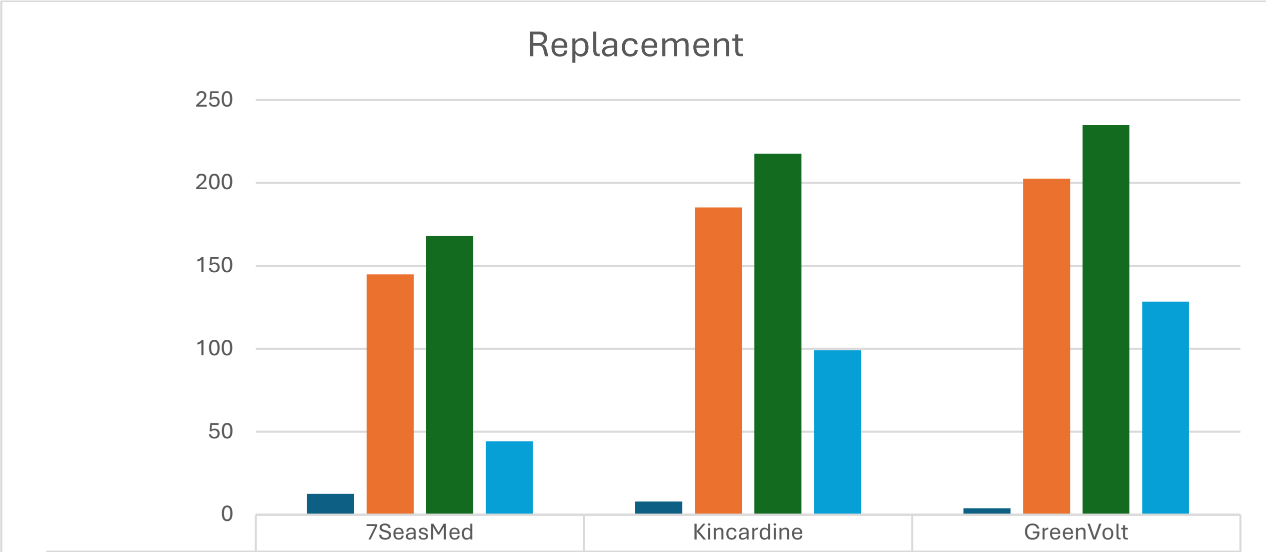
- **Autumn**



	7SeasMed	Kincardine	GreenVolt
Operat_Comp	49	37	22
Costs (1.000*€)	95,46	115,90	160,17
Total Time (h)	44,70	59,61	82,01
Waiting Time (h)	10,30	26,69	47,40

Figure 40. Site comparison - Autumn - Small repair - Generator case

In autumn, performance decreases across all sites, as winter months start to be reached. For **Small Repairs**, 7SeasMed remains efficient with 49 interventions, average time of 44.7 hours, and costs around €95.500. GreenVolt drops significantly to 22 interventions, with nearly 82 hours of average total time and costs over €160.000, indicating a return to more challenging weather. Kincardine shows intermediate figures: 37 repairs, 59.6 hours of time, and moderate cost levels.



	7SeasMed	Kincardine	GreenVolt
Operat_Comp	13	8	4
Costs (10.000*€)	144,90	185,19	202,60
Total Time (h)	168,09	217,75	234,90
Waiting Time (h)	44,22	99,11	128,51

Figure 41. Site comparison - Autumn - Replacement - Generator case

For **replacements**, the situation becomes increasingly critical for North Sea sites. 7SeasMed keeps a solid performance with 13 operations, costs around €145.000, and completion times around 168 hours. Kincardine drops to 8 replacements, with completion times exceeding 217 hours and waiting times over 99 hours. GreenVolt is hit hardest, with only 4 replacements, average time over 234 hours, and waiting exceeding 128 hours. This confirms that as the season worsens, offshore access becomes critical, especially in remote areas.