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Numerical Modeling of Operation and Maintenance Costs for Floating Offshore Wind Farms in the Mediterranean Sea

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"If a thing is humanly possible,
consider it within your reach"
- Marcus Aurelius

Abstract

As floating offshore wind energy becomes an increasingly viable solution for harvesting renewable energy in deep-water regions, understanding and optimizing operations and maintenance (O&M) costs is essential for ensuring economic sustainability. This thesis aims to investigate main O&M strategies for floating offshore wind farms in the Mediterranean Sea region, due to its potential in both production and accessibility, with a particular emphasis on operational expenditure (OPEX) modeling, by considering the components more prone to failure, the metocean conditions and weather windows.

The thesis is organized as follows: firstly, an analysis about existing ports and vessels availability in the Mediterranean region is conducted, to provide context about the current logistic infrastructure to support the growing interest around FOWT.

After a literature review about the existing cost models, a MATLAB-based simulation tool is developed to evaluate the impact of maintenance strategies and site-specific accessibility constraints on OPEX outcomes. The tool integrates turbine characteristics, cost parameters, and sea-state data related to different O&M strategies of each component to compute OPEX for corrective maintenance approaches. A comparative case study between two offshore sites, one located in the North Sea and the other in the Mediterranean Sea, highlights how metocean conditions can affect accessibility, downtime, and cost efficiency.

Results show that site-specific weather patterns significantly impact O&M logistics and the overall OPEX. In the North Sea, OPEX/MW is 60.7% higher than in the Mediterranean, driven by 55% extra weather downtime and a medium cost per failure approximately €200.000 greater. These findings offer valuable insights for optimizing maintenance planning and decreasing LCOE in floating offshore wind projects, providing meaningful perspectives into how existing support infrastructure in the Mediterranean Sea can be strengthened and expanded to meet the growing demand for offshore wind energy, unlocking the full potential of the region.

Summary

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Acronyms

FOWT:

Floating Offshore Wind Turbine

FOWF:

Floating Offshore Wind Farm

FOW:

Floating Offshore Wind

O&M:

Operations and Maintenance

CAPEX:

Capital Expenditure

OPEX:

Operational Expenditure

FBWT:

Fixed Bottom Wind Turbine

HLV:

Heavy-lift Vessel

TRL:

Technology Readiness Level

TLP:

Tension-Leg Platform

DP:

Dynamic Positioning

ROV:

Remotely Operated Vehicle

LCOE:

Levelized Cost of Energy

AEP:

Annual Energy Production

CTV:

Crew Transfer Vessel

JUV:

Jack-Up Vessel

SOV:

Special Operation Vessel

T2P:

Tow To Port

T2S:

Tow To Shallow waters

NREL:

National Renewable Energy Lab

DIAC:

Dynamic Inter-Array Cable

CLV:

Cable-Laying Vessel

Chapter 1: Introduction to Floating Offshore Wind Turbines

1.1 Overview of Offshore Wind Energy

Offshore wind power is a renewable and infinite energy source, obtained from the generation of electricity through the harnessing of kinetic energy by clusters of wind turbines (so-called Wind Farms), placed on large bodies of water where strong winds allow for greater production.

Given the profound transformation of the global energy landscape due to the urgent need of reducing greenhouse gas emissions and transitioning to a sustainable energy system, offshore wind power has risen as one of the most promising solutions to meet decarbonization goals of 2030 and 2050 by respectively 45% less and net-zero emissions to keep global warming below 1.5°C [1].

Since the commissioning of the first offshore wind farm in Vindeby in 1991, showed in Figure 1.1 [2], the offshore wind industry has undergone a profound transformation. From a modest 0.45 MW pilot project, the sector has matured into a cornerstone of the global energy transition, supported by innovation, policy and rapidly falling costs.

Figure 1.1: Vindeby Offshore Wind Farm

By the end of 2024, global operational offshore wind capacity surpassed 80.9 GW, as shown in Figure 1.2, representing a 15% increase over the previous year. This growth was spearheaded by China, which added 6.9 GW in a single year, maintaining its global lead with a cumulative capacity of 39.1 GW [3], represented in Figure 1.3. Europe followed closely, with the United Kingdom remaining the largest European player, contributing approximately 15 GW of capacity by 2023 [4]. The Netherlands also saw significant growth, with 1.7 GW added in 2024 [3].

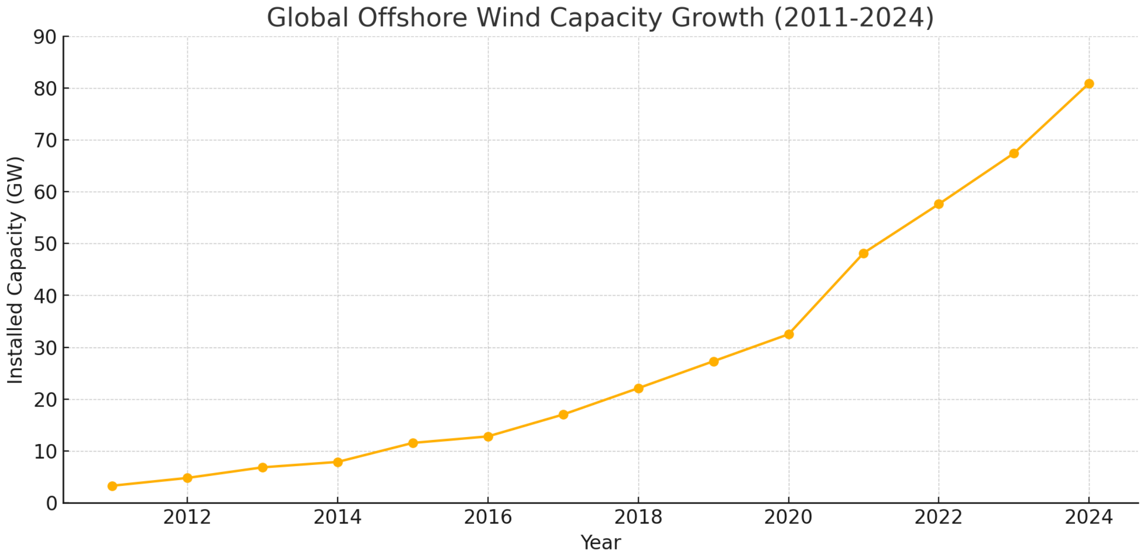


Figure 1.2: Global Offshore Wind Growth

The global market's momentum is reflected in ambitious national targets. The UK aims to reach 50 GW by 2030 [4], while the European Union plans for at least 111 GW by the same year as part of its Green Deal strategy. Meanwhile, the United States, though a late entrant, is targeting 30 GW of offshore wind by 2030, backed by federal funding, tax incentives and infrastructure investment [5].

The industry's explosive growth is underpinned by advances in turbine design and engineering. Early turbines like those at Vindeby featured capacities under 0.5 MW, but modern installations now employ turbines rated at 12–15 MW, with prototypes even larger under testing [6]. Turbine hub heights have grown from 35 meters in the 1990s to over 120 meters today, with rotor diameters spanning more than 220 meters, significantly increasing swept area and energy capture [6].

Floating offshore wind technology is another breakthrough, allowing deployment in deeper waters beyond the continental shelf. This expands geographical possibilities to previously inaccessible markets like the western United States, Japan and parts of the Mediterranean [7].

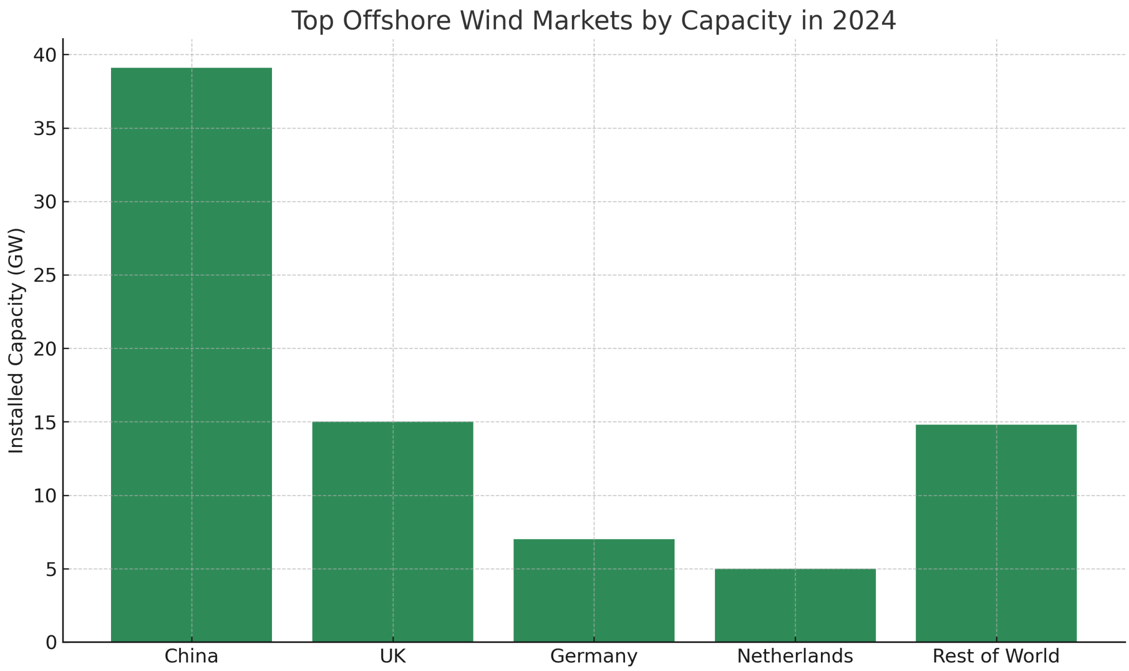


Figure 1.3: Top Offshore Wind Markets by Capacity in 2024

The levelized cost of electricity (LCOE) for offshore wind has declined by almost 60% since 2010, driven by economies of scale, improved logistics and higher turbine efficiency [9]. In some markets, such as the UK and the Netherlands, offshore wind now competes directly with fossil fuels on price, even without subsidies [7].

In addition to environmental benefits, offshore wind generates significant economic value. The sector currently supports over 500,000 jobs globally, a number projected to more than double by 2030 [8]. Port development, vessel construction, grid upgrades, and local supply chains all benefit from long-term investments.

According to the Global Wind Energy Council (GWEC), global offshore wind capacity is expected to reach 270 GW by 2030 and 447 GW by 2032, as shown in Figure 1.4, assuming current policy trajectories are maintained [10]. Annual installations are forecasted to surpass 20 GW by 2025, with China, the UK and the USA dominating new capacity additions [8][9].

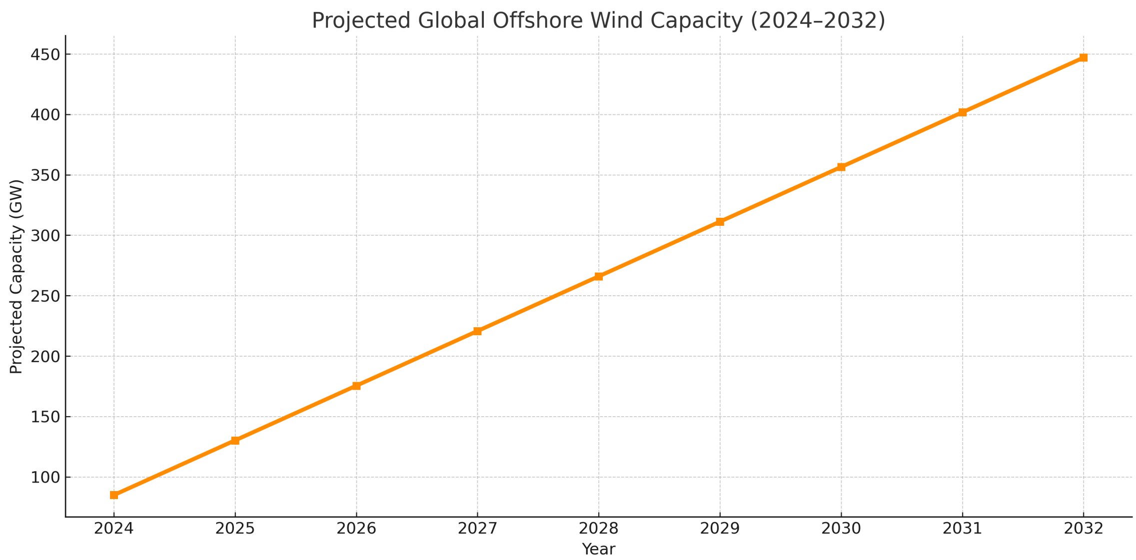


Figure 1.4: Projected Global Offshore Wind Capacity (2024-2032)

Crucially, this scaling aligns with international climate goals: offshore wind can supply over 10% of global electricity demand by 2050, avoiding more than 3 billion tons of CO_2 emissions annually [9]. Its strategic placement, close to coastal demand centers, also enhances energy security and grid resilience.

Offshore wind energy has evolved from a Danish experiment into a global clean energy powerhouse. Backed by technology, policy and economics, it is poised to play a decisive role in the world's efforts to decarbonize by 2030 and reach net-zero emissions by 2050. Continued international collaboration, innovation and investment will be essential to realizing the full potential of offshore wind in the decades ahead.

1.2 Fixed-bottom Vs. Floating Wind Turbines

This section presents a comparison between the fully developed concept of Fixed-Bottom Wind Turbines (FBWTs) and the emerging technology of Floating Offshore Wind Turbines (FOWTs), which represents the core focus of this thesis.

Fixed-bottom turbines are anchored directly to the seabed using foundations such as monopiles, jackets, tripods or gravity-based caissons. These foundations provide stable support on shallow continental shelves, typically in water depths up to 60m. Monopiles are the most prevalent, featuring simplicity and cost-effectiveness; jacket structures, composed of steel lattice frameworks, are favored in intermediate-depth waters for their structural efficiency. An image representation can be found on Figure 1.5 [10].

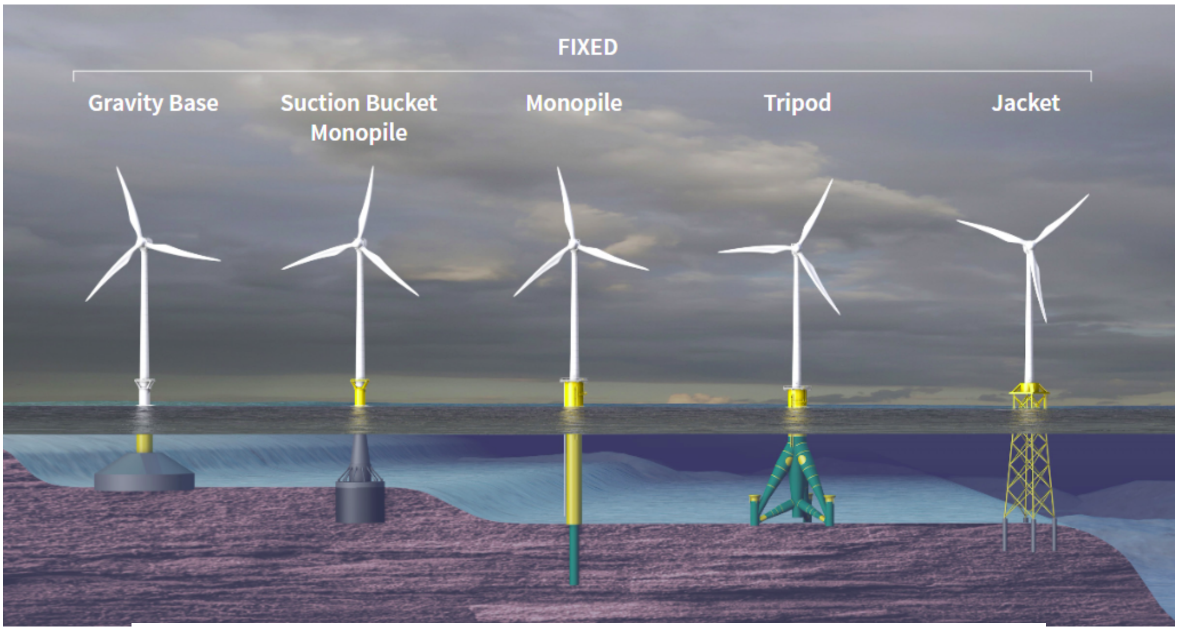


Figure 1.5: Types of foundation for FBWTs

Installation involves transporting pre-installed towers and foundations using HLV (Heavy-lift Vessel) or Jack-up Vessel, in Figure 1.6 [11], subsequently to a seabed preparation, piling and leveling activities that are highly sensitive to weather windows.
Routine inspections and repairs are facilitated by predictable access via jack-up vessels. The fixed nature of the foundation ensures steady work platforms and manageable weather windows, keeping O&M costs relatively low.

Figure 1.6: Voltaire, the world's biggest Jack-up Vessel, owned by Jan De Nul Group

Fixed-bottom technology is fully commercialized, with mature supply chains, optimized cost structures and a global installed capacity of 75 GW at the end of 2023, according to Global Wind Energy Council [12].

On the other hand, Floating technology, of which technical differences are briefly highlighted on Table 1.1 and further discussed in the next session, presents elevate operational complexity, sophisticated planning and resource allocation, with a TRL 6-8 and commercial-scale deployment still on the beginning [13].

Nonetheless, floating substructures allow the development of offshore wind in context of higher water depths inaccessible to FBWT, resulting in the increasing of offshore wind capacity in both existing and new markets, reducing emissions and providing more energy.

Table 1.1: Comparative Summary of Fixed-Bottom vs. Floating Turbines

Aspect	Fixed-Bottom	Floating
Deployment Depth	0-60 m	60-1000+ m
Foundation Types	Monopile, Jacket, Gravity	Spar, Semi-sub, TLP
Installation Vessels	HVL, Jack-up	Tug, Tow, DP vessels
Tech Maturity	TRL 9 (commercial)	TRL 6-8 (pre-commercial)
CAPEX/OPEX	Lower	~15–20 % higher, decreasing with scale
O&M Complexity	Moderate (predictable)	High (platform motion, towing logistics)

1.3 Principal Components

FOWTs consist of several critical components adapted from fixed-bottom turbine technology, but often reinforced or re-engineered to accommodate dynamic marine conditions. These components include the nacelle, rotor, tower, floating substructure, mooring systems and dynamic electrical cables.

1.3.1 Nacelle

The nacelle, in Figure 1.7 [14], is the structural and functional heart of a wind turbine, housing the key mechanical and electrical systems that convert rotational energy from the rotor into electrical energy. In FOWTs, nacelle design is adapted to account for the additional loads and dynamic motions induced by the floating platform.

Figure 1.7: GE's Haliade-X 12 MW nacelle

Nacelle is typically enclosed in mid-grade steels and cast spheroidal graphite (SG) iron, which offer the lowest cost per unit fatigue strength [15].
Key elements housed within the nacelle include:

- Main Shaft and Bearings: transfers rotational energy from the rotor to the drivetrain;
- Gearbox: increases the rotor speed to match the generator's input requirement;
- Generator: converts mechanical energy into electricity;
- Yaw System: actively orients the nacelle into the prevailing wind direction, as floating platforms have six degrees of freedom (heave, pitch, roll, surge, sway, yaw);
- Cooling System: maintains acceptable operating temperatures for drivetrain and electronics;
- Braking System: ensures safe shutdown during overspeed or fault conditions.

Other components such as control and condition monitoring systems are included in the nacelle.

1.3.2 Rotor

The rotor is responsible for capturing the kinetic energy of wind and transferring it into mechanical energy. It consists of blades, hub casting, blade system, bearings and pitch system.

Blades are typically constructed from composite materials (e.g., fiberglass-reinforced epoxy or carbon fiber [15]) to achieve a balance between strength, weight and flexibility. Each blade is attached to a bearing, which in turn is bolted to a central hub on the main shaft. The bearing allows the pitch mechanism to rotate the blade, enabling adjustments to its angle. This helps regulate the turbine's power output, reduce mechanical loads and control turbine operation such as initiating startup or performing shutdowns when needed.

Individual pitch control for each blade helps mitigate asymmetric loading and fatigue caused by wave-induced rotor misalignment [16].

To properly distance every turbine form each other, the rotor diameter is taken into consideration as a distance measure, to avoid turbulences which could interfere with the production (wake effects). Based on the type of turbine, 7-10 diameters apart in the wind's direction and 3-5 diameters apart in the perpendicular direction to the wind are considered a common guideline.

1.3.3 Tower

The tower serves a critical structural function, supporting the nacelle and rotor at a sufficient height to access stronger and more consistent wind speeds. It consists of a tubular steel structure which contains control and electrical equipment and provide protection and housing for internal access systems, such as ladders or lifts. Newer research also explores hybrid towers using steel-concrete combinations to reduce weight and lower the center of gravity [17].

Design of FOWT towers is primarily governed by fatigue life considerations, extreme environmental loading and compliance with natural frequency constraints to avoid dynamic amplification and buckling.

The optimal tower height is typically set to the minimum required for compliance with maritime safety standards, particularly ensuring sufficient blade-tip clearance above sea level [15].

Due to the relatively low wind shear offshore, which refers to the change in wind speed or direction with height above the sea surface, taller towers do not offer substantial performance gains that justify their increased cost and structural complexity.

1.3.4 Electrical System

The electrical system is responsible for the generation, transformation, transmission and control of electrical power from the turbine to the onshore grid. While functionally similar to FBWTs, the electrical system of FOWTs must address additional challenges related to platform motion, flexible cable routing and dynamic environmental loads.
Primary elements of the FOWT electrical system include:

- Generator, previously discussed as part of the Nacelle;
- Power converters;
- Transformers: located either in the nacelle or tower base, these step up the voltage (typically from 690 V to 33-36 kV) to reduce current losses during transmission;
- Dynamic inter-array cables: these connect multiple turbines in a wind farm and must accommodate the motion of floating platforms;
- Export cables: transmit power from the offshore substation to the onshore grid.

To optimize power delivery, floating wind farms often use medium-voltage AC (MVAC) transmission over short distances. For far-from-shore projects, high-voltage AC (HVAC) or HVDC (high-voltage direct current) transmission is required to reduce losses.
The electrical system is not limited to individual turbines, as it is integrated into farm-wide energy management systems, including offshore substations, supervisory control and data acquisition systems (SCADA) and energy storage and hybrid systems.

1.3.5 Cables

Cables are essential to the operation of FOWTs, serving as the primary infrastructure for electrical system previously discussed, data communication and control signaling.
The main types of cable used are:

- Inter-array cables: MVAC (medium-voltage AC) cables (typically 33-66 kV) that connect individual turbines within the wind farm, transferring electricity to a central collection point or offshore substation;
- Export cables: HVAC (high-voltage AC) or HVDC (high-voltage DC) cables used to transmit aggregated power from the offshore site to the onshore grid;
- Dynamic cables: specialized flexible cables used in FOWTs to handle continuous mechanical motion and wave-induced forces;
- Internal cables: located within the turbine's nacelle and tower, including low-voltage cables for auxiliary power and fiber-optic cables for SCADA systems and condition monitoring.

Standard subsea power cables used in FOWTs typically consist of conductors surrounded by multiple layers including sealing barriers, electrical insulation to maintain a uniform electric field within the cable, structural fillers and mechanical armoring for protection. A detailed structure recap can be found on Appendix A.
In AC offshore configurations, the cables are generally three-cores, with each core transmitting one phase of the electrical power. In contrast, onshore AC systems usually use single-core cables, which are grouped in sets of three to form a complete circuit. DC cables, both for land and subsea use, also employ single-core designs, with one core for each polarity (positive and negative) per transmission circuit. [15]
There are three primary insulated core designs for high-voltage power cables:

- Dry design – utilizes a lead sheath extruded over the insulation layer, creating a fully impervious moisture barrier;
- Semi-wet design – incorporates a polyethylene sheath over a metallic screen that is not entirely impervious to moisture;
- Wet design – omits an additional sheath, relying solely on a non-impervious metallic screen, allowing limited moisture ingress.

As subsea cables for FOWTs has to withstand the movement of floating substructures, hence resulting in a greater fatigue loading, armoring is carefully studied to provide mechanical protection against tensions and compressions due to platform motion, external impact from marine debris and seabed interaction and torsion during cable laying and operation, which has to be limited to a specified minimum bend radius for not increasing the risk of damaging the cable. This section is typically made up of galvanized steel wires or copper wires, often arranged in two counter-helix layers for torque balancing, as shown in Figure.

Figure 1.8: Dynamic array cable section

Also, dynamic cables are provided of buoyancy and ballast modules to maintain a certain shape in the water column, as in Figure 1.9 [15].

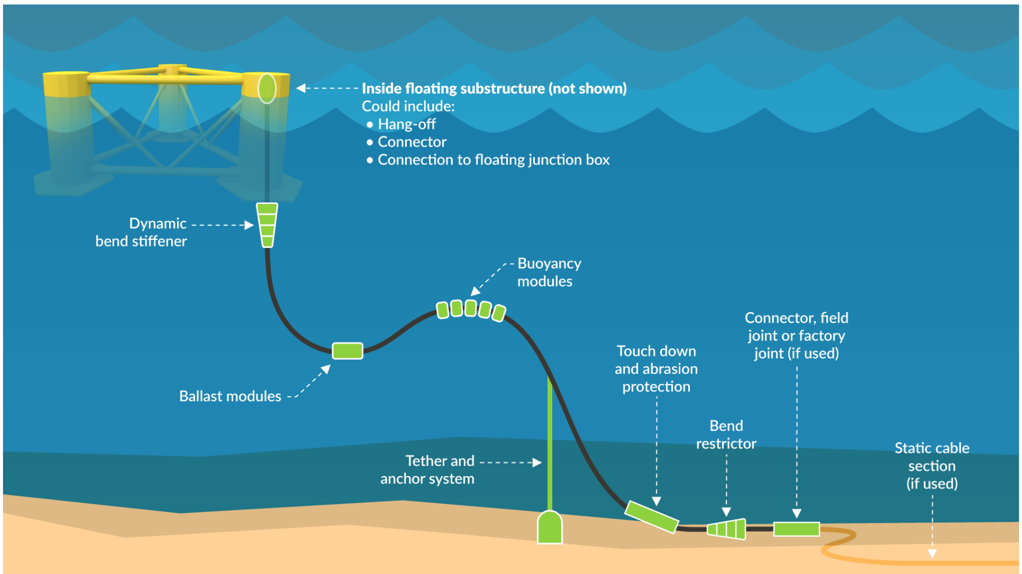


Figure 1.9: Floating offshore wind dynamic cable system

Cable manufacturers are continuously investing in research and development of dynamic designs to enhance the evolution of floating offshore wind sector. As an example, Prysmian, the leader manufacturer in production, supply and design of subsea cables, recently developed a new dynamic HVAC 245 kV cable studied for granting higher performances and resistance to marine conditions.

1.3.6 Offshore Substation

The offshore substation is responsible for collecting, transforming and exporting the electricity generated by wind turbines to the onshore grid. It serves as the central hub where the inter-array cables from individual turbines converge and are connected to export cables that transmit the power to shore. The substation may be installed on a fixed, as in Figure 1.10 [15], or floating platform.

Figure 1.10: A fixed offshore substation, part of Hornsea One project

They consist of a main electrical power system and auxiliary systems, housed on a topside structure.
Their primary functions are:

- Voltage transformation: converts medium voltage (33-66 kV) from the wind turbines to higher transmission voltages (132 kV or more for HVAC, ±320 kV for HVDC);
- Protection and Control: houses switchgear, protection relays, SCADA systems and communication infrastructure to monitor and control power flow.
- Power Quality Management: ensures voltage stability, reactive power compensation and harmonic filtering;
- Export Connection: facilitates the connection between offshore and onshore grids via submarine export cables, as shown in Figure 1.11 [18].

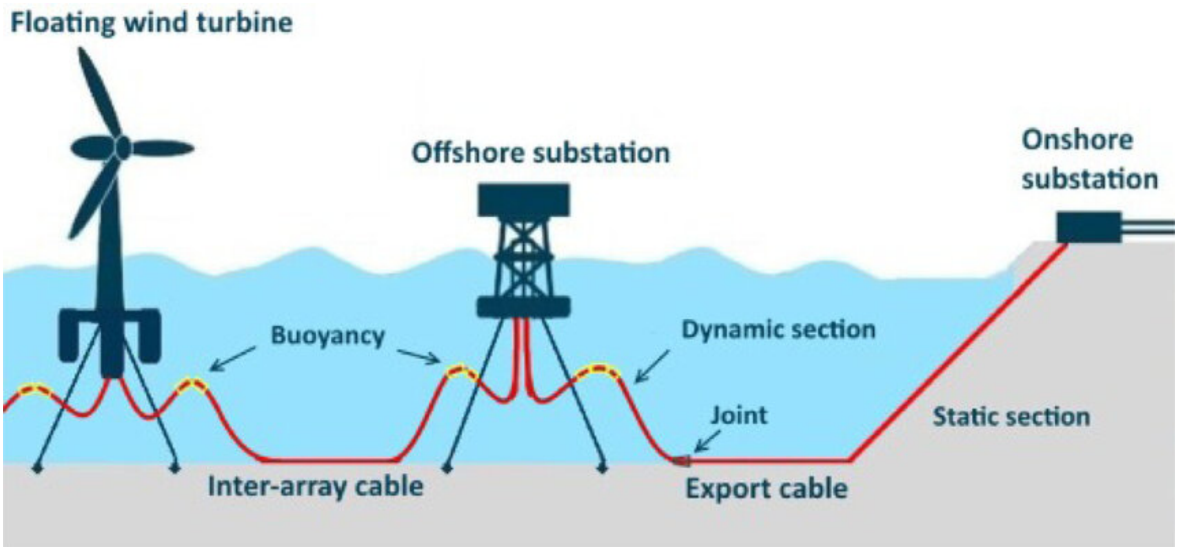


Figure 1.11: Typical electrical system of a FOW farm, showing connection between Turbine, Offshore substation and Onshore substation

As the offshore wind industry moves toward deeper waters with FOWTs, the concept of floating substation is gaining traction. These are mounted on floating platforms, such as semi-submersible or spar-type structures, and anchored similarly to floating turbines.

1.3.7 Onshore Substation

The onshore substation serves as the critical interface between the offshore wind farm and the terrestrial electricity transmission grid. After power is conducted via submarine export cables from the offshore substation, it arrives at the onshore substation where it undergoes final voltage transformation, monitoring and distribution into the national grid network.

Like its offshore counterpart, the onshore substation has functions of voltage transformation, up to 400 kV, and conversion to three-phase AC in case a HDVC export cable is used. It also provides switchgear to protect the grid from the wind farm, and vice versa, for fault conditions.

The location of the onshore substation is strategically selected base on proximity to landfall point of the export cable, existing grid infrastructure, environmental and permitting constraints.

The substation is generally divided into two different parts: a larger wind farm side owned by the offshore transmission owner and the grid side owned by the relevant grid operator [15].

1.3.8 Floating substructure

Floating substructure enables deployment in water depths typically exceeding 60 meters, where fixed-bottom foundations become technically or economically unfeasible. These structures support the wind turbine and maintain stability by counteracting environmental forces from wind, waves and currents through a combination of buoyancy, mooring and ballast systems.

Its key functions regard structural support, dynamic response control, cable and mooring interface.

Four main types of substructures are used in FOWTs: Spar-buoy, Semi-submersible, Tension-leg Platform (TLP) and Barge. All of them are described in Table 2 and showed in Figure 1.12 [19].

Table 1.2: Main Types of Floating Substructures

Type	Characteristics	Example Projects
Spar-buoy	Deep draft, stable due to low center of gravity; requires deep ports for assembly	Hywind Scotland, Hywind Tampen
Semi-submersible	Multiple columns and pontoons; widely used; stable with low draft; easier assembly	WindFloat Atlantic, Kincardine
Tension-leg platform (TLP)	Buoyancy held in place by taut mooring lines; minimal vertical motion	Demonstration only (e.g., PelaStar)
Barge	Shallow draft, flat-bottomed; suitable for near-shore, calm environments	Limited to low-energy sites

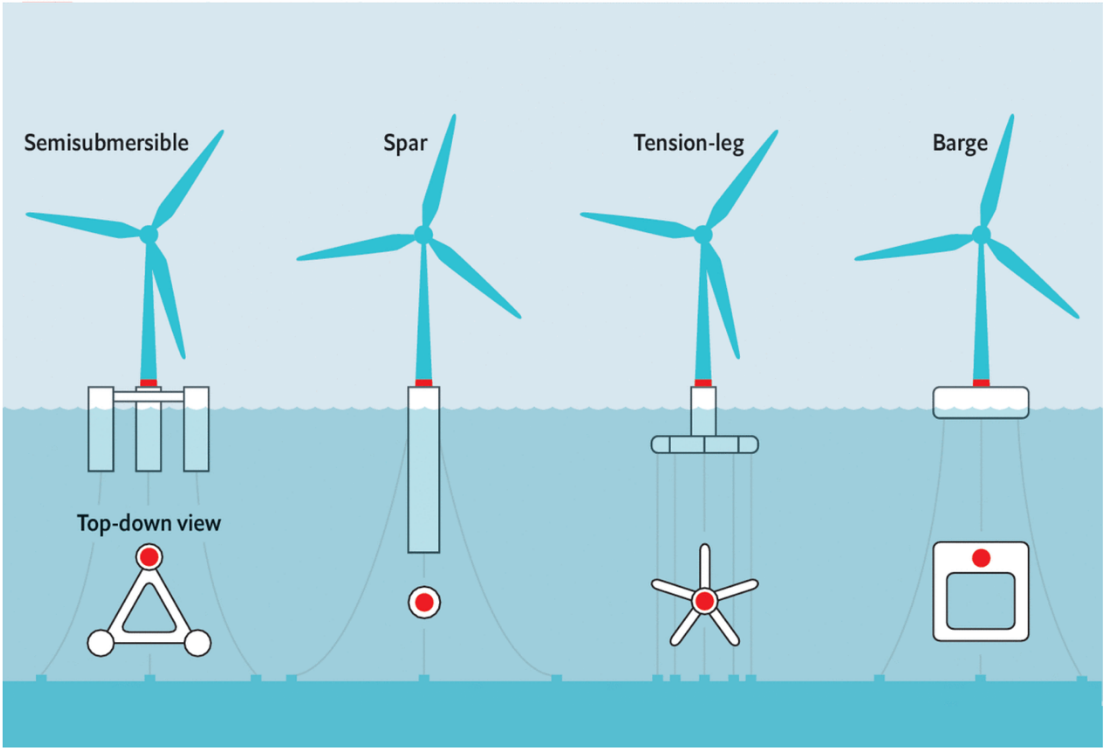


Figure 1.12: Comparison between the four main types of floating substructure

As mentioned in the nacelle section, a FOWTs has six possible degrees of freedom due to movements and rotations along three axes, as shown in Figure 1.13 [20]. Hence, designing floating substructure involves balancing hydrodynamic performance, structural efficiency and cost effectiveness, which all converge into key feature like natural frequency separation from wave and rotor-induced loads to avoid resonance, mass distribution etc.

Recent design tools increasingly rely on coupled aero-hydro-servo-elastic simulations to accurately model the complex interactions between the wind turbine and its floating support system.

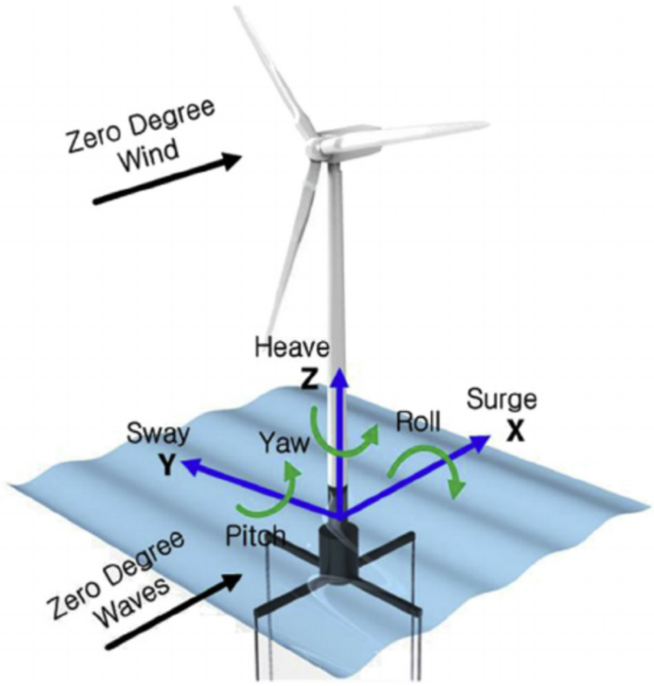


Figure 1.13: Movements and rotations of a FOWT along the three axes

Floating substructures are typically fabricated using steel or concrete, depending on cost, supply chain availability and local industrial capacity. Hybrid solutions are also being developed.

1.3.9 Mooring System

The mooring system serves as an anchoring of the floating substructure to the seabed, maintaining its position within specified tolerances under varying environmental conditions. Unlike FBWTs, the floating ones depend on flexible station-keeping systems that accommodate motion while ensuring structural integrity and grid connectivity.

Its main functions regard: station-keeping, for the prevention of excessive drift and maintaining of positional accuracy; load transfer, to safely transfer environmental loads from the floating platform to the seabed through mooring lines and anchors; damping, to reduce motion, especially in pitch and surge; stability support, contributing directly to vertical stability in some configurations (e.g., TLP).

The mooring system is principally composed of:

- Mooring lines, made of chains, wire ropes or synthetic ropes (e.g. nylon, polyester or HMPE [15]). Usually, a mooring line is made of different materials along its full length as it can have three different sections: upper, middle and ground. More specifications about this can be found on Appendix B;
- Anchors, which could be the type of drag embedment, suction, driven piles or vertical load. Their selection depends on seabed composition, mooring load profile and water depth.
- Fairleads and Connectors, mechanical interfaces between the mooring lines and the floating platform or anchor, that must accommodate movement, tension variation and corrosion over the Wind Farm's life cycle (usually 20-25 years).

Different kinds of configurations for mooring are available, as shown in Table 3 below.

Table 1.3: Mooring Configurations

Configuration	**Description**	**Typical Use**
Catenary	Uses heavy chain resting on seabed; cost-effective; high footprint	Semi-submersible
Taut-leg	Tensioned synthetic or wire lines; low seabed impact; more vertical loads	TLP, deep water
Semi-taut	Hybrid between catenary and taut; balances cost, performance and footprint	Deep water semi-submersible
Spread mooring	Mooring lines radiate in multiple directions from the floater	Most common for floating wind farms
Single point	Turbine can weathervane around central mooring; reduces fatigue	Under development for floating arrays

A scheme of mooring systems components can be found on Figure 1.14 [15], showing all the typical elements discussed before. However, not all of these are used at the same time into an actual system.

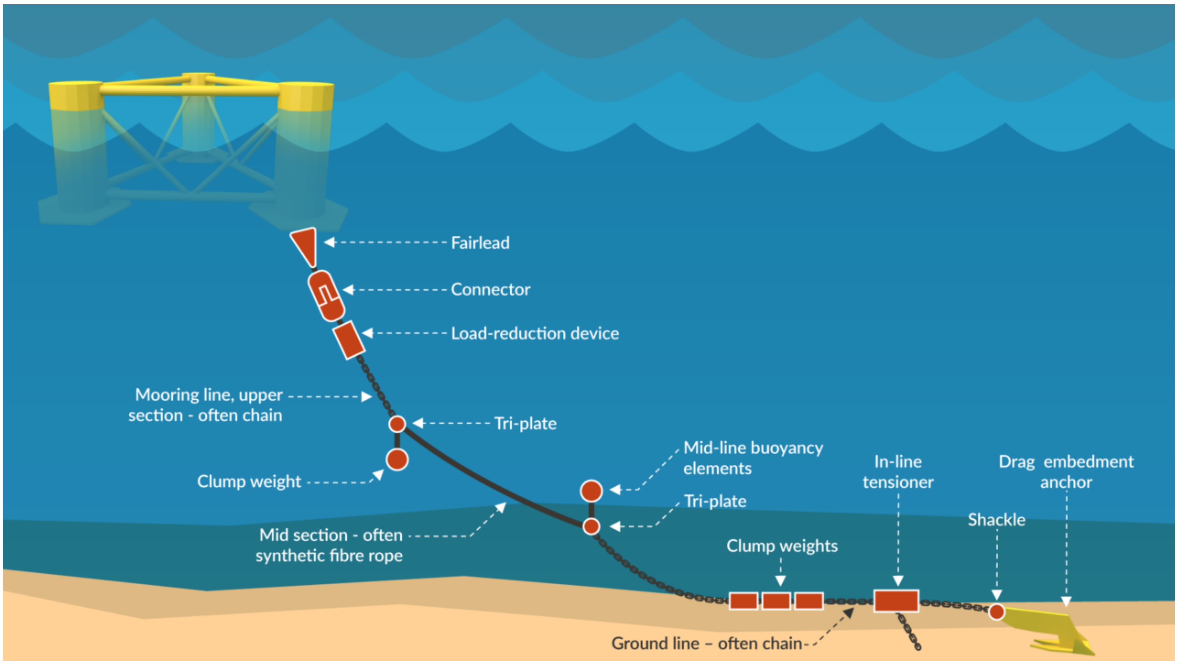


Figure 1.14: Typical mooring system components for FOWTs

1.4 Installation

Installation of FOWTs is a critical phase that significantly affects both the economic feasibility and operational success of a project.

In contrast to FBWTs, floating equivalents can be largely assembled and commissioned onshore. The floating substructure, together with the tower and nacelle, is often integrated in port, allowing for full system testing prior to offshore deployment. This approach, commonly known as the tow-to-site strategy, utilizes standard tugboats, as in Figure 1.15 [21], to transport the complete turbine unit to its offshore location, thereby minimizing reliance on expensive offshore construction assets and reducing weather window sensitivity.

Figure 1.15: FOWT tow-out from Rotterdam to Scotland

Typically, the installation process begins from the transportation of major components, from the manufacturing sites to the construction port. Here, the floating substructure is first ballasted and positioned for turbine integration with heavy lifting equipment being used to assemble the tower, nacelle and blades.

In parallel, offshore works begin with the installation of the offshore substation, transported from its fabrication site and installed on a pre-laid foundation.

Subsequently, cable installation is conducted, after a route planning and survey to detect UXOs (Unexploded Ordinance), followed by a PLGR (Pre-Lay grapnel run) to clear debris from cable route. This operation is conducted by dragging a grapnel train, shown in Figure 1.16, along the planned route to remove possible obstructions from seabed.

Figure 1.16: Typical grapnel train configuration

It follows a central lane plus two lateral ones called wing lines, about 5 meters of tolerance each.
An additional Route Clearance could be performed to remove out-of-services cables already present in the seabed.
A post-lay burial is required after, to bury the cable inside the trenches by using ROVs or other tools. All these operations are conducted by a Cable-Laying vessel, like the one in Figure 1.17 [22], used for both export and inter-array cables.

Meanwhile, anchor and mooring systems are pre-installed at the offshore site. These systems comprise suction or piled anchors and mooring lines deployed using anchor-handling vessels equipped with winches, cranes and ROVs.
Once ready, the assembled floating wind turbine is towed out under strict weather conditions, with wave heights below 1.5 m and speeds below 14 m/s [15]. Transit speeds of 3-4 knots are typical, and nacelle acceleration is monitored to avoid structural damage.

Upon arrival at the site, the floating turbine is hooked up to its mooring system and array cables, completing the mechanical connection phase. The final step is commissioning, which is divided between the turbine supplier and the EPCI contractor. Key activities include verification of installation, energization of subsystems, SCADA and emergency system checks, prior to a gradual turbine start-up leading to first generation.

Figure 1.17: Prysmian Monna Lisa Cable-Laying Vessel

Environmental conditions are critical factors influencing tow-out and hookup operations. To address this, installation planning relies on high resolution weather forecasting and digital twin simulations that model hydrodynamic responses in real time, ensuring operational efficiency and safety.

1.5 Challenges in Operations & Maintenance (O&M)

Operations and maintenance (O&M) of FOWTs pose a unique set of challenges distinct from those encountered in fixed-bottom wind turbines, primarily due to the dynamic nature of the floating platforms, increased distance from shore and reliance on marine infrastructure.

O&M in this context encompasses both the strategic and technical activities required to ensure turbine availability and system integrity throughout the asset's life.

A key distinction of FOWT operations is the complexity introduced by platform motion. The low-frequency oscillations of floating structures increase the difficulty of safe access and handling of tools and components, particularly at height. This motion also exacerbates technician fatigue and risk, especially during manual or rope-access work, such as blade maintenance.

Preventive and corrective maintenance strategies must be adapted accordingly.

Preventive maintenance is typically scheduled during periods of low wind, aiming to reduce revenue losses, while corrective actions must be swiftly executed to avoid prolonged downtimes. However, performing in-situ major repairs offshore remains particularly challenging.

Current limitations in motion-compensated lifting technologies mean that turbine components often need to be serviced onshore. This requires towing the floating platform to a suitably equipped port, disconnecting it from mooring and cabling infrastructure, resulting in a costly and time-intensive operation.

Turbine O&M is often contracted during the initial defect notification period (typically five years), with specialist OEMs or independent service providers (ISPs).

There is an industry trend toward developing in-house capabilities for long-term O&M to reduce lifecycle costs and increase flexibility.

Access logistics also present a significant challenge. Crew Transfer Vessels (CTVs) are typically used for wind farms near shore, while larger farms rely on Service Operation Vessels (SOVs) to house maintenance personnel for extended durations. Helicopters may be used to supplement these strategies.

The lack of sufficient nearby port infrastructure for tow-to-port operations adds further constraints. Suitable O&M ports must accommodate deep-draft floating structures and provide quay space, cranes, warehouses, and administrative facilities.

Digital tools, including SCADA systems, digital twins and condition monitoring, are central to modern floating wind O&M, along with the integration of AI-based failure prediction. These systems provide real-time diagnostics and prognostics, enabling early fault detection and data-driven decision-making. Blade inspections are increasingly automated using drones

equipped with thermographic and high-resolution imaging systems, reducing the need for risky human interventions.
Balance of plant (BoP) components such as mooring lines, dynamic cables, and offshore substations also demand rigorous monitoring and maintenance. The integrity of these systems is essential due to their exposure to harsh marine conditions and their critical role in asset stability and power transmission.
Remotely operated vehicles (ROVs) and divers are commonly used to inspect and repair subsea infrastructure, while scour protection and corrosion mitigation measures must be maintained throughout the asset's lifetime.

Furthermore, the immaturity of the global floating wind supply chain, including vessel and port availability, trained technicians, and tailored maintenance equipment, adds to uncertainty and risk during the O&M phase. Although lessons from early projects like Hywind Scotland and WindFloat Atlantic have informed design-for-maintenance improvements, many floating wind farms will require bespoke O&M strategies until industry-standard practices emerge for deeper water and harsher environments.

In summary, the O&M of floating offshore wind turbines is marked by high logistical complexity, enhanced safety risks, and limited repair options. Innovation in access technology, predictive analytics and modular component design will be key to overcoming these challenges and driving down the levelized cost of energy (LCOE) from floating wind.

1.6 Decommissioning

Decommissioning marks the final stage in the lifecycle of a floating offshore wind farm and involves the safe, environmentally responsible and cost-effective removal of turbines, substructures, mooring systems, and electrical infrastructure at the end of their operational life, typically after 20 to 25 years. Although FOWTs offer certain logistical advantages in the decommissioning phase compared to fixed-bottom systems, significant challenges remain due to deep-water operations, regulatory uncertainty and the complexity of subsea infrastructure removal.

One of the primary benefits of floating wind decommissioning is the reversibility of installation. Unlike monopiles or jacket foundations that are driven or embedded into the seabed, floating substructures are anchored using mooring lines that can be recovered with relatively minimal seabed disruption. Substructures, once disconnected from moorings and electrical cables, can be towed back to shore using conventional anchor-handling or tug vessels. This reduces the need for energy-intensive offshore lifting operations and enables many activities, such as disassembly, material recycling, and hazardous waste treatment, to occur in controlled port environments [15][23].
The decommissioning process typically begins with a detailed engineering assessment, followed by environmental impact evaluations and engagement with marine regulators.

The actual process involves several key steps:

1. Disconnecting and recovering export and inter-array cables, which may be removed entirely or, in some jurisdictions, left in situ if deemed environmentally acceptable;
2. Detaching dynamic cables from the floating platforms and safely bringing them to the surface using cable-handling vessels;
3. Disconnection of mooring lines, which may be recovered in full or cut and left with biodegradable tailings, depending on local environmental policies and economic feasibility;
4. Towing of floating platforms back to shore for dismantling and material recovery;
5. Site clearance, which includes the removal of anchors (e.g., drag embedment or suction piles), subsea equipment, and other residual debris [24].

Despite the theoretical simplicity of tow-back decommissioning, the actual costs and risks remain high. According to industry analysis, decommissioning may account for up to 5–10% of total project lifecycle cost, with uncertainty stemming from limited commercial precedent, especially for deep-water floating systems. Furthermore, offshore weather conditions, environmental protection zones and variability of site-specific conditions complicate planning and execution. Regulatory frameworks for decommissioning are evolving but remain fragmented across jurisdictions. While the UK and EU have established environmental directives, others are still developing clear decommissioning guidelines for floating systems.

A major opportunity for reducing decommissioning costs lies in the design-for-decommissioning approach, where platforms, mooring systems and cables are pre-engineered for simplified retrieval. In addition, material recycling and circular economy strategies, like the examples in Figure 1.18 and 1.19 [25], are increasingly being considered. Steel from substructures, copper from cables and rare earth elements from turbine generators represent valuable resources that could be recovered if dismantling is well planned. Future innovations, such as biodegradable mooring tailings or modular floating platforms, may further reduce decommissioning risks and environmental impact.

Figure 1.18: Two discarded turbine blades used to construct a bridge outside Cork City

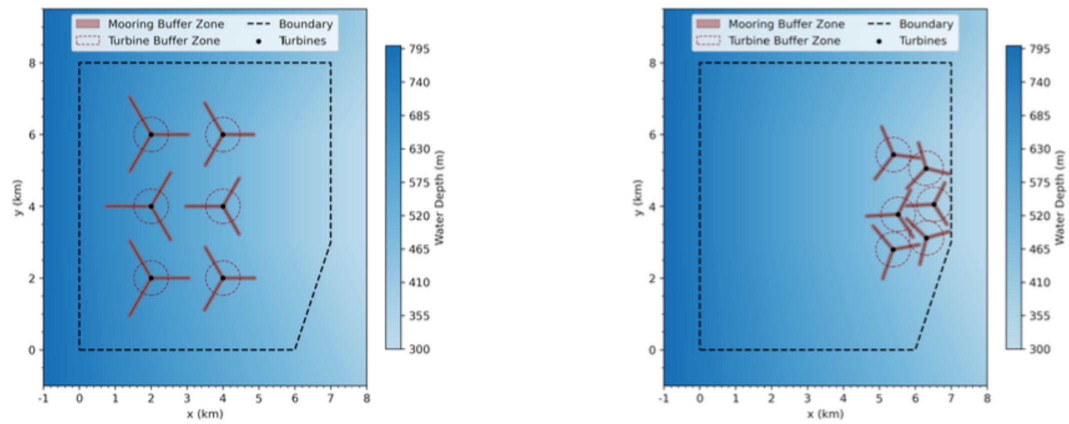
Figure 1.19: Turbine blades used as a bike shelter at the port of Aalborg

1.7 Importance of Site-Specific Analysis

Floating Offshore Wind Farms represent a complex interplay of technological, environmental and economic factors, each significantly influenced by the unique conditions at each deployment site. A detailed and insightful site-specific analysis is therefore crucial, not merely beneficial, to optimizing the layout, performance and long-term economic sustainability of these projects.

The seabed's heterogeneity, involving variations in bathymetry and soil composition, profoundly affects mooring system designs and associated installation and maintenance strategies. Seabed slopes and varied geological conditions can dramatically alter mooring requirements, anchor placement, and installation procedures. Hall et al. (2024) [27] demonstrate the practical implications of ignoring these variations: failure to properly adapt the mooring system to local seabed characteristics can significantly increase costs and risks. Conversely, recognizing and strategically using site-specific bathymetric data enables substantial cost savings and reductions in operational complexity.

In the example showed in Figure 1.20, Hall et al. consider a sloped seabed with depth being the only factor driving the mooring system cost. It is shown that by clustering the turbines in the shallowest region of the area, a cost reduction of 11% is obtained.

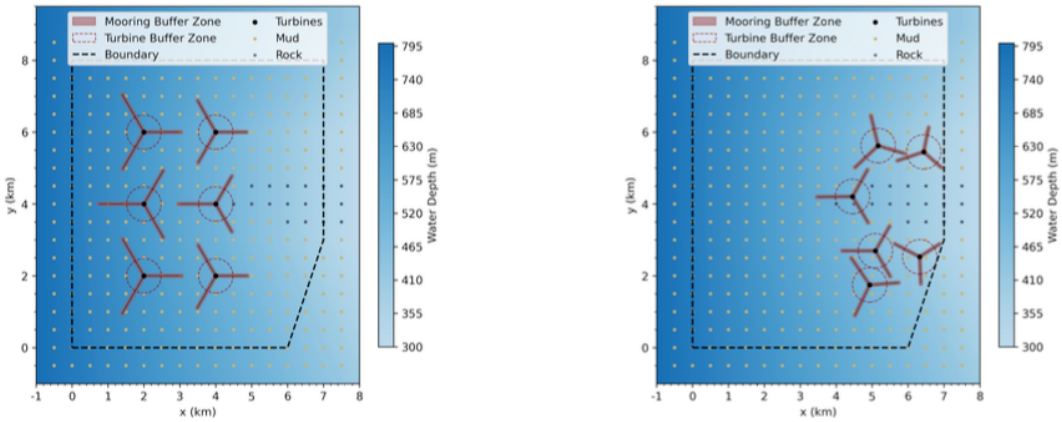


(a) Initial layout (b) Optimized layout

Figure 1.20: Layout configurations in case of sloped seabed

The integration of mooring system adaptability is an advanced development crucial for FOWFs deployment. Automated algorithms that dynamically adjust anchor placements and mooring line lengths according to specific seabed conditions represent a transformative approach. These sophisticated methodologies ensure that floating turbines maintain operational stability and consistent energy output, even in variable marine environments. Such innovations underscore the importance of moving beyond traditional fixed assumptions toward flexible, data-driven solutions tailored explicitly to local conditions.

As in Figure 1.21, Hall et al. now considers a rocky seabed in which, by placing turbines in a region where anchor positions avoid this area entirely, a cost reduction of 8.7% is obtained.



(a) Initial layout (b) Optimized layout

Figure 1.21: Layout configurations in case of rocky seabed

Wake losses, arising from interactions between turbines, directly decrease AEP. Traditional approaches have focused on static turbine placements, inherently limited by spatial constraints. Mahfouz et al. (2024) [26] introduced a strategic insight into leveraging the inherent mobility of floating turbines via carefully designed mooring systems: by enabling passive displacement based on prevailing wind directions, this approach significantly reduces wake-induced energy losses (up to 2.1% AEP improvement), representing a notable shift from static to dynamic wind farm management strategies.

A nuanced site-specific analysis offers more than mere technical benefits as it provides strategic economic insights. By identifying optimal configurations and positioning that minimize both CapEx and OpEx, project developers can significantly enhance economics. The substantial reductions in mooring system costs identified in research (nearly 30% in some scenarios) highlight the critical economic potential of site-specific analyses. Furthermore, understanding site-specific dynamics can proactively inform maintenance schedules, predict fatigue and degradation patterns and streamline operational procedures, ultimately enhancing project longevity and profitability.

The strategic importance of site-specific analysis will only increase as floating wind technology advances into deeper waters and more challenging environments. The integration of dynamic cable analysis, fatigue load assessments and innovative mooring systems will become standard practice, driving further optimization and cost reduction.

Insights drawn from detailed site-specific analysis today lay the groundwork for future advancements in floating wind farm technology, ensuring sustainability, resilience, and economic viability, as it represents not only a foundational requirement but also a key strategic advantage in floating offshore wind energy deployment. It allows developers and operators to optimize turbine layouts, mooring designs and operational strategies effectively, aligning technical performance with economic and environmental sustainability.
With the floating offshore wind sector expanding, sophisticated, tailored approaches based on detailed site analyses will increasingly dictate the success and feasibility of future projects.

1.8 Floating Offshore Wind in the Mediterranean Sea

1.8.1 Current and Future total installed capacity

The Mediterranean Sea represents a highly promising region for floating offshore wind energy development due to its abundant offshore wind resources, favorable climate conditions and strategic geopolitical positioning. Currently, the total installed floating offshore wind capacity in the Mediterranean remains limited, largely constrained by technical, economic and regulatory factors. However, significant growth is anticipated as multiple Mediterranean countries have ambitious plans to enhance their renewable energy portfolios, focusing extensively on floating offshore wind technologies.

According to recent studies, the technical capacity potential for floating offshore wind in the Mediterranean is substantial. Notably, Libya, Tunisia, Italy and Greece collectively account for approximately 72.2% of the Mediterranean's total technical potential, which is estimated at 782 GW. These nations exhibit favorable conditions for floating wind farms, characterized by suitable water depths, wind speeds and proximity to infrastructure that enhance economic feasibility [28].
Currently, several pilot projects and initial deployments are underway, particularly in the western Mediterranean, including offshore sites near islands such as Crete, Chios, Corsica and Sardinia. These projects serve as critical demonstrations to evaluate technology viability, economic competitiveness, and environmental impacts. For instance, the Levelized Cost of Energy (LCOE) for optimal sites near these islands has already demonstrated promising

competitiveness, reaching as low as approximately 80 €/MWh at the most favorable locations [28].

Moreover, European Union initiatives, such as the REPowerEU plan and the EU strategy on offshore renewable energy, underline ambitious targets aiming for an installed offshore wind capacity of 60 GW by 2030 and up to 300 GW by 2050 across Europe, inclusive of Mediterranean states. Specifically, the Mediterranean region itself has an estimated floating offshore wind potential of around 4,629 TWh annually, predominantly achievable through floating technologies due to the steep bathymetric profiles that limit fixed-bottom installations [29].

The Mediterranean's offshore wind energy development is also influenced significantly by national and regional regulatory frameworks and policies. Countries such as France and Spain have already delineated specific Offshore Wind Development Areas (OWDAs), which streamline planning and approval processes. Conversely, other Mediterranean nations are still developing regulatory frameworks to accommodate offshore wind farm installations adequately, particularly regarding environmental impact assessments within Marine Protected Areas (MPAs) and Natura 2000 sites [30].

Strategically, floating offshore wind developments in the Mediterranean could provide substantial socio-economic benefits, including job creation in manufacturing, installation and operation phases, and contribute to regional energy security by diversifying energy sources and reducing fossil fuel dependence.

In conclusion, while the Mediterranean's current floating offshore wind capacity is modest, robust technical potential and favorable economic projections indicate a significant expansion soon. The proactive establishment of regulatory frameworks, combined with advancing technological developments and increasing political support, positions the Mediterranean as a future hotspot for floating offshore wind energy.

1.8.2 Vessels Availability

Operational performance of FOWFs in the Mediterranean Sea critically depends on the availability of specialized vessels for installation, maintenance and major component exchanges. An estimation analysis was conducted in support of this thesis work, providing the following results showed in Table 4.

Table 1.4: Mediterranean sea Vessel Fleet Analysis

Vessel Type	Total Global Fleet	Mediterranean Availability
Jack-Up Vessel (JUV)	100-150	Very Low
Heavy Lift Vessel (HLV)	50-80	Low
Crew Transfer Vessel (CTV)	200-300	Low
Service Operation Vessel (SOV)	30-50	Very Low
Specialist Field Vessel (SFV)	150-250	Low
Anchor Handling Tug Supply Vessel (AHTS)	400-600	Medium
Tug Vessel	1000-1500	High
Cable Laying Vessel (CLV)	50-100	Low

This estimation was conducted considering the total global fleet as vessels not solely used for the purpose of FOWFs, but which can be fitted for the tasks involved in them.

The availability classification, using Mediterranean specific scale ("Very Low" = 0-2 vessels, "Low" = 5-15 vessels, "Medium" = 20-40 vessels, "High" = 50+ vessels), highlights critical limitations:

- Jack-Up Vessels (JUV) and Service Operation Vessels (SOV) are in very low supply, posing a bottleneck for major component exchanges and routine service tasks;
- Heavy Lift Vessels (HLV) and Crew Transfer Vessels (CTV) exhibit low availability, requiring careful scheduling and logistics planning to avoid downtime;
- Anchor Handling Tug Supply Vessels (AHTSVs) have medium availability, sufficient for anchoring operations but may become scarce during concurrent farm campaigns;

- Tug Vessels are abundant, enabling robust station keeping and emergency towing capabilities;
- Cable Laying Vessels (CLVs) remain limited, underscoring the need to optimize cable installation windows.

Consequently, O&M strategies in the Mediterranean must prioritize the use of high-availability vessels (tugs, AHTSVs) for critical tasks while aligning JUV and SOV intensive operations with periods of lower regional demand. Collaborative chartering agreements, staggered maintenance campaigns and cross-border resource sharing can mitigate availability constraints, ensuring cost-effective and reliable O&M support for Mediterranean floating wind farms.
More technical details about the vessels can be found on Appendix C.

1.8.3 Ports Availability

With equivalent scope as Vessels Availability, an analysis regarding the existing port infrastructure to support installation and O&M in the Mediterranean Sea was conducted.
Ports were filtered based on following requisites [15]:

- Presence of jetties for CTVs, with approximately 35 m per vessel, depending on the size of CTV used, and a minimum draft of 3 m, often with 2t SWL telescopic boom jetty cranes;
- Quaysides for SOVs, with approximately 100m quayside per vessel and minimum draft of 7 to 8 m;
- Warehouses for spare parts;
- Workshops for work such as sorting equipment brought back from site, kitting of parts and equipment to go to site and minor refurbishment;
- Office buildings to house the operations control center and other project operations staff;
- Convenient access for O&M technicians.

Furthermore, the presence of diverse types of cranes (Fixed, Mobile and Floating cranes) was considered to better sort which mediterranean ports could be feasible to be O&M ports.

The results, available for a full consulting in Appendix D, showed a total of seventeen ports between France, Italy, Spain, Greece, Turkey and Malta suitable for hosting O&M of FOWFs. While some of them are already considered in existing or future projects like Augusta, the others still need to be adequately prepared and expanded, where needed.
Nonetheless, ongoing projects like DEOS [31], which aims at establishing a platform for the construction and assembly of FOWTs in the port of Marseille – Fos sur Mer starting in 2028, are currently under developing and pushing the growing of Floating Offshore Wind market in the region.

Chapter 2: Literature Review

2.1 Overview of O&M for Offshore Wind

O&M for FOW plays a critical role in the life cycle cost and reliability of these projects, as it encompasses all activities to ensure turbines remain available and safe to operate, including routine inspections, preventive maintenance, repairs of failures and major components replacements. Numerous studies indicate that O&M expenditures represent a significant portion of the total energy cost, on the order of 20-30% of the Levelized Cost of Energy (LCOE) [31].

In fact, one assessment found the exploitation (O&M) phase to be the single largest life-cycle cost component for a floating wind farm, surpassing even manufacturing and installation costs [32]. Thus, effective O&M is pivotal for driving down the LCOE of floating wind to competitive levels. The basic formula for LCOE is given by Equation 2.1, which averages all life-cycle costs (capital and operating) over the energy produced:

$$\text{LCOE} = \frac{\sum_{i=1}^{T}\{(CAPEX_i\} + OPEX_i)(1+r)^{-i}}{\sum_{i=1}^{T} AEP_i(1+r)^{-i}} \qquad 2.1$$

where CAPEX_i and OPEX_i are the capital end operational expenditures in year i, AEP_i is the annual energy production, r is the discount rate and T is the project lifetime [33]. Clearly, reducing the Operational Expenditures and increasing turbine availability through better O&M directly lowers the LCOE.

Floating wind O&M inherits many challenges from fixed-bottom offshore wind but also introduces new complexities, as heavy maintenance in the latter is often performed in situ using jack-up crane vessels, which cannot operate in water depths higher than 60 meters, typical of floating sites [31]. This has led to new maintenance strategies for FOW such as towing the entire turbine back to port for major repairs, which operations fall under the name of Tow To Port (T2P).

For example, the Hywind Scotland pilot wind farm recently employed a tow-to-shore campaign, as all five 6 MW FOWTs were disconnected and towed to a Norwegian harbor for their first major maintenance overhaul in summer 2024, a process spanning four months [34].
Nevertheless, T2P has been a necessary strategy in early projects given the lack of specialized floating HLV vessels and the challenges of performing extensive repairs offshore on a moving platform.
The floating substructures (spar, semi-sub, TLP) also induce motions that can complicate on-site maintenance, requiring calmer sea states or active motion compensation for safe crew transfers [31]. Weather conditions and accessibility windows are therefore a critical concern for FOW O&M, as discussed next on Section 2.4.

Despite these challenges, floating wind O&M also presents opportunities. The ability to tow platforms to sheltered water (T2S) or port (T2P) means certain tasks can be performed in controlled environments, reducing offshore work risks.
Floating projects can also leverage experiences from the oil & gas sector for mooring and dynamic cable maintenance.

Moreover, the industry is exploring advanced solutions such as remote monitoring, robotics and digitalization to enhance O&M efficiency. Employing autonomous or remotely operated vehicles for inspections can minimize risky human offshore interventions and allow more frequent checks at lower cost [35][36]. For instance, unmanned aerial drones and ROVs have been tested for blade, hull and mooring inspections, with the goal of transitioning some inspections from crewed vessels to robotic platforms. Early results suggest multi-robot systems could significantly reduce on-site inspection time, although the high upfront cost of such systems must be justified by the OPEX savings.
In parallel, enhanced data analytics and digital twins are being developed to predict failures and optimize maintenance schedules.

In summary, O&M for floating offshore wind is a substantial cost driver and logistical challenge, but it is also an area of rapid innovation. An overview of O%M strategies (preventive vs. corrective maintenance) is presented below, followed by discussions of cost drivers, weather impacts and the latest O&M cost modeling tools.

2.2 O&M Strategies: Corrective, Preventive

O&M activities are commonly classified into corrective and preventive approaches.

Corrective maintenance refers to unscheduled repairs performed after a component failure or performance degradation is detected. This includes minor fixes (e.g. replacing a sensor or tightening bolts) as well as major corrective interventions like exchanging a failed gearbox or generator. Corrective maintenance inevitably leads to turbine downtime and lost energy production until the fault is addressed.

In contrast, preventive maintenance is performed before failure occur, on a planned schedule or condition-based basis, with the aim of improving reliability and minimizing unplanned outages. Preventive tasks include regular inspections, servicing and replacement of certain wear-prone parts at fixed intervals. In offshore wind practice, turbines typically undergo annual scheduled maintenance and more extensive overhauls every 5 years or so [37]. Such calendar-based maintenance is often supplemented by condition-based maintenance, where data from condition monitoring systems, like SCADA signals, is used to predict failures and trigger pre-emptive repairs.

A landmark study by van de Pieterman et al. (2011) [38] formalized these categories, with unplanned corrective events further classified by severity (minor repair, major repair or major replacement) and corresponding mean time to repair distributions. This Reliability-Centered Maintenance approach has been widely applied in wind farm O&M modeling to represent realistic maintenance demands.

For FOW, all the above maintenance categories remain relevant, but the logistical execution or maintenance can differ from FBW. Floating turbines enable a new dichotomy between in situ (offshore) maintenance versus onshore maintenance (T2P). Traditional offshore wind O&M was constrained to in situ repairs using SOVs or JUVs, but a floating turbine can be disconnected and towed to a harbor or sheltered water to repair. This has led researchers to expand maintenance strategy taxonomies beyond simply “preventive vs. corrective”. As noted in a recent review, there is a clear shift in FOW literature from classifying maintenance by timing (scheduled vs. unscheduled) to also by location (i.e. task done on-site or with the turbine towed to harbor) [31].

Table 5, taken from [31], summarizes examples of maintenance strategy frameworks from the literature. For instance, Castella et al. (2019) [39] assume a base case of both corrective and preventive repairs conducted at an onshore facility (after towing the turbines). Dewan & Asgarpour (2019) [40] compare a permanently offshore strategy with an accommodation vessel station at the farm for quicker in-situ response against a T2S strategy for major jobs. Rinaldi et al. [41] focus on corrective maintenance only but distinguish repairs done on site versus those done on land.

Table 2.1: Maintenance strategies for FOW modeling

Publication	Maintenance Activity Classification	Additional Information
Castella et al. [39]	Corrective & preventive	Harbor or shore
Dewan & Asgarpour [40]	Corrective and calendar based	Permanent base, offshore based strategy, T2S
Rinaldi et al. [41]	Corrective only	Maintenance split by onshore and in situ
Brons-Illing [42]	N/A	Onsite vs onshore
Utne [43]	Preventive and corrective	N/A
Martini et al. [44]	N/A	Light repair, heavy repair operations
Gray [45]	Preventive and corrective	Major/Minor Onsite/offsite
Elusakin et al. [46]	Condition Based Monitoring	4 types of maintenance: 1) heavy with crane requirement; 2) small with internal crane; 3) small inside nacelle; 4) small outside nacelle

Gray (2022) [45] considers preventive and corrective tasks further split into minor vs. major and on-site vs off-site categories. Meanwhile, Elusakin et al. (2022) [46] explore a condition-based strategy, defining four maintenance types by size and location:

1. Heavy corrective repairs requiring large crane vessels;
2. Smaller repairs using the turbine's internal crane;
3. Minor fixes inside the nacelle;
4. Minor external fixes via rope access.

Across these studies, one common theme is that T2P is reserved for major components replacements, whereas routine inspections and minor repairs are generally done using CTVs or SOVs. The T2P option, while reducing the need for expensive HLV at sea, incurs significant turbine downtime due to transit and re-installation, thus it tends to be justified only for corrective maintenance of major failures that cannot be handled offshore [31].
In fact, it is estimated that implementing a T2P strategy for major replacements could reduce overall maintenance costs by about one-third compared to an all-offshore scenario, although this comes at the expense of longer production outages per event.

Preventive maintenance in FOW is evolving with the aim of minimizing human offshore exposure and catching problems early. Operators increasingly use remote monitoring and inspections: for example, drones or crawling robots can perform blade and hull inspections, as showed in Figure 2.1 [47], transmitting high-resolution images to shore [36].

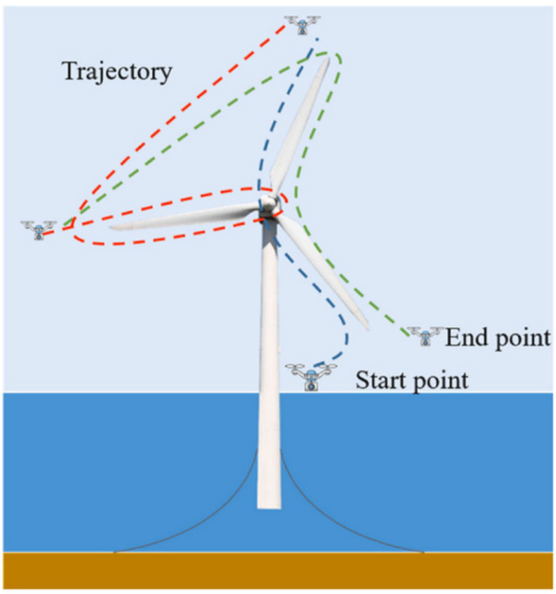


Figure 2.1: UAV inspection for FOWT blades

These robotic inspections fall under preventive maintenance and can be done more frequently and safely than manned inspections, albeit requiring investment in new technology. A cost-benefit study by Khalid et al. (2024) [36] assessed a multi-robot platform for FOW turbine inspections and found it could cut total inspection time by circa 58%, although the added equipment costs pushed annual OPEX slightly higher than their base case. The implication is that robotics and automation may improve preventive maintenance effectiveness through continuous monitoring and quicker fault detection but must be carefully integrated to ensure they reduce net costs.

Another aspect of prevention is predictive maintenance, where data analytics forecast failures so that components are replaced with a JIT (Just-In-Time) logic. Serri et al. (2024) [35] highlight that moving towards automated inspections and predictive maintenance is a key cost-reduction strategy, especially for far-offshore farms where access is difficult and addressing issues proactively during scheduled weather windows can avoid more costly corrective interventions later.

In summary, FOW O&M strategies are characterized by a mix of traditional preventive and corrective maintenance planning and novel considerations of where and how to service the turbines. Early projects have demonstrated the viability of both offshore repairs and onshore maintenance, with the optimal strategy likely being a combination of both: routine inspections and minor fixed performed in situ to maximize availability, with the flexibility to tow turbines to port for complex repairs or overhauls that are impractical to execute offshore. Moving forward, increased use of condition monitoring, opportunistic maintenance and robotics will further refine these O&M strategies to minimize downtime and cost.

2.3 Key Cost Drivers in O&M for Floating Wind

The costs associated with operating and maintaining a FOW are driven by a variety of technical and logistical factors. Understanding these drivers is essential for developing cost models and identifying opportunities for cost reduction.

In Figure 2.2 a representative breakdown of OPEX from Khalid et al. [36] (2024), relative to a floating wind farm composed of 100 turbines of 15 MW each, is illustrated, divided by major maintenance categories. In this example, blade inspections and repairs and mooring system maintenance constitute the largest portions of OPEX, reflecting the high criticality and frequency of these activities in floating wind operations.

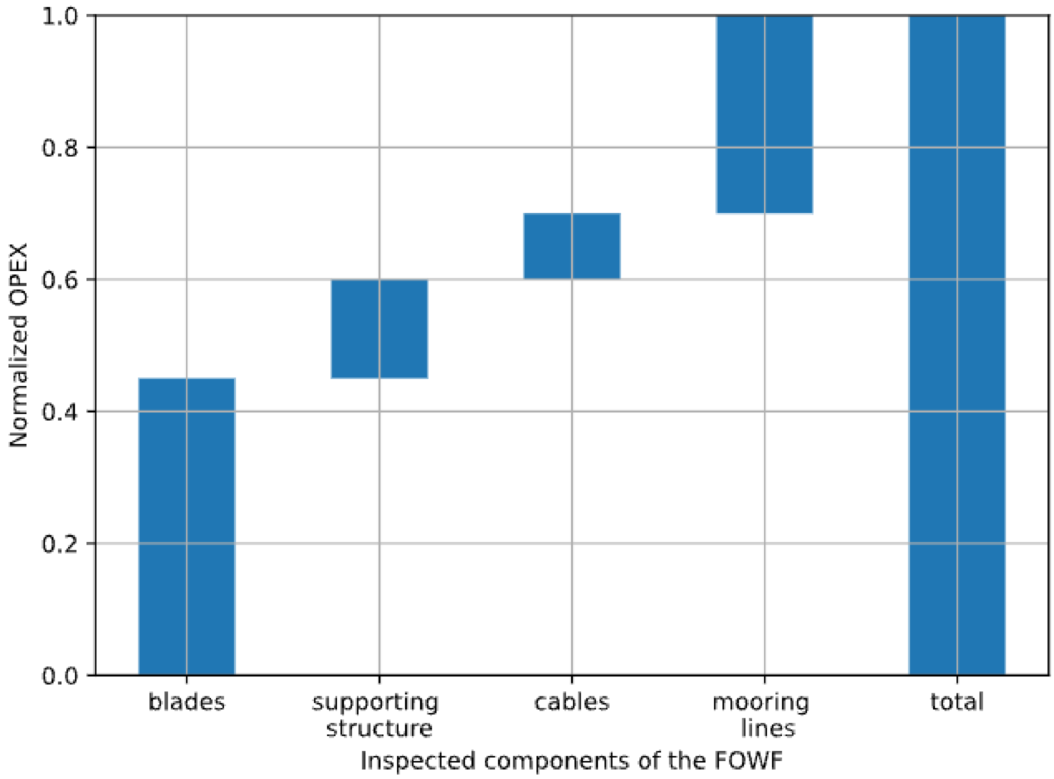


Figure 2.2: OPEX breakdown component structure from Khalid et al.

By contrast, inspections of the supporting structure, array cables and export cables form a smaller share of the O&M costs in this scenario. This breakdown underscores that certain components demand more maintenance resources: rotor blades are prone to erosion and require regular checks; mooring lines and anchors are unique to floating systems and are subject to significant loads and wear in the marine environment. These component-level cost drivers align with industry experience that blade repairs and marine power cable issues are frequent O&M pain points, joined by mooring upkeep for floating farms.

Beyond individual components, several external factors and operational parameters strongly influence O&M costs in floating wind:

- Distance to Port: the farther a wind farm is from its O&M base port, the higher the travel time, fuel use and vessel hire costs for each maintenance visit. Martinez & Iglesias (2022) [33] found that, in regions with similar wind resources, distance to shore is the primary variable affecting LCOE for floating wind farms. Every additional kilometer offshore adds transit time that must be paid for in vessel operating hours and crew costs. For instance, one study assumed a baseline O&M cost of €138,000 per MW-year for a site 200 km offshore, plus an extra €40 per MW-year for each kilometer of distance. Although towing a turbine to port for major repairs avoids needing a crane vessel offshore, it incurs its own transit costs and downtime. As a result, distance offshore has a two-fold cost impact: it raises the direct logistics costs and tends to increase turbine downtime during maintenance;
- Metocean Conditions (Weather Windows): the site's wave climate, wind conditions and overall accessibility have a direct effect on O&M cost by governing how often maintenance can be performed and how long repairs are delayed. High sea states or strong winds can halt maintenance activities, creating wait times that translate to lost production (opportunity cost) and prolonged outages. In fact, a significant portion of O&M cost can be attributed not just to repair expenses but to revenue lost during downtime, as if a turbine is idled waiting for a calm weather window, the forgone energy yields an economic loss. As projects move into more energetic offshore zones, weather delays become a critical driver of the effective O&M cost. Conversely, more benign conditions can improve accessibility, like for certain Mediterranean sites, which generally experience milder wave climates than the North Sea. However, even in calmer seas, storms and seasonal rough weather will impact maintenance timing. Weather impacts and modeling of accessibility are discussed in detail in Section 2.5, but it is noted here that metocean conditions influence not only the duration and risk of each maintenance operation but also failure rates (e.g. more extreme weather can induce higher loads and potentially more frequent component failures) [31];
- Failure Rates and Reliability: the intrinsic reliability of turbine components and the floating platform systems is a fundamental driver of O&M cost. If components fail frequently, more corrective interventions are needed, driving up costs. Floating turbines include all the usual subsystems of a wind turbine (blades, gearbox, etc.) plus additional components like hull structure, mooring lines, chain connectors and

dynamic cables, as previously explained in Chapter 1. These new components introduce additional failure modes and uncertainties in lifetime. For example, mooring line failures, though infrequent, can be costly to repair and may require heavy work vessels or even towing the turbine. Electrical dynamic cables, moving with the platform, might have different reliability profiles compared to static cables. Since the floating wind industry is still in a demonstration phase, there is limited field data on failure rates for these novel components. This uncertainty complicates accurate O&M cost estimation. Nonetheless, sensitivity studies consistently show that improved reliability dramatically reduces O&M costs, as each prevented failure avoids a costly offshore repair mission and turbine downtime. Therefore, investments in better component engineering (for instance, corrosion-resistant mooring coatings or dynamic electrical cables) can pay off through lower lifetime O&M expenditure. Understanding the failure rates is essential to reducing O&M costs via proper maintenance planning;

- Maintenance strategy and execution: the chosen O&M strategy itself (discussed in the previous section) is a cost driver. Relying mainly on corrective maintenance can lead to high downtime and emergency repair costs, whereas a preventive approach may increase planned O&M spending but reduce catastrophic failures. Studies have shown that including condition-based maintenance can improve availability but requires upfront costs for monitoring equipment and analysis. The decision to perform a major replacement offshore versus onshore has cost implications: on site repair might need a €200,000-€300,000/day HVL but minimizes production loss, whereas T2P avoids that vessel cost but the turbine could be offline for weeks [48]. As another example, maintaining a full-time service vessel and crew on standby offshore (a permanent SOV deployment) will increase fixed O&M costs, but can sharply reduce response time to failures. Thus, strategy-related parameters like vessel selection, crew scheduling, spare parts logistics and the possible use advanced tools like robotics, all feed into the overall cost. There is often a trade-off between higher upfront O&M spending and reduced risk of long downtime, with the optimal balance depending on site specifics and risk tolerance;
- Port Infrastructure and Supply Chain: an often-underappreciated cost factor is the availability of suitable ports, vessels and maintenance infrastructure. Floating projects require ports with sufficient draft and crane capacity to handle large substructures and turbines coming in for assembly or heavy maintenance, as shown

in Chapter 1. If a local port is not fully capable, developers may incur additional costs (e.g. reinforcing quays or towing turbines to a farther port that has the needed infrastructure). Serri et al. (2020) [50] note that port readiness in the Mediterranean will be crucial as commercial-scale FOW deployments begin. Similarly, the availability of trained maintenance crews and specialized vessels in a region affects cost. For example, if a floating wind farm in the Mediterranean needs a crane barge that is only available in the North Sea, the transit and mobilization fees will inflate O&M cost. Conversely, developing a strong regional supply chain can help drive down costs over time. Economies of scale also come into play as more FOW farms are installed in Europe and globally. Indeed, recent analyses project that floating wind LCOE can decline steeply by 2050 thanks in part to O&M learning effects, potentially reaching 50 USD/MWh.

In quantitative terms, O&M costs for current floating wind prototypes are still higher than for fixed-bottom offshore wind.
According to one industry report, floating wind O&M costs are expected to be 20-30% higher than fixed-bottom in early projects, due to the added complexity of dynamic systems and limited operational experience. However, as floating turbines grow larger to 10-15 MW classes and farm size increase, some economies of scale should materialize. A larger farm can justify the continuous presence of an SOW or even a small offshore base, spreading that fixed cost over more turbines. Maintenance crews can be scheduled more efficiently when many turbines are co-located, and inventory of critical spare parts can be pooled.

Ioannou et al. (2018) [37] provided parametric OPEX formulas indicating that O&M costs increase sub-linearly with wind farm capacity, implying unit OPEX per MW decreases for bigger farms, and that OPEX has a significant dependance on distance to port but only a weak dependence on water depth. These factors will be extensively discussed in the next section.
To summarize, the key cost drivers in floating wind O&M include remoteness of the site, harshness of the environment, equipment reliability, chosen maintenance strategy and the state of the local infrastructure/supply chain.

2.4 OPEX Modeling

FOW Operational Expenditure (OpEx) embraces all ongoing costs to operate and maintain a wind farm over its life, after commissioning. These costs are significant, estimated to contribute roughly 20-50% of total lifetime energy cost for floating project, and thus accurate modeling is critical [49].

Below, a review of how OpEx is broken into fixed and variable components, how maintenance and failure rates are incorporated into models and regional considerations for the North Sea and Mediterranean region is conducted, with summarization of key models and formulations from both academia and industry.

2.4.1 Fixed vs. Variable OpEx Components

It is common to split OpEx into fixed (operational) costs and variable (maintenance) costs. Fixed OpEx refers to recurring annual costs that do not strongly depend on output or failures, while variable OpEx scales with turbine operation, wear and repair needs [50]. In other words, fixed part covers baseline operating expenses incurred each year regardless of energy production, whereas variable part covers maintenance activities that vary with usage and component failures. For example, one study's LCOE formula explicitly separates a fixed OpEx term (€/MW/year) from a variable OpEx term (€/MWh).

Fixed costs are largely time-based. They include expenses like site leasing or rental fees, insurance, onshore support facilities and core O&M staff and vessels on standby [31][51]. Such costs often scale with project size (number of turbines or MW capacity) but are incurred regardless of short-term turbine performance. For instance, port and harbor fees, fixed crew salaries and grid access changes are typically budgeted as a fixed annual amount per MW. Some models simply assume fixed O&M as a percentage of capital cost or a fixed rate per kW. For floating wind in the early 2020s, studies have used values on the order of €100-150k per MW per year for the fixed OpEx component [50].

Variable elements correspond to maintenance and operating costs that scale with turbine activity, failure incidents or energy output. Variable OpEx includes costs for scheduled servicing, unscheduled repairs, spare parts, vessel charters for repairs and performance-related costs. In formal models, this is sometimes represented as a cost per unit of energy (€/MW) added on top of fixed costs [50]. For example, a study in the Italian Mediterranean assumed an annual fixed OPEX per MW plus a variable OPEX per MWh produced to account for wear-and-tear maintenance that scales with production. In general, repair and replacement costs and the failure frequency are the dominant drivers of variable OPEX. This means that a higher rate of component failures or more frequent major repairs will directly increase the variable O&M expenditures.

Many techno-economic models use streamlined formulas to estimate OpEx as a combination of fixed and variable terms. A common approach is a linear model scaling with farm size and distance from shore, like in Equation 2.2 from Martínez & Iglesias (2022) [33] and others:

$$\text{AnnualOpEx} = P_{farm}\left[k_p + k_d \cdot d_{shore}\right] \tag{2.2}$$

where P_{farm} is the farm capacity in MW, d_{shore} is distance to port, k_p is a fixed cost coefficient and k_d is a distance-dependent cost coefficient. This effectively treats the base maintenance as a fixed cost per MW and the logistics penalty as a variable add-on. Such formulations are convenient for high-level LCOE mapping and are often calibrated to industry data. However, they are "O&M-agnostic" as they do not explicitly model failure or weather delays.

Advanced cost models break OpEx into finer sub-categories, covering seabed rental, insurance, grid fees, monitoring and regular personnel costs, while maintenance costs cover all scheduled servicing and unplanned repair interventions [31][51]. The maintenance costs can further be split into direct costs (actual repair vessel trips, technicians, etc.) and indirect costs (e.g. support infrastructure, spares inventory holding or downtime penalties). This granularity is useful for identifying cost drivers.

2.4.2 Maintenance Cost Modeling and Failure Rate Integration

Maintenance-related OpEx is modeled using a spectrum of approaches, from deterministic estimates to probabilistic simulations. At its core, failure rate data is a key input: how often components fail and require repair directly influences annual maintenance costs.

Simple models use an expected failure rate per turbine per year multiplied by a unit cost per repair to estimate unscheduled maintenance cost. For instance, if a turbine is expected to have λ failures/year and each repair on average costs €X (including parts, vessel use and labor), then annual corrective maintenance cost is approximated as $(\lambda \cdot €X)$. Industry data from fixed-bottom offshore wind is often used as a proxy for FOWTs. A landmark analysis by Carroll et al. (2015) [52] found an average failure frequency of 8.3 failures per turbine per year in offshore wind fleets. This comprised mostly minor repairs (6.2 small fixes/year) and a few major repairs (1.1) and replacements (0.3). Such empirical failure rates are commonly plugged into OPEX models for floating wind, since real-floating specific reliability data are limited. As a result, reliability assumptions are a major uncertainty.

OpEx models also distinguish between unscheduled (corrective) maintenance, which occurs in reaction to component failures, and scheduled (preventive) maintenance, which is planned at intervals to avert failures. Integrating both requires data on failure probabilities and planned maintenance cycles. Advanced models therefore incorporate maintenance strategies. For example, a fully corrective strategy means run-to-failure: maintenance costs arise only from repairs after failures, whereas a preventive strategy schedules regular interventions to replace or refurbish components before they fail [49]. Studies show that corrective-heavy maintenance can reduce upfront O&M effort but leads to more turbine downtime and higher long-run costs, while preventive maintenance reduces failure and downtime but incurs higher routine service costs.

To cope with that, the most comprehensive OPEX models use probabilistic simulations or reliability-based algorithms to capture the stochastic nature of failures and weather downtime. For instance, the 2024 model by Centeno et al. [49] employs continuous-time Markovian chains and reliability block diagrams to simulate each turbine’s component states and maintenance actions. In their framework, each component has a failure rate and repair time distribution; the model computes turbine availability and expected number of corrective and preventive tasks over a year for a given site. The annual OpEx is then summed over all turbines and components as Equation 2.3 [49]:

$$\mathrm{OpEx_{farm}} = \mathrm{n_{tur}} \sum_{i=1}^{n_c} \left[C_{corr,i}\left(n_{fail,i}\right) + C_{prev,i}\left(n_{serv,i}\right) \right] \qquad 2.3$$

where n_{tur} is number of turbines, n_c is number of components per turbine and $C_{corr,i}(n), C_{prev,i}(n)$ are the total corrective/preventive maintenance costs for component i given n such tasks. The cost functions C_{corr} and C_{prev} aggregate vessel costs, technician labor and materials for the require number of tasks, as shown in Equations 2.4 [49] and 2.5 [49]:

$$C_{corr,i}(n) = C_{v,i}^{corr}(n) + C_{t,i}^{corr}(n) + C_{m,i}^{corr}(n) \quad 2.4$$

$$C_{prev,i}(n) = C_{v,i}^{prev}(n) + C_{t,i}^{prev}(n) + C_{m,i}^{prev}(n) \quad 2.5$$

summing the vessel charter cost, technician cost and material cost for the n maintenance actions on component i. In this way, the model explicitly links failure rates ($n_{fail,i}$ expected failures of component i) and maintenance strategy (which sets $n_{serv,i}$, the number of planned preventive tasks) to the overall OPEX. Weather conditions enter by limiting maintenance crew access (e.g. a repair might be delayed until waves are below a threshold, prolonging downtime). These effects are captured by modeling accessibility windows or including a weather delay factor in C_v (vessel costs increase if waiting on weather) and in turbine downtime costs. The latter itself is an implicit cost because it reduces energy yield; some models account for it by valuing lost energy or by computing availability as a KPI alongside cost.

Across different modeling approaches, certain cost drivers consistently emerge for floating wind O&M. NREL [53] identifies failure frequency and repair/replacement costs as the primary determinants of OpEx. In other words, improving component reliability or reducing the cost of each repair has a direct impact on lowering OpEx.

2.5 Weather Impact and Accessibility Modeling

Weather conditions and accessibility are critical considerations for planning offshore wind O&M, and this is especially true for floating wind farms. Adverse metocean conditions (high waves, strong winds, currents) can prevent vessels from accessing turbines or make it unsafe for personnel to work, thereby imposing weather downtime on maintenance activities. As noted, one of the main costs in O&M is the opportunity cost of lost energy production when a turbine is down and waiting for a suitable weather window. Therefore, accurate modeling of weather impacts is essential for realistic O&M cost estimation and scheduling optimization.

In fixed-bottom offshore wind, accessibility is often modeled using threshold limits such as a maximum significant wave height (Hs) of 1.5-2.0 m for CTVs operations and perhaps 2.5-3.0 m for larger service vessels or JUVs, along with wind speed limits (e.g. 10-15 m/s for safe crane lifts or 20 m/s for helicopter flights) [36].

For FOW, the same metrics apply with additional considerations: the motion of the floating platform itself, for example, can make docking a CTV or climbing onto the turbine unsafe. Thus, some studies define operational limits in terms of allowable turbine nacelle acceleration or velocity in certain directions. In practice, these motion limits correlate with wave conditions, but modeling them may require coupling a response model of the floater.

Two main approaches are seen in the literature for modeling weather downtime in O&M simulations:

- Statistical/Monte Carlo Methods: many models use Monte Carlo simulation with probabilistic representations of weather windows. For example, the Markovian Chain Monte Carlo (MCMC) model by Rinaldi et al. (2021) [34] treats the sequence of weather and failures stochastically. In their adapted model, time-series of weather (wind, wave, current) are generated from hindcast data, and maintenance can only proceed when conditions fall below the thresholds required for that activity. The model evaluates two T2P strategies: one requiring a single continuous weather window long enough to tow the turbine to port, repair it and tow back (very restrictive), and another discontinuous strategy where the transit phases and onshore repair phases are decoupled. The latter requires multiple smaller weather windows (for outbound tow and return tow), assuming onshore repair is not weatherdependent. By simulating many realizations of annual weather, such Monte Carlo models estimate the probability distributions of waiting times and repair durations. Rinaldi et al. found that requiring one long continuous window greatly extended downtime for major repairs, whereas allowing a split operation significantly reduced weather delay impact. This illustrates how weather modeling can inform strategy, as it may be beneficial to allow turbines to be detached during rough weather and only towed when a short calm window arises, rather than waiting for a multi-week calm period to do everything in one go;

- Analytical/Deterministic Window Analysis: some O&M models use an analytical approach, inputting parameters like mean waiting time for a given operation based on historical weather statistics. For instance, an O&M access model might include a module where, given a required operation duration (say 48 hours) and weather thresholds, it calculates the expected delay (perhaps via a Weibull distribution for calm period length). McMorland et al. (2022) [31] note that Petri net models can incorporate such statistical distributions. A Petri model is a graphical interface tool in the form of a flowchart with four fundamental features being: places, transitions, arcs and tokens. Elusakin et al's Petri-net-based O&M scheduler [46] uses a Weibull distribution to represent time-to-failure and likely also encodes probabilistic timing for repair tasks and weather waiting. These methods are useful when full time-series are not available, as they can approximate weather downtime by drawing from distribution fits. However, a limitation is that they might not capture seasonality unless multiple distributions are used.

In recent studies, the time series approach has gained favor as computational power allows long-term hindcasts to be directly used. For example, Gonzalez et al. (2020) [54] and Hawker et al. (2018) [55] both looked at the impact of various weather and logistics parameters on offshore wind O&M, using simulated weather time-series to drive their models. They showed that as wind farm move further offshore (and into harsher environments), weather windows become the dominant constraint. This is an important insight for floating wind in the Atlantic and North Sea, as improvements in vessel tech, like motion-compensated gangways, will directly translate to reduced weather downtime.

For the Mediterranean, where significant wave heights are typically lower on average, accessibility might be higher, but conversely the wind resource is lower, so there is a smaller

margin for downtime before LCOE is affected. In any case, site-specific metocean analysis is a prerequisite in floating wind O&M planning.
Developers are advised to perform detailed hindcast studies to quantify how many maintenance days per year can be expected and plan their O&M strategy accordingly.
As an example, Italy's national wind energy R&D program is developing high-resolution metocean databases (e.g. the EOLIAN wind atlas [35]) to inform where floating wind farm can operate with acceptable O&M risk in the Mediterranean.

Another weather-related factor is the transport of assets to port during storms. Floating turbines are typically designed to resist weather storms in place; however, if a turbine is en-route to port and a weather event arises, it could be vulnerable. This risk is usually mitigated by carefully choosing tow weather windows or having escape strategies (e.g. temporary sheltered mooring points). O&M models sometimes include logic for weather interruptions, with operation pausing if a repairs in progress and weather exceeds limits. Gintautas et al. (2022) [56] introduced a methodology for dynamic scheduling that adjust maintenance activities in real time based on forecast changes in weather. This kind of dynamic scheduling is increasingly applied in industry.
By integrating forecast models with O&M decision tools, unnecessary waits can be avoided and the safety of operations improved.

In conclusion, weather impact modeling for FOW O&M has advanced from simple averages to sophisticated simulations incorporating wave, wind and platform motion criteria, with all these insights feed into the design of O&M strategies and into the development of cost modeling tools, addressed next.

2.6 State-of-the-Art in O&M Cost Modeling Tools

Given the complexity of floating wind O&M and the many interdependent factors described, a variety of specialized modeling tools and software frameworks have been developed to simulate O&M activities and estimate costs. These tools are invaluable for predicting O&M

performance during the project planning phase and for optimizing maintenance strategies throughout the project life.

The offshore wind industry has over a decade of experience with O&M simulation tools for bottom-fixed farms, and many of these have been adapted for floating. A comprehensive list of academic and industry O&M models can be found in literature (e.g. DNV GL's 2019 review [57]). Instead of reinventing the wheel, several searchers have modified well-established models to handle floating specific inputs.
A prominent example is the ECN O&M Tool, originally developed by the Energy Research Centre of the Netherlands and widely used for fixed offshore wind O&M studies. The ECN tool is a Monte Carlo based simulator that can calculate long-term availability and O&M costs given inputs like failure rates, vessel specs, weather data and maintenance strategies. Castella et al. (2017) [39] and Dewan & Asgarpour (2019) [40] both employed versions of the ECN tool adapted for floating wind, specifically adding the option for T2P maintenance within the model logic. Its modulation to floating involved modifying certain cost calculation (for instance, removing jack-up vessel usage and including mooring detachment time for towing) and adding new vessel types. Notably, the GL (Germanischer Lloyd)-validated version of this tool serves as the basis for an updated floating O&M model that will incorporate features like human fatigue limits and advanced vessel hydrodynamics.

Another commonly used model is NREL's O&M Cost Estimator and its successors. Myhr et al. (2014) [58] and Bjerkseter & Ågotnes (2013) [59] used a tool referred to as "OMCE" (Operation and Maintenance Cost Estimator) to calculate O&M inputs for their floating wind cost studies. Though details are often proprietary, these tools likely use parametric or simplified Monte Carlo methods to output metrics like average annual O&M cost and downtime under given assumptions.

The Shoreline O&M simulation tool is a commercial software that has also been leveraged for floating wind scenarios. Amorim et al. (2020) [60] utilized Shoreline's model with custom modifications for a floating farm case study. This tool is a discrete-event simulation environment where the user defines vessels, failure rates, weather time-series etc., for stochastically simulating logistical operations. Its use in floating contexts shows it was flexible enough to model T2P by effectively scripting a towing operation and onshore repair as part of the event sequence.

Another adaptation was by Gray (2022) [45], who combined modules from DTOcean (an open source wave energy project O&M tool) with wind turbine O&M models to analyze a hybrid floating wind-wave concept. This kind of cross-sector adaptation indicates that underlying O&M processes are similar across marine renewables, and existing frameworks can be repurposed with appropriate tweaks.

In addition to adapting existing tools, several new modeling approaches have been developed specifically to address floating wind nuances. Brons-Illing (2018) [42] created an Excel based model comparing scenarios of near-, mid- and far-shore floating farms, each with sub-scenarios of with versus without T2P operations. This study provided early insight into how distance and maintenance philosophy impact cost. A more sophisticated model by Martini et al. integrated three sub-models: a discrete-event O&M logistics model, a floating platform dynamic response model (to determine when conditions force shutdowns) and a wind farm power production model. These were linked to simulate the interdependencies between environmental conditions, turbine motions and maintenance activities. The results is a more realistic assessment of energy production losses and repair scheduling for FOW.

Elusakin et al. (2022) [46] proposed a novel Petri-net model for FOW O&M, providing a graphical, mathematically rigorous way to model concurrent processes with randomness, which suits the O&M scheduling problem with multiple turbines, crews and uncertain events. In their framework, "places" represent states (e.g. turbine operational, turbine under repair) and "transitions" represent events. Tokens flow through the net triggered by events, capturing the stochastic evolution of the system.

Elusakin's model explicitly incorporated FOW-specific challenges, adding extra places for the floating substructure components and models their failure rates, accounting for the limited accessibility windows due to weather and resource constraints. One reason they chose Petri nets was the ability to easily use a Weibull distribution for time-to-failure, suitable for new tech with sparse failure data. Petri net models are less common in wind O&M than Monte Carlo simulations, but they offer transparency and could be scaled up as computing improves.

The state-of-the-art tools, whether adapted or new, generally provide a suite of outputs: annual O&M cost (often broken into preventive and corrective), turbine/farm availability (percentage of time able to produce, failure frequency and downtime per failure type, waiting times for vessels and sometimes financial metrics like net present value (NPV) or cost-

benefit ratios for different strategies. For example, many studies report the LCOE as a final KPI, which incorporates O&M costs alongside capital costs, while some also compute the IRR for a project given revenue assumption.
Another trend in modern tools is including risk and uncertainty analysis, since many input variables like failure rates or weather patterns are uncertain and tools like ECN O&M model and others perform sensitivity or scenario analyses to identify which factors contribute most to cost uncertainty.
In 2023-2025, increasing collaboration between research institutions and industry has risen to refine O&M modeling for FOW. One notable development is NREL's WOMBAT (Windfarm Operations and Maintenance cost Benefit Analysis Tool), which was used by Khalid et al. (2023) [36] for the robotics cost-benefit study. This is a new-generation tool that can simulate both conventional O&M and novel technologies in modular way, giving output metrics such as annual OPEX, inspection times and even residual risk which quantifies the benefit of a strategy in terms of risk reduction.
The coupling of installation and maintenance is another frontier currently explored, emphasizing the overlap of the two processes and suggesting that an integrated view can yield cost savings.

Finally, a crucial aspect of state-of-the-art modeling is validation and data feedback. As the first commercial floating projects report their O&M data, modelers are calibrating their tools against real world observations, to further enhance accuracy and converge as best practices emerge.
In summary, the toolkit for floating wind O&M cost modeling is rapidly maturing, with practitioners that have access to adapted industry-grade simulators as well as advanced research models. These tools allow stakeholders to evaluate different O&M strategies, predict long-term costs and identify bottlenecks before projects are built. Moreover, these models support policy and R&D by highlighting which innovations would yield the greatest cost reductions.
Continued refinement of O&M modeling, grounded in real data, will be the key to reducing uncertainty and facilitating the scale-up of FOW in Europe and globally.

Chapter 3: Methodology

3.1 Research Approach

How do site-specific metocean conditions and maintenance strategy choices interact to shape the long-term O&M costs of floating offshore wind farms, and can Mediterranean projects exploit their milder sea states to close the cost gap with North Sea benchmarks?
Addressing to this question was the main purpose of this thesis work, and the methodological architecture has therefore been built to isolate, quantify and compare the two chief drivers of OPEX: weather-induced accessibility and maintenance-execution philosophy, under strictly controlled boundary conditions.

Since very few studies in literature currently exist confronting Mediterranean and North Sea in terms of O&M impact in overall cost and even fewer feature a techno-economic tool for computing the different cost voices contribution by taking into account metocean conditions, wind farm characteristics and failure rates of components across different types of maintenance, hereby the goal was to develop an easy-to-use MATLAB simulation script to calculate various cost components contributing in O&M to compare across different regions and wind farms.

Two region-representative floating offshore wind farms were selected to provide climatic contrast, as Mediterranean is slightly less productive while having milder sea weather with respect to North Sea.

3.2 Overview of the Developed MATLAB Script

The resulting script, which flowchart is in Figure 3.1, is modular, user interactive and designed around the LAUTEC-ESOX weather window Excel-based workbook, that supplies per-hour accessibility flags for any vessel/constraint combination, based on ERA-5 metocean data.

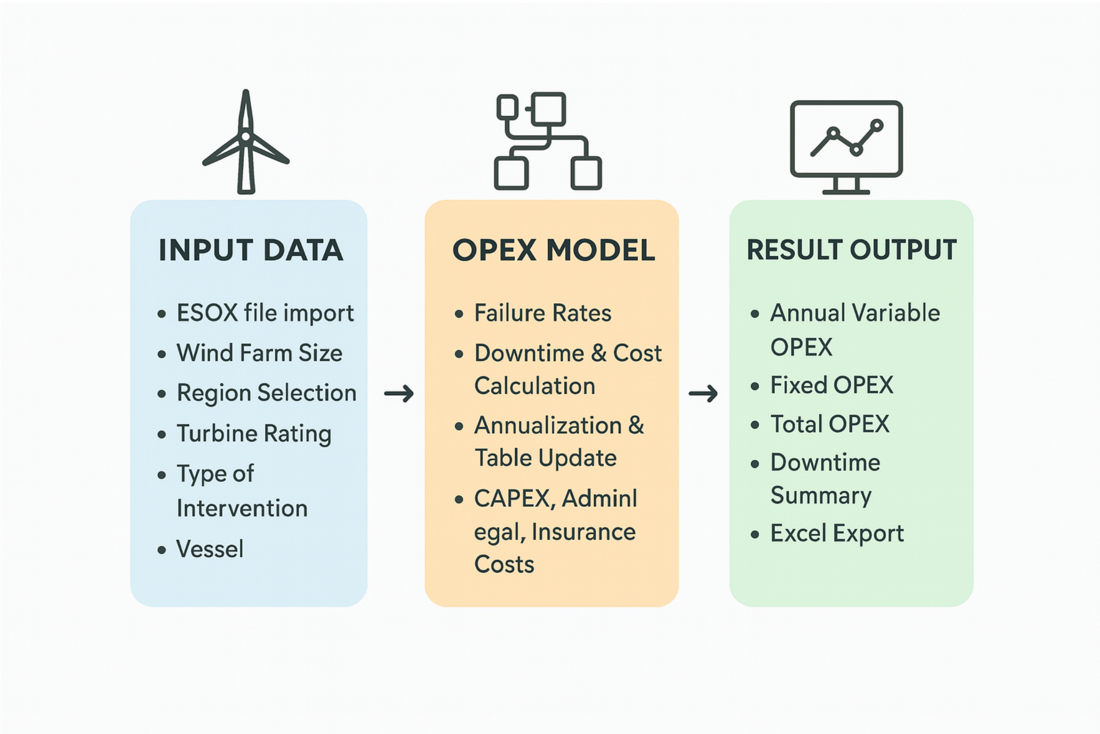


Figure 3.1: MATLAB script flowchart

At run-time, the user is guided through a cascade of graphical list dialogs, as shown in Figures 3.2, 3.3 and 3.4, that permits a selection of (i) total installed capacity (within a range of 50 to 800 MW), (ii) geographical climate regime (North Sea or Mediterranean) and (iii) single-turbine rating (from 9.5 to 15 MW).

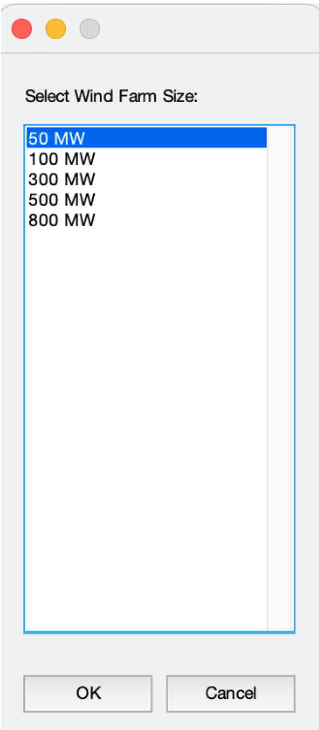


Figure 3.2: Wind Farm total capacity selection

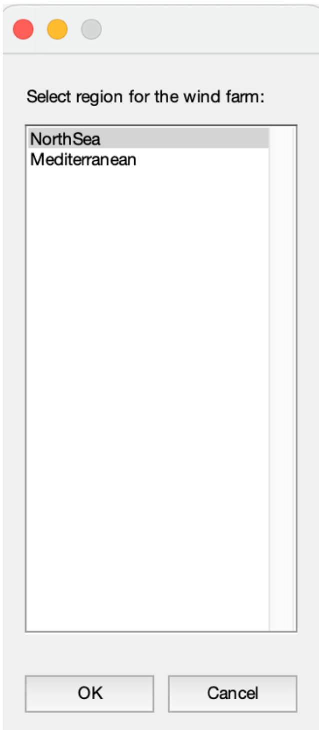


Figure 3.3: Region selection

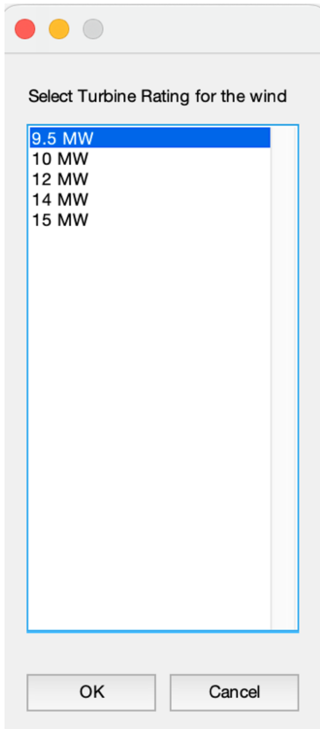


Figure 3.4: Turbine rating selection

These choices instantiate global constants like electricity strike price π, capacity factor CF and CAPEX gradient, before any heavy I/O is attempted, thereby guaranteeing data coherence across the session.

The core loop processes a stack of "OUTPUT_QA" sheet from ESOX Excel files, with each one representing one maintenance intervention template containing a chronologically ordered weather-window log. For every workbook, the user specifies both vessel class (12 options with daily rate associated) and intervention class (to use the proper failure rate). The script immediately parses the sheet via detectImportOptions, derives weather-excluded hours by string-matching the PROGRESS field, converts downtime to both revenue loss and charter effort and finally scales the result by a component and region-specific quarterly failure frequency, as demonstrated in a code snippet on Figure 3.5.

```
% --- Load Data ---
sheetname = 'OUTPUT QA';
opts = detectImportOptions(fullpath, 'Sheet', sheetname);
data = readtable(fullpath, opts);

% --- Compute per-event costs (single turbine, single quarter) ---
hourlyDowntimeCost = turbine_MW * CF * price;
if any(strcmpi(data.Properties.VariableNames, 'PROGRESS'))
    is_weather_downtime = contains(string(data.PROGRESS), 'Downtime:', 'IgnoreCase', true);
else
    error('Column "PROGRESS" not found.');
end
weather_downtime_hours = sum(is_weather_downtime);
turbine_downtime_hours = height(data);
charter_days = ceil(turbine_downtime_hours / 24);

C_opportunity_per_event = turbine_downtime_hours * hourlyDowntimeCost;
C_charter_per_event = charter_days * vesselDayRate;
C_var_per_event = C_opportunity_per_event + C_charter_per_event;
```

Figure 3.5: MATLAB code snippet

All intermediate objects (row vectors and scalar accumulators) are memory-resident, avoiding repeated disc I/O and allowing progress to be echoed to the console in real time.

Three design decisions align the tool with best practice in techno-economic energy modelling: (a) a single-pass aggregation algorithm converts quarterly expectations to annual metrics only after the file loop terminates, preserving the analyst's ability to inspect per-event data; (b) a container-map look-up for CAPEX versus farm scale eliminates nested if-elseif branches and yields constant-time performance; (c) a fail-fast strategy aborts execution if any indispensable filed like scenario pick, vessel selection or spreadsheet column is missing, preventing silent error propagation.

The script closes by exporting a tidy ledger named OPEX_Detailed_and_Total.xlsx into the same directory as the source weather files, conforming to the FAIR principle that derived data must reside alongside raw data and remain machine-readable.

The output Excel file contains different cost and weather-related voices, as showed in Table 3.1.

Table 3.1: Excel output files content

File Name	Name of the file to which all the row values refer to
InterventionClass	Major Replacement, Small Repair or Small Replacement for every component
Vessel	Type of vessel considered
OpportunityCost_perEvent	Cost incurred due to energy production lost (€)
CharterCost_perEvent	Chartering cost of vessel (€)
TotalVarCost_perEvent	Sum of Opportunity and Chartering Cost (€)
FailureRate_perQuarter	Failure rate per component and type of intervention, referred to a specific quarter
ExpectedVarOPEX_perQuarter_perTurbine	Sum of all component and intervention variable costs per quarter (€)
WeatherHours_perEvent	Weather downtime hours
TurbineHours_perEvent	Turbine downtime hours
TotalVarOPEX_Annual_perTurbine	Sum of all Variable OPEX costs (€)
TotalVarOPEX_Annual_perFarm	Variable OPEX costs multiplied per number of turbines in a farm (€)
WeatherHours_Annual_perFarm	Weather downtime hours per farm in a year
TurbineHours_Annual_perFarm	Turbine downtime hours per farm in a year

If the analysis is conducted with the full stack of files for a single wind farm as the script was intended to be used, representing all possible interventions per quarter and component, every row will be referring to a single component and type of maintenance in a single quarter, hence resulting in a full OPEX overview for a single farm. The simulation, however, can run also for a single file or a restrained number.

3.3 Input Data and Assumptions

3.3.1 Turbine and Farm Characteristics

As stated before, two wind farms were chosen to be representative of the Mediterranean and North Sea regions. In this section we outline their characteristics presenting first their real-world configurations and technical details, then noting a simplification used in our OPEX model regarding turbine count.

The Mediterranean reference site, labelled "NP POZZALLO", is an 800 MW commercial-scale floating wind project, still in its development phase, proposed in the Malta Channel about 41 km south of Pozzallo, Sicily, where bathymetry drops from roughly 120 m to beyond 200 m. Its precise coordinates can be found on Table 3.2 alongside those of North Sea farm. The concession filing shows a radial layout of 54 machines, 44 Vestas V235-15 MW plus 10 14 MW units, on semi-sub platforms with catenary moorings taken into consideration as long as other mooring types; the schematic layout used is shown on Figure 3.6 [61].

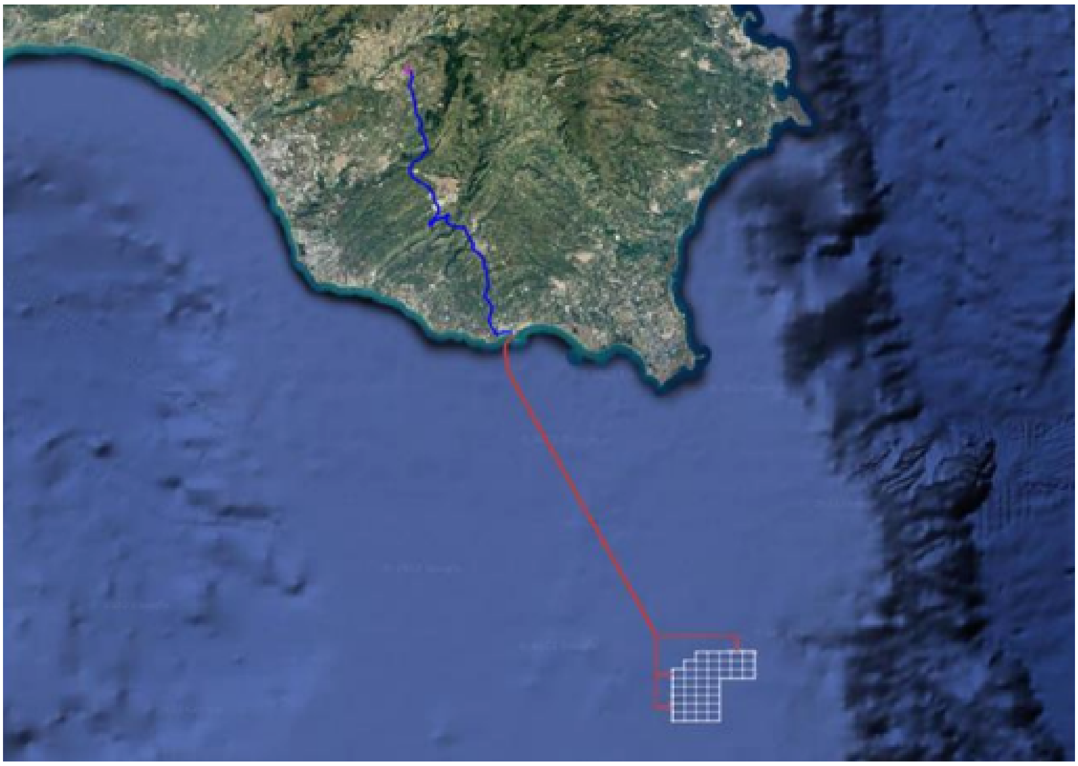


Figure 3.6: NP Pozzallo layout

Subsequent project briefs confirm the same capacity and sea-area envelope, specifying a total lease of 88.3 km^2 and three floating offshore substation that will export at 200 kV to the Ragusa grid node [61].
The V236 rotor (236 m diameter, 115.5 m blade length) sets a hub height of 140 m MSL and nacelle mass above 900 t, dictating T2P heavy-lift interventions for major replacement.

By contrast, the North Sea comparator, Kincardine, occupies a 24.2 km^2 lease 15 km off Aberdeen in 60-80 m water. It consists of five Vestas V164-9.5 MW turbines and a legacy V80-2 MW demonstrator, all mounted on WindFloat semi-sub hulls that are towed to port for heavy work [62][63]. Commissioned in 2021, the array delivers 200 GW/yr and has validated large-rotor floating operation in sea states where Hs exceeds 5 m and peak winds regularly surpass 25 m/s [64]. Its layout is shown on Figure 3.7 [65].

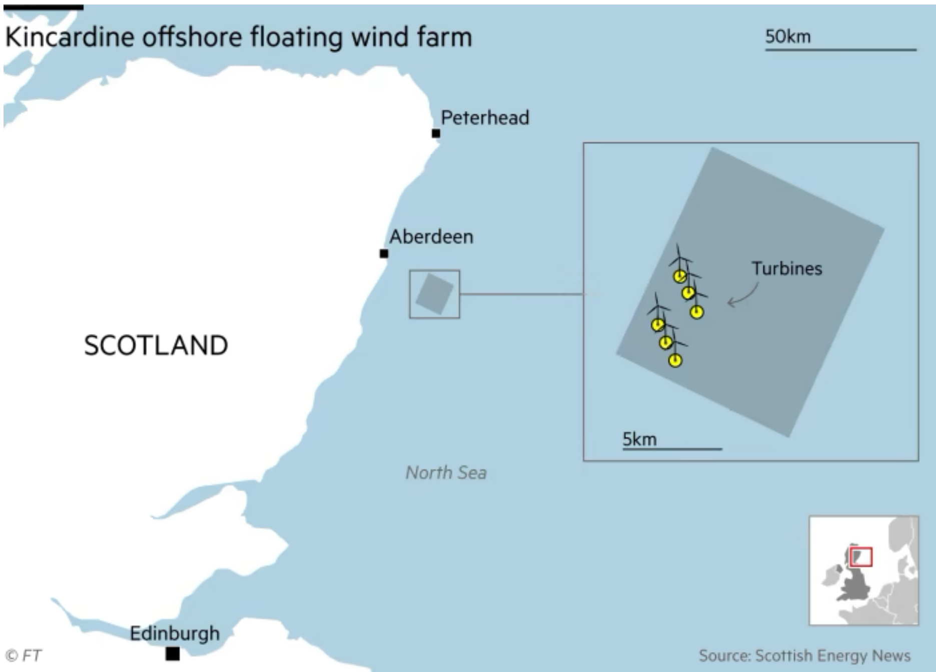


Figure 3.7: Kincardine layout

For computational tractability, the MATLAB model recomputes the turbine count internally as $N = P_{farm}/P_{turb}$; hence NP Pozzallo is idealized as 54 identical 15 MW units and Kincardine as an integer multiple of 9.5 MW machines, a simplification that preserves total capacity, floating-foundation class and port distance, the dominant O&M cost drivers, while eliminating heterogeneity that would otherwise add little explanatory power to the annual OPEX comparison.

Table 3.2: NP Pozzallo and Kincardine coordinates in latitude and longitude

	Latitude φ	Longitude λ
NP Pozzallo	36° 24’ 35.9’’ N	14° 49’ 12’’ E
Kincardine	57° 00’ 00’’ N	1° 51’ 46.8’’ W

3.3.2 Weather Data for Site Accessibility

Hourly hind-cast wind and wave series for both reference sites were downloaded from the LAUTEC ESOX platform, shown in Figure 3.8 [66], which republishes ERA-5 on a 0.25° grid in ready-to-use CSV form. The Mediterranean file, n36.25_e15.25.csv, corresponds to the nearest point available in the platform to NP Pozzallo wind farm, at 36° 15’ 00’’ N, 15° 15’ 00’’ E and spans from 1st January 1990 through 31st December 2019; statistical interrogation of the records gives a mean significant wave height Hs = 0.98 m, a 95th-percentile Hs95 = 2.37 m, a mean 10-m wind speed U10 = 5.63 m/s and U10,95 = 11.7 m/s. The North sea data set, n57.00_e-e-1.75.csv, centered in the closest point to Kincardine available at 57° 00’ 00’’ N, 1° 45’ 00’’ W, covers the same 1990-2019 horizon and yields Hs = 1.31 m, Hs95 = 2.89 m, U10 = 7.50 m/s and U10,95 = 13.7 m/s.

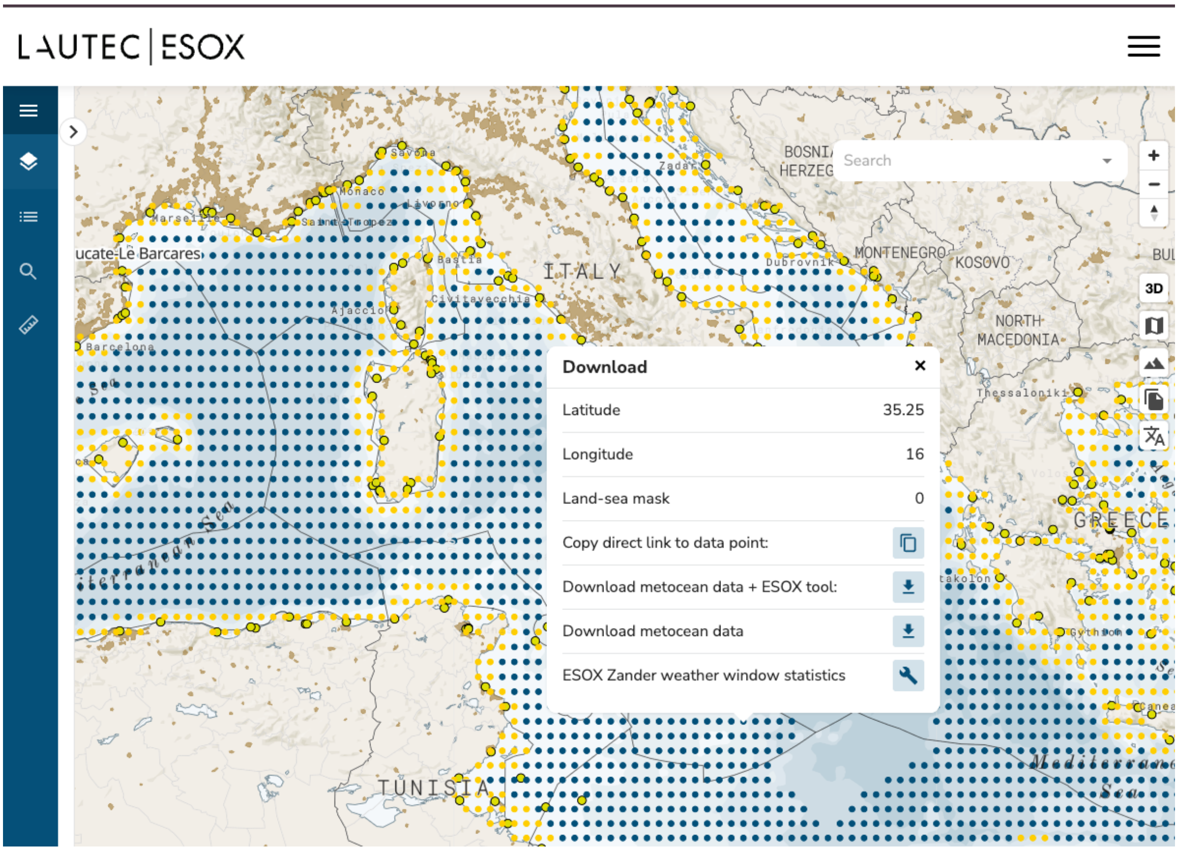


Figure 3.8: LAUTEC | ESOX map

When a CSV is uploaded to ESOX, the platform: (i) reads the full 30-year record, (ii) lets the user define operability thresholds and minimum-window duration per vessel type, (iii) calculates continuous-window statistics for every year in the record and (iv) export an Excel macro-workbook in which OUTPUT_QA holds the *hour-by-hour Boolean accessibility flags for the last year only (2019), while ancillary sheets retain long-term exceedance and persistence metrics computed from the entire 1990-2019 horizon, like Best and Worst Year on dataset to perform operations based on weather constraints.
Consistent with ESOX guidance, 2019 was adopted as a representative operational year as the MATLAB OpEx engine ingests only the OUTPUT_QA sheet, treating its 8760 hourly flags as the deterministic accessibility calendar for that site and quarter, while the deeper ESOX statistics are retained offline to support sensitivity checks discussed in Chapter 4.
An example of the OUTPUT_QA sheet can be found on Appendix E.
Using a single processing pipeline for both basins guarantees methodological symmetry and, because ESOX applies identical ERA-5 physics and quality control to every grid point, removes source-bias while still grounding the analysis in a 30-year climatological context.

3.3.3 Cost Parameters

All monetary inputs are split into two layers: a deterministic fixed-overhead envelope applied once per operating year and a stochastic event-dependent cost term evaluated every time the simulator schedules an intervention.
Each scalar loaded by MATLAB script is traceable either to a peer-reviewed cost survey or to a transparent mid-quartile market benchmark.

The annual fixed overhead combines administration/legal expenses and insurance premia. Administration-legal is assumed at €100,000 per turbine per year, as both the sea regions considered wind farms incur on the order of €50,000-€150,000 per turbine per year [67][68][69], with roughly €7,000-€10,000 per MW-year under late-2020s cost assumptions. Insurance is assumed as 1% of CAPEX per annum.
CAPEX itself is capacity-scaled through a five-point lookup, from €4.6 M/MW at 50 MW tapering to €3.4 M/MW at 800 MW, fitted to the logarithmic regression released in the same BVG report [69].
Failure intensities originate from Carroll et al. [52]. The annual rates per component and type of intervention are down-scaled to quarter-year values, assuming Major Repair as Small

Replacement instead. As mostly referred to North Sea, the rates were assumed to be scaled down for deriving Mediterranean values by computing two scaling factors for wind and wave as follows: Chirosca & Rusu (2022) [70] lists the 50th-percentile significant wave height for each basin, showing 1.1 m for the Mediterranean, whereas North Sea has 2.7 m; hence the downscaling-ratio for wave climate was assumed as $1.1 \div 2.7 = 0.41$. The study does the same for wind speed along representative routes; Route R5 (Mediterranean) records 12.75 m/s while Route R3 (North Sea) shows 14.51 m/s, hence the ratio is calculated as $12.75 \div 14.51 \approx 0.88$. These two ratios are used directly, without additional averaging or heuristics, as scaling factors for components whose reliability is assumed dominated by wave-induced fatigue or motion (Dynamic inter-array cables, moorings, tower, floating substructure) in the case of 0.41, and those components which are most affected by wind loading and turbulence (blades, pitch system, gearbox, generator) for 0.88.

The final λ-matrix of failure per turbine per year (whose values are further divided by 4 into the MATLAB script to respect quarter division) is showed in Table 3.2.

Table 3.3: Annual failure rates per component, type of intervention and region

Component	Intervention class	North-Sea baseline (failures · turbine^{-1} · year^{-1})	Scaling factor	Mediterranean result (failures · turbine^{-1} · year^{-1})
Blades	Major repl.	0.001	0.88 (wind)	**0.000 88**
	Small repl.	0.010	0.88	**0.008 8**
	Small repair	0.456	0.88	**0.401 3**
Gearbox	Major repl.	0.154	0.88	**0.135 5**
	Small repl.	0.038	0.88	**0.033 4**
	Small repair	0.395	0.88	**0.347 6**
Generator	Major repl.	0.095	0.88	**0.083 6**
	Small repl.	0.321	0.88	**0.282 5**
	Small repair	0.485	0.88	**0.426 8**
Pitch / Hydraulics	Major repl.	0.001	0.88	**0.000 88**
	Small repl.	0.179	0.88	**0.157 5**
	Small repair	0.824	0.88	**0.725 1**
Dynamic inter-array cable	Major repl.	0.004 5 [1]	0.41 (wave)	**0.001 85**
	Small repl.	0	0.41	0
	Small repair	0	0.41	0

For every simulated event, the code evaluates the opportunity cost as Equation 3.1:

$$C_{opp} = h_{turb} \cdot P_{turb} \cdot CF \cdot \pi \tag{3.1}$$

Where h_{turb} is turbine downtime hours, P_{turb} is the turbine power in MW, CF is the capacity factor and π is the strike price. The three elements P_{turb}, CF and π together represents the Hourly Downtime Cost. Capacity factors are assumed at 0.45 for the North Sea and 0.32 for Mediterranean, as different studies suggest range of values in the order of 0.30-0.35 for the latter and 0.40-0.50 for North Sea region [28][71].
Strike prices anchor at €80 MW/h and €100 MW/h respectively for North Sea and Mediterranean, being assumed as in 2024 the average price was about €78.5 MWh and €141 MW/h [72][73].

The chartering cost is computed as Equation 3.2:

$$C_{charter} = \left\lceil \frac{h_{turb}}{24} \right\rceil \cdot R_v \tag{3.2}$$

Where h_{turb} is turbine downtime hours as before and R_v is the vessel daily rate, taken by Ramachandran et al. (2022) [74].
The script aggregates $C_{opp} + C_{charter}$ per event, multiplies by the component-specific quarterly λ to obtain the expected variable OPEX per quarter and turbine, converts to an annual figure and scales by the computed turbine count N.

3.4 Accessibility Modeling Based on Sea States

The MATLAB script inherits a binary timeline from ESOX tool but recasts it into per-event metrics via a rolling-window routine. For each selected vessel class, the script counts (i) weather downtime hours, as rows in OUTPUT_QA whose PROGRESS string contains "Downtime:" (as shown in a code snippet on Figure 3.8), and (ii) total intervention hours, i.e. the row count of the sheet (each row = 1h). The weather downtime hours enter the opportunity loss term, whereas vessel presence is monetized via daily rate once for every completed 24-h block (rounded up with ceil). Technicians wage and other costs associated with the maintenance work were not considered.

The analysis deliberately operates on quarter-year slices rather than annual blocks to capture seasonal amplitude in Hs and daylight length. Quarter cut-off dates as 10 Mar, 10 Jun, 10 Sep and 10 Dec respectively representative of Q1, Q2, Q3 and Q4 were chosen based on:

- Quarter-median representation: for a standard 90-day quarter the median falls on day 45; the 10-th of the last month (day 69-70) still lies within the inter-quartile range but avoids the early-month volatility associated with New Year restart (Q1) or post-Easter mobilization (Q2). Empirically, ERA-5 analyses for both case-study basins show that cumulative wave-height exceedance curves evaluated on the 10-th differ by <2% from full-quarter means, making the date a statistically unbiased proxy for the quarter's central tendency;
- Alignment with industrial reporting cycles: charterers and insurance underwriters typically close operational ledgers on the second Friday of the final month to allow two working weeks for invoice verification before corporate quarter close. The 10^{th} day approximates this practice, ensuring that downtime cost tallies produced by the model map cleanly onto real invoice bundles and quarterly cash-flow statements;
- Integer-day, equal-length bookkeeping with deterministic boundaries: by anchoring representative points on 10 Mar, 10 Jun, 10 Sep and 10 Dec, each quarter retains its natural calendar span, so the sum of λ values divided by four recovers the annual failure frequency exactly, yet the modeler needs to store only one high-resolution weather window slice per quarter. This minimizes memory and CPU overhead while keeping Poisson intensity integrals free from edge-effects that arise when events straddle month ends.

3.5 Maintenance Strategy Scenarios Implemented

Because this thesis focuses on the corrective burden that most strongly differentiate harsh and mild weather basins, the ESOX workbooks are configured for three intervention severities only: major replacement (MR), small replacement (SmR) and small repair (SmRp). No preventive or condition-based work was modeled.

For each turbine component and quarter, the ESOX file is set up by inserting (i) total duration of activity without downtime, (ii) minimum weather window duration required for activity to start, (iii) mean wind speed at 10 m above MSL and (iv) Significant wave height, as shown in Figure 3.9.

DURATION	WEATHER WINDOW	WIND 10	WIND 100	Hs
Total duration of activity without downtime	Minimum weather window duration required for activity to start	Mean wind speed at 10 m above MSL	Mean wind speed at 100 m above MSL	Significant wave height
[hours]	[hours]	[m/s]	[m/s]	[m]
3,00	3,00	100	100	100
3,00	5,00	13,00	100	1,80
16,00	24,00	13,00	100	1,80
6,00	8,00	13,00	100	1,80
48,00	72,00	16,00	100	100
6,00	8,00	13,00	100	1,80
16,00	24,00	13,00	100	1,80
3,00	5,00	13,00	100	1,80

Figure 3.9: ESOX file input for Blades Major Replacement

Total duration of activities for components maintenance was estimated based on literature and industry references, with minimum duration values being considered for the acitivity without downtime and maximum duration for the minimum weather window required. About those operations regarding the vessel used, as "Sail from site to Port" or T2P, the speed of the vessel used was considered along with distance from wind farm to O&M port, being 57.1 nm from NP Pozzallo to Augusta Port and 9.3 nm from Kincardine to Aberdeen port. It was assumed that the minimum weather window duration for those kinds of operations requires 2 more hours than the total sailing duration, with a vessel speed cut by half in case of towing the turbine to port or back to site.

For small replacement and small repair, it was assumed that CTVs are used as vessels for all components, while for major replacement HLVs perform the activities in all cases except for Dynamic Inter-Array Cables, where CLV is used.

The weather-window modeling is then executed as explained in the previous section.

Vessel details, alongside with their speed, can be found on Appendix C, while types of intervention details are shown on Appendix F.

3.6 OPEX Calculation Framework

After all the above operations are concluded, the MATLAB script excel output presents a condensed database containing all cost voices per quarter and type of intervention of the five components considered in this analysis, assumed as the most impactful in terms of O&M costs (Blades, Gearbox, Generator, Pitch System and Dynamic Inter-Array Cables).
Defined:

- $S = \{s_1, \dots, s_5\}$ the five components listed above;
- $K = \{MR, SmR, SmRp\}$ the type of interventions set;
- $q \in \{1, 2, 3, 4\}$ the industrial quarters 10 Mar, 10 Jun, 10 Sep and 10 Dec;
- $r \in \{Mediterranean, North\ Sea\}$ the region.

For every (s, k, q) tuple the script provides:

- $h_{s,k,q}$ as the deterministic downtime hours for one event in quarter q;
- $R_{v,s,k}$ as the vessel daily rate attached to that intervention class;
- $\lambda_{s,k,r,q}$ as the quarterly failure rate from the λ-matrix in section 3.3.3.

Let P_t be the turbine rating (MW), CF_r the regional capacity factor, π_r the energy price (€/MWh), N the turbine count computed by the script, C_{admin} the admin/legal allowance per turbine (100 k €/y) and $C_{ins} = 0.01\ CAPEX_{farm}$ the annual insurance premium.
Using whole-day charter billing, the expensive annual OPEX total formula, as shown Equation 3.3 below, is:

$$OPEX_{year}^{r} = N \sum_{q=1}^{4} \sum_{s \in S} \sum_{k \in K} \lambda_{s,k,r,q} [h_{s,k,q} \cdot P_t \cdot CF_r \cdot \pi_r + \left(\frac{h_{s,k,q}}{24} \right) \cdot R_{v,s,k}] + N \cdot C_{admin} + C_{ins} \qquad 3.3$$

First term is the variable OPEX expectation as opportunity loss plus charter hire, weighted by the probability of each failure type in each quarter per type of intervention and component, second term is farm-scaled fixed overhead for administration and legal compliance, and third term is farm-level insurance premium.

In code the computation is realized in three vectorized passes:

1. Event pass: calculate the bracket [] once per maintenance template;
2. Expectation pass: multiply by $\lambda_{s,k,r,q}$ and accumulate in per-quarter scalars sum_variable_opex_per_turbine, sum_weather_hours, sum_turbine_hours;
3. Aggregation pass: multiply by 4 quarters, scale by N, append $N \cdot C_{admin} + C_{legal}$ then write the ledger row to OPEX_Detailed_and_Total.xlsx

In figure 3.10 below these passes are shown in a code snippet.

```
        % --- Use correct region/intervention failure rate (per quarter) ---
        failure_rate_quarter = failureRatesPerQuarter.(region).(event_type);

        % --- Variable opex for this intervention/quarter, per turbine ---
        variable_opex_this_file_per_turbine = C_var_per_event * failure_rate_quarter;
        sum_variable_opex_per_turbine = sum_variable_opex_per_turbine + variable_opex_this_file_per_turbine;

        sum_weather_hours = sum_weather_hours + weather_downtime_hours * failure_rate_quarter;
        sum_turbine_hours = sum_turbine_hours + turbine_downtime_hours * failure_rate_quarter;

        % --- Fill all columns for robust Excel ---
        TotalVarOPEX_Annual_perTurbine = variable_opex_this_file_per_turbine * 4;
        TotalVarOPEX_Annual_perFarm = TotalVarOPEX_Annual_perTurbine * num_turbines;
        WeatherHours_Annual_perFarm = weather_downtime_hours * failure_rate_quarter * 4 * num_turbines;
        TurbineHours_Annual_perFarm = turbine_downtime_hours * failure_rate_quarter * 4 * num_turbines;

        row = {filenames{i}, intDisplay{intIndex}, selectedVessel, ...
            C_opportunity_per_event, C_charter_per_event, C_var_per_event, ...
            failure_rate_quarter, variable_opex_this_file_per_turbine, ...
            weather_downtime_hours, turbine_downtime_hours, ...
            TotalVarOPEX_Annual_perTurbine, TotalVarOPEX_Annual_perFarm, ...
            WeatherHours_Annual_perFarm, TurbineHours_Annual_perFarm, []}; % DummyCol
        results = [results; row];
    end

    %% --- AGGREGATE ANNUAL OPEX ---
    annual_variable_opex_per_turbine = sum_variable_opex_per_turbine * 4; % all quarters
    annual_variable_opex_per_farm = annual_variable_opex_per_turbine * num_turbines;
    total_opex_per_farm = annual_variable_opex_per_farm + C_admin_legal_farm + C_insurance_farm;
    fixed_opex_per_farm = C_admin_legal_farm + C_insurance_farm;
```

Figure 3.10: Code snippet regarding the part of variable OPEX computing

3.7 *Limitations of the Model*

A series of limitations must be acknowledged, to pave the road for future improvements of this work:

1. Representative-year weather: only the 2019 ERA-5 timeline feeds the baseline run, hence considered as a year-type, so risk tails are not embedded in the headline OPEX;
2. Static failure intensities: λ values are held constant, omitting age-related wear-out. This biases late-life costs downward and is flagged for future work using a non-homogeneous Poisson process. Furthermore, values regarding FOWTs still does not exists, as the ones taken into consideration by literature refer to smaller FBWTs;
3. Single-vessel and single-turbine spread: multi-vessel parallel campaigns (e.g. two CTVs working the same small-repair batch) are not modelled, hence charter clustering and potential economies of scale are ignored. Also, multiple-turbines parallel operations can be considered;
4. Halved towing speed: a flat 0.5 factor is applied to every tow-out without considering sea-state-dependent slowdown or DP holding. This simplification marginally underestimates weather downtime for the heaviest sea states;
5. No preventive synergy: because the study purposefully suppresses time-based and condition-based maintenance, any logistical synergy between corrective and scheduled tasks is excluded, again biasing absolute euros upward but leaving the relative Mediterranean-North Sea gap largely intact;
6. Few OpEx cost voices included: since only Chartering costs and Opportunity costs were included in the model, one could think of expanding it by adding more, to have a further detailed breakdown (i.e. cost of technicians, cost of components replaced etc.).

Chapter 4: Case study, Mediterranean vs North Sea

4.1 O&M Simulation Results

4.1.1 Accessibility Analysis

Figure 4.1 confirms that the modeling reproduces the empirical intuition: North Sea events endure a far wider spread of weather delay (IQR ≈ 210 h; median ≈ 260 h) than the Mediterranean (IQR ≈ 90h; median ≈ 130 h).

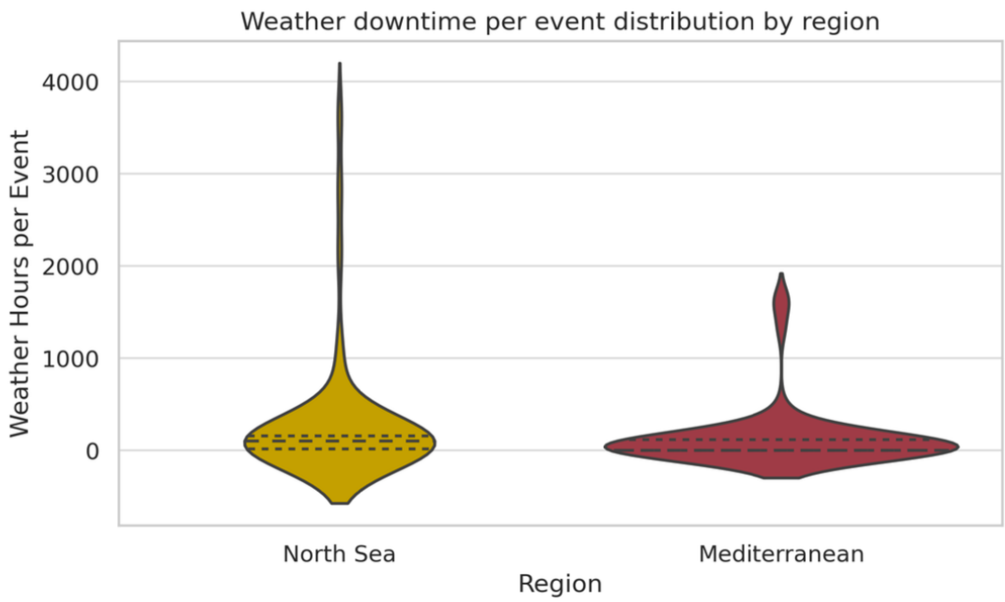


Figure 4.1: Weather downtime per event distribution by region

Each violin represents a distribution of weather delays. The North Sea's wide, tall shape indicates frequent and prolonged stoppages due to harsh weather conditions, often extending to many hours or week. In contrast, the Mediterranean's shape, while not extending to extreme delays, shows a wider base. This signifies that even under generally calmer sea conditions, numerous maintenance tasks experience brief pauses ranging from a few hours to a few days, keeping stoppages shorter but more broadly distributed.

Seasonality, in Figure 4.2, shows the average weather downtime along all types of interventions per quarter and region, amplifies this contrast, as the wave height probability matrix pushes North Sea Q4 downtime beyond 440 h/event, whereas the Mediterranean enjoys near-flat accessibility (< 330 h) all year.

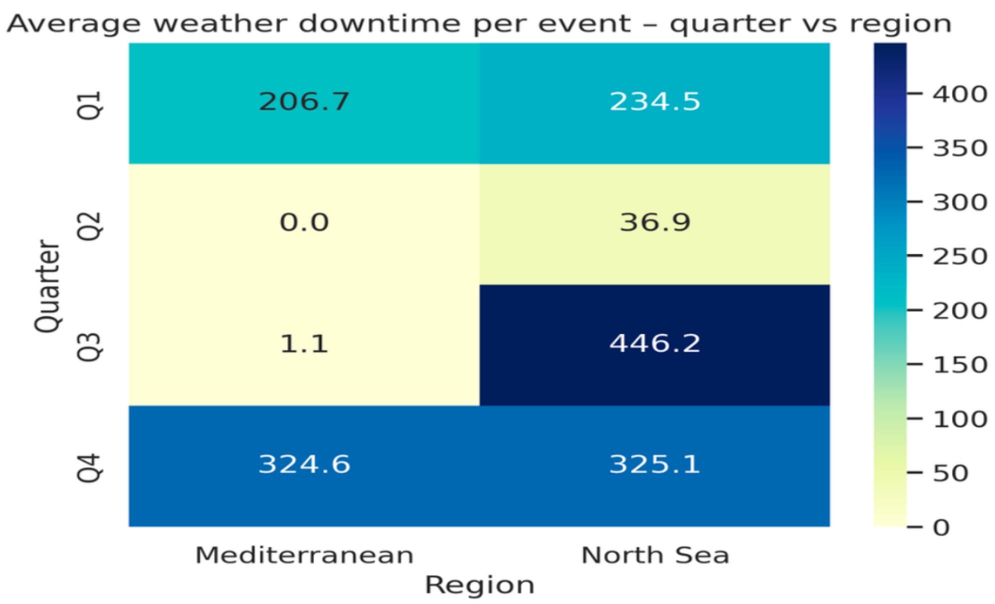


Figure 4.2: Quarter x region heat-map of average weather downtime per event

The environmental input time-series supplied by ESOX already capture the harsher North Sea climate, and our operational model faithfully converts those data into the longer waiting windows seen in the previous Figures.

4.1.2 Failure and Maintenance Event Modeling

The simulated Poisson failure counts translate into Figure 4.3. North Sea points cluster in the upper-right quadrant (high failure frequency and high variable OPEX), indicating that turbines in this region experience higher failure frequency and consequently incur greater variable OPEX, leading to a substantial increase in the quarterly O&M cost.

By contrast, Mediterranean points huddle lower left with smaller markers, telling that faults are rarer, cheaper to fix and therefore pull fall less cash out of the O&M budget.

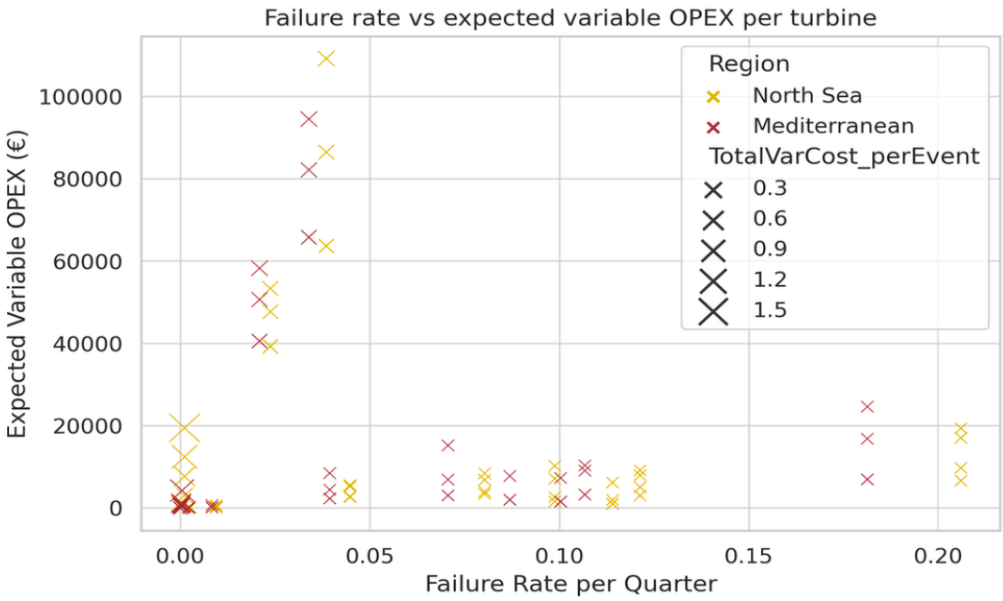


Figure 4.3: Failure rates of components vs expected variable OPEX per turbine

This outcome highlights that major interventions are acutely sensitive to climate conditions, as Figure 4.4 illustrates an approximate 3x downtime premium for North Sea major replacements compared to the Mediterranean. This result align with realistic operational challenges, where HLVs and CLVs are frequently bottlenecked by stringent access criteria in harsher conditions, while small repairs, primarily handled by CTVs, remain comparatively insensitive to metocean conditions.

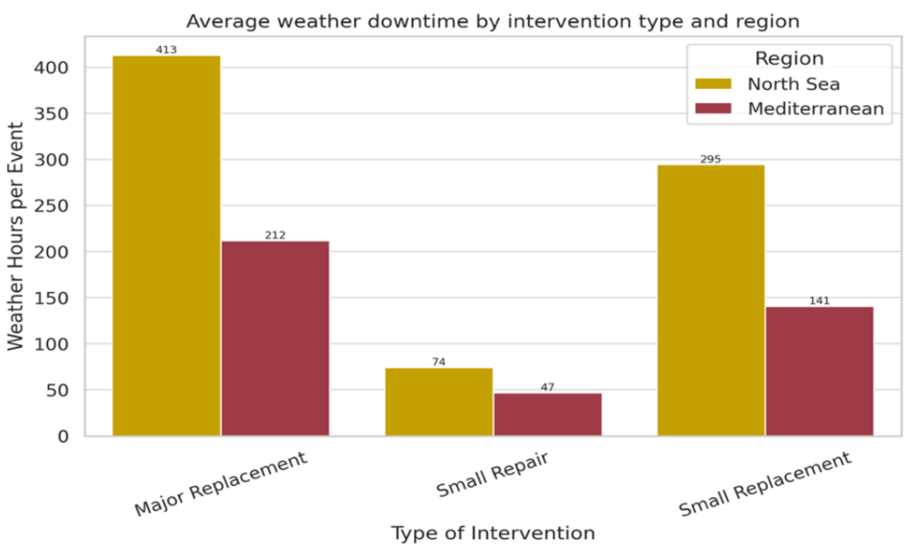


Figure 4.4 Average weather downtime per intervention type and region

4.1.3 OPEX Results per Strategy

Figure 4.5 reveals that absolute annual OPEX is higher in the Mediterranean (~ € 17.6 m) by design due to a larger plant and more turbines (800 MW vs. 50 MW), yet Figure 4.6 proves at € 352 k/MWy the North Sea OPEX/MW is roughly 61% higher than the Mediterranean's € 219 k/MWy.

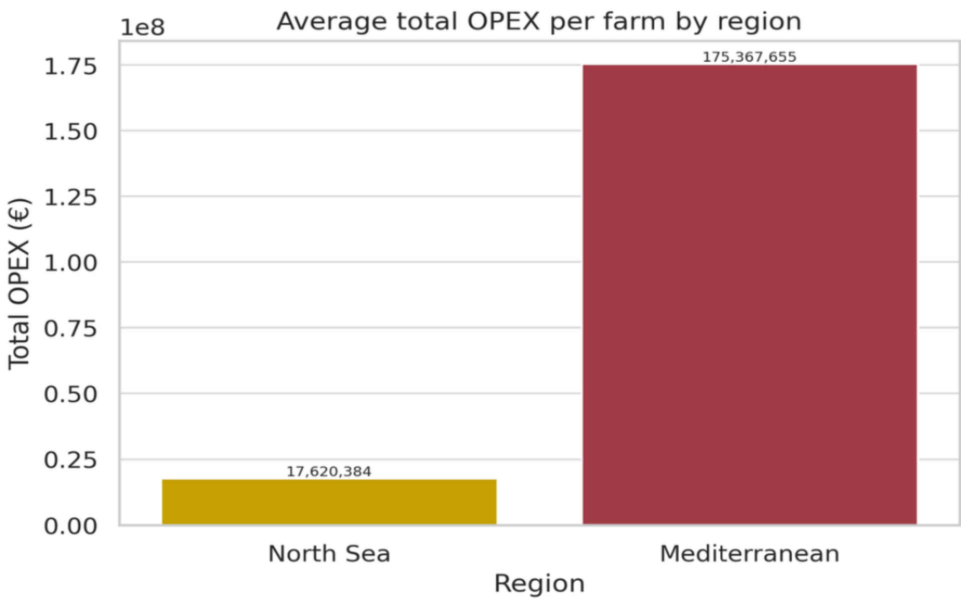


Figure 4.5: Average total OPEX per farm by region

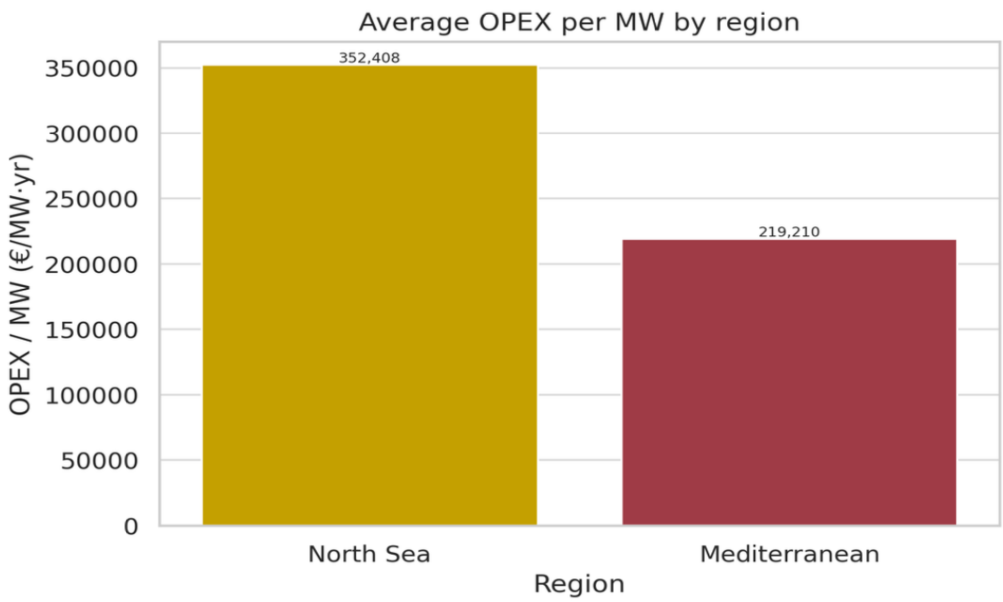


Figure 4.6: Average OPEX/MW per region

The cost classification output, shown in Figure 4.7 echoes modelling decisions from Section 3.4: 82% of Mediterranean cost is fixed base, whereas variable cost dominates the North Sea result (46% of total) because of poor weather.

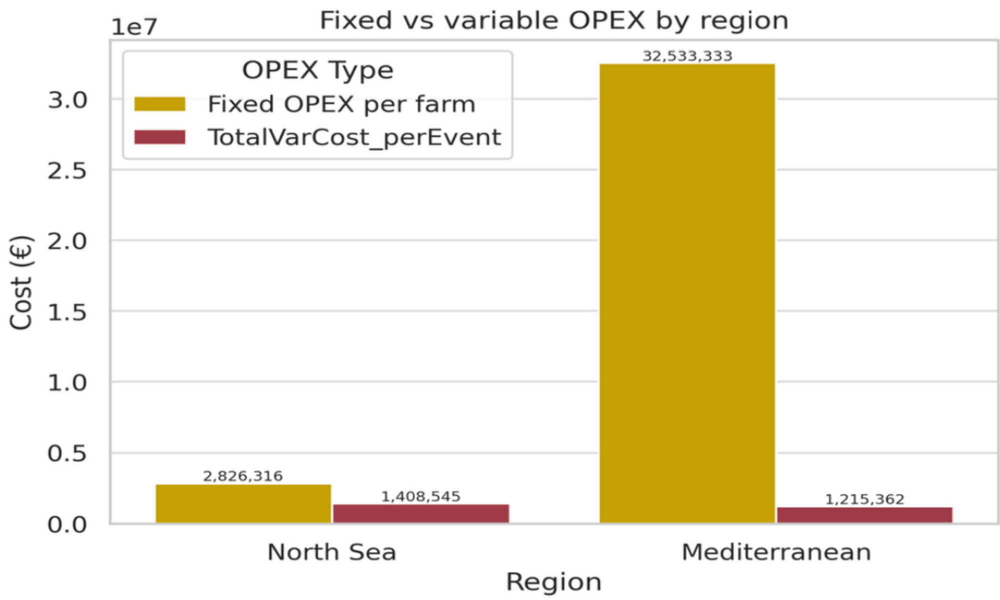


Figure 4.7: Fixed vs. Variable OPEX by region

In the quarterly variable OPEX profile displayed in Figure 4.8, the line chart tracks variable O&M spending normalized by installed capacity, so the number represents euros per megawatt each quarter. The North Sea curve sits consistently higher, as costs start around € 85 k/Mw in Q1 going to € 55 k/MW in Q2-23 before spiking to € 94 k/MW in Q4, whereas Mediterranean runs lower throughout, at about € 53 k/MW in Q1, €34 k/MW mid-year and € 57 k/MW in Q4.
The spreads confirms that harsher winter weather and pricier heavy-lift logistics keeps North Sea MW costlier to maintain.

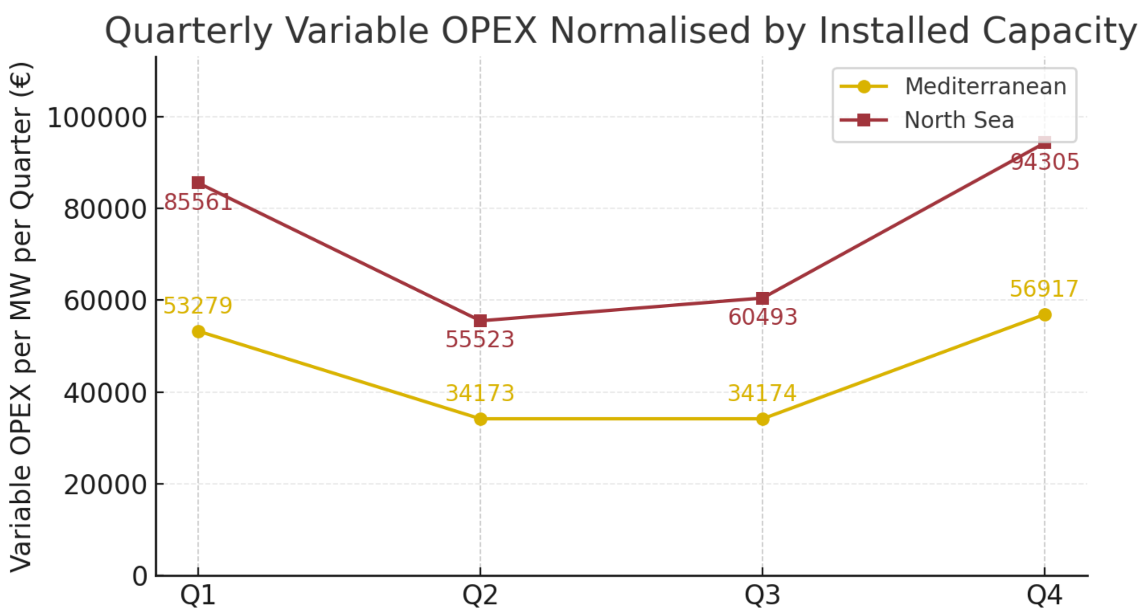


Figure 4.8: Quarterly expected variable OPEX/MW

4.2 Comparative Analysis

4.2.1 Key Cost Drivers

Figure 4.9 stacks the variable OPEX per component and event. Dynamic Inter-Array Cable (DIAC) incidents are notably more expensive in the North Sea (constituting roughly 62% of the event cost compared to 38% in the Mediterranean). Conversely, the relative cost share Pitch Systems, Gearbox, Generator and Blades is slightly higher in the Mediterranean. This suggests that the dominant cost factors for these components might be less acutely influenced by severe metocean conditions, or that their associated heavy-lift logistics present more comparable costs across both basins.

The Sankey in Figure 4.10 zooms out to the whole budget; its dominant purple stream shows that major replacements absorb the vast majority of variable OPEX, and most of that money funnels into DIAC and Pitch System work, with only thin trickles allocated to small repairs or small replacements.

Figure 4.11 directly illustrates that chartering costs for major replacement interventions are substantially higher in the North Sea than in the Mediterranean. This confirms that vessel charter hours, particularly for major replacements, are a dominant cost factors in the North

Sea (contributing over 90% to the total chartering cost depicted for major replacements), consistently with insights from other figures in this analysis, and not primarily opportunity loss.

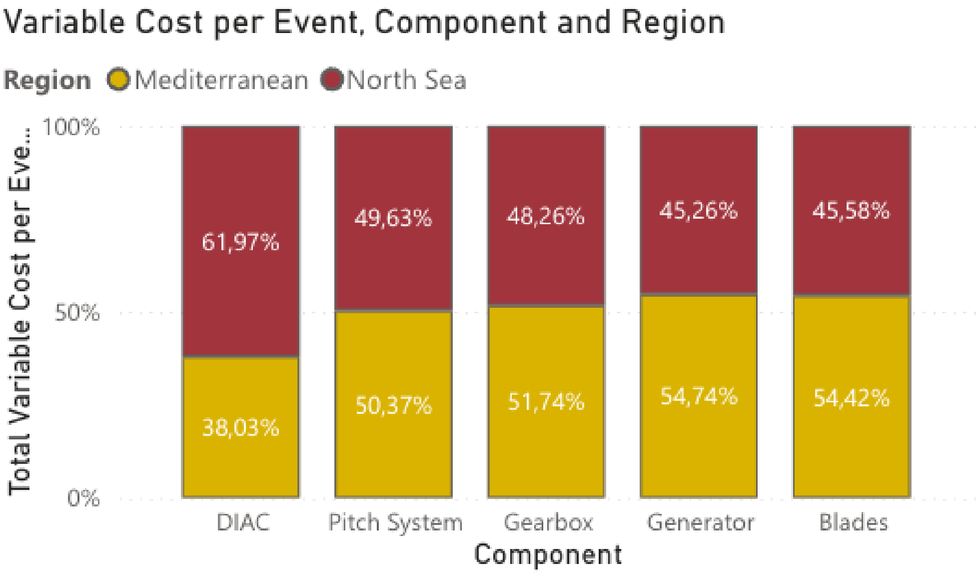


Figure 4.9: 100% stacked column chart of Variable OPEX share per component and region

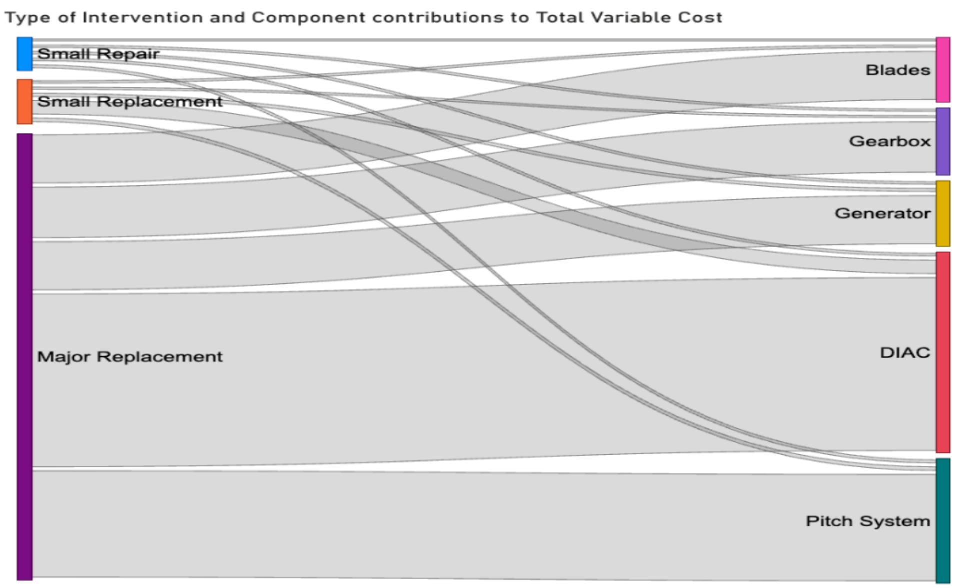


Figure 4.10: Sankey chart of intervention to component contributions to total variable cost

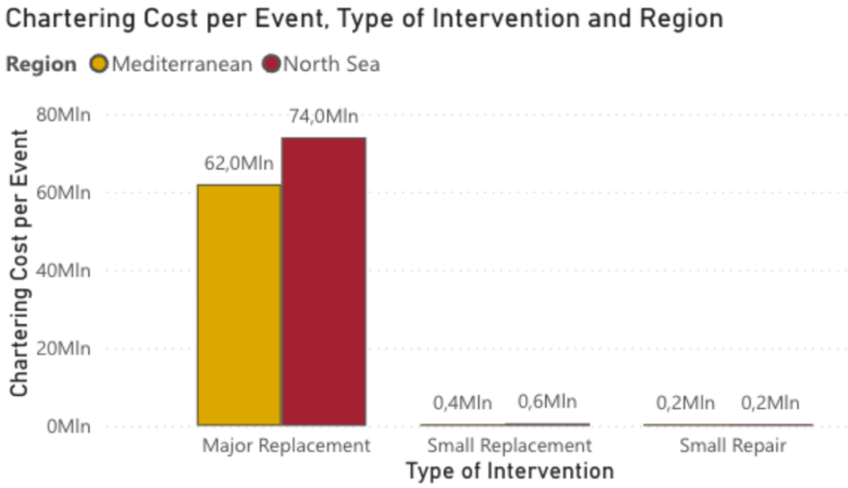


Figure 4.11: Chartering cost per event by intervention type and region

4.2.2 Downtime and Availability

Weather downtime totals 11600 h/y in the Mediterranean and 18000 h/y in the North Sea, as shown in Figure 4.12. When multiplied by the local capacity factors (0.32 vs. 0.45), the resulting availability loss is 0.9 percentage point for the Mediterranean and 2.8 for the North Sea, small in absolute energy terms but large in revenue impact.
Most of Mediterranean downtime falls in Q2-Q3, when revenue stakes are lower and calm windows are frequent; North Sea farm loses fewer absolute hours in Q1-Q3 but is hit by a Q4 spike that couples directly to cash outflow in Figure 4.13.

Annual Weather Hours per Farm

Component	Mediterranean	North Sea
Blades	2.314,77	321,01
DIAC	319,33	166,95
Gearbox	4.246,66	1.113,85
Generator	12.274,84	1.500,97
Pitch System	13.772,19	1.950,09

Figure 4.12: heat matrix of annual weather hours per farm and component

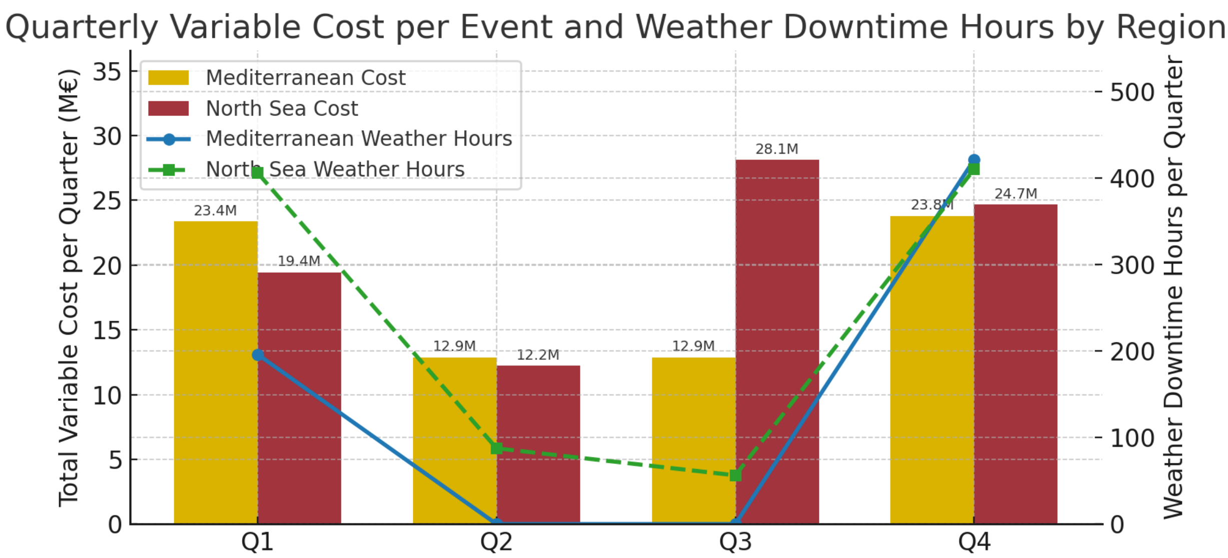


Figure 4.13: Quarterly interplay of variable cost and weather hours by region

4.2.3 Economic Implications

The waterfall in Figure 4.14 steps down from the North Sea benchmark (€ 358 k per MW) to the Mediterranean benchmark (€ 222 k per MW). Each grey block shows how much one driver shaves off the gap: weather downtime (€ 54 k/MW), charter daily rate (€ 54 k/MW), failure frequency (€ 17 k/MW) and strike price exposure (€ 7 k/MW). Together they fully account for the € 136 k/MW cost difference, making it clear which levers matter the most economically.

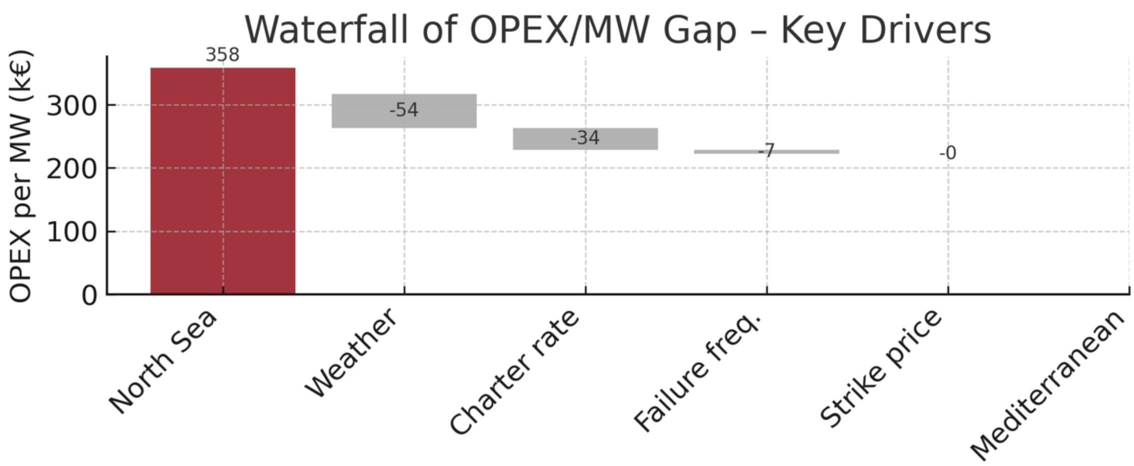


Figure 4.14: Waterfall chart of OPEX/MW gap

In Figure 4.15, each column begins with the farm's gross revenue, assumed very simply as in Equation 4.1:

$$Rev = C \cdot CF \cdot 8760h \cdot \pi \qquad 4.1$$

Where C is the total installed capacity of a farm, CF is the capacity factor, 8760 h are the hours in a year and π is the strike price.

For the 800 MW Mediterranean farm, a 32% capacity factor and a 100 €/MWh strike price yield about € 225 million a year, while the 50 MW North Sea farm, running at 45 % and earning an 80 €/MWh, delivers only ~€16 million. The colored lower block of each bar is the weather-driven variable OPEX already derived before (€143 mln vs €15 mln); the pale upper block is the cash margin left after those costs. Because harsh weather inflates North Sea OPEX while the farm is small, the margin almost disappears (≈€1 mln), whereas the larger and calmer Mediterranean site still retains ~€81 mln. Thus, the figure links the engineering drivers to business reality: the same weather gap that raises unit OPEX in the North Sea nearly wipes out project-level profitability.

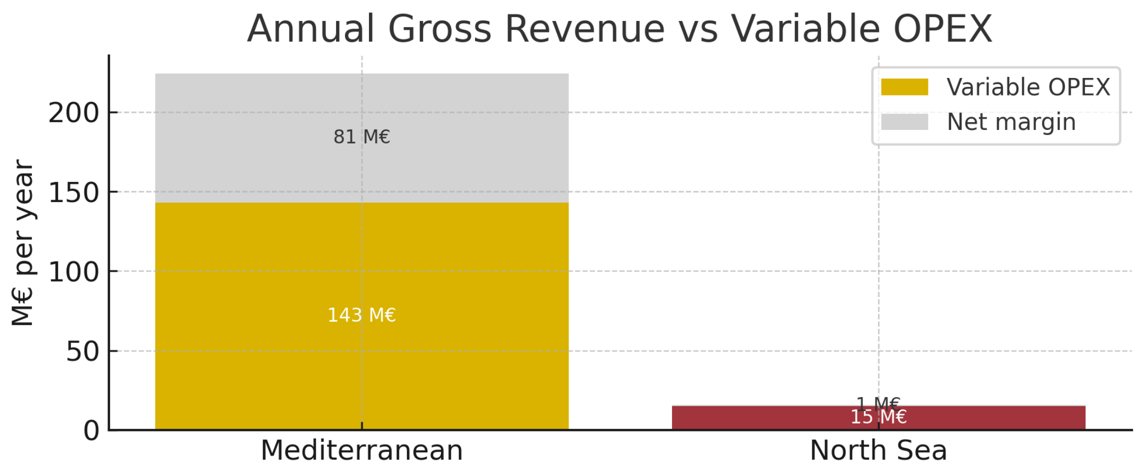


Figure 4.15: Annual Gross Revenue vs. Variable OPEX

4.3 Sensitivity Analysis

A critical step when evaluating a cost model is determining its robustness to changes in real-world behavior, which is achieved in this case by addressing three practical questions:

1. Which levers move annual OPEX/MW the most?
2. How large a shock does it take to turn the business case red?
3. Where should owners spend their next euro to cut risk or cost?

To answer these, a sensitivity analysis is performed as a structured "what if" to identify what most significantly impact the model's outcome (in this case, the annual OPEX/MW). This analysis stress-tested the four cost drivers detailed in Table 4.1 below:

Table 4.1: Sensitivity Analysis cost drivers

Driver (x_i)	What it perturbs
Weather hours (W)	Waiting time in charter & opportunity-loss formulas
Failure hours (F)	Time considered in charter & opportunity-loss costs
Charter daily rate (C)	Vessel cost per hour
Strike price (S)	Value of curtailed energy

To quantify how strongly OPEX/MW output responds to a small percentage change in each driver, a constant elasticity model was employed, assuming a power-law relationship of the form $OPEX \propto (X_i)^{\beta}$, where the coefficient β represent the local elasticity, that is the percentage change in OPEX for a 1% change in the driver. These β-values were derived by performing a log-log linear regression on the simulation results over 21 points (from -10%

to +10% in 1% steps). The resulting R^2 values, which were near unity for all regressions, confirm that the constant elasticity model is an excellent fit for the simulation data over this interval. This validates the use of the derived β-values as constant elasticities in the subsequent tornado and Monte-Carlo analyses.

Full β-values for both regions are shown on Table 4.2 below.

Table 4.2: β-values for Mediterranean and North Sea regions

Driver *(i)*	**βi (North Sea)**	**βi (Mediterranean)**
Weather downtime hours	**0.445**	**0.279**
Failure frequency	**0.525**	**0.700**
Charter day-rate	**0.967**	**0.966**
Strike price	**0.030**	**0.033**

Initially, the analysis employs a Tornado Diagram, as in Figure 4.16, by using the β-values to predict the effect of a ±20% shock (up or down), by plugging the single β-values into Equation 4.2:

$$\Delta OPEX = OPEX_0[e^{\{\beta_i \ln(1 \pm 0.20)\}} - 1] \qquad 4.2$$

The Tornado Diagram shows the final OPEX/MW value after the shock.

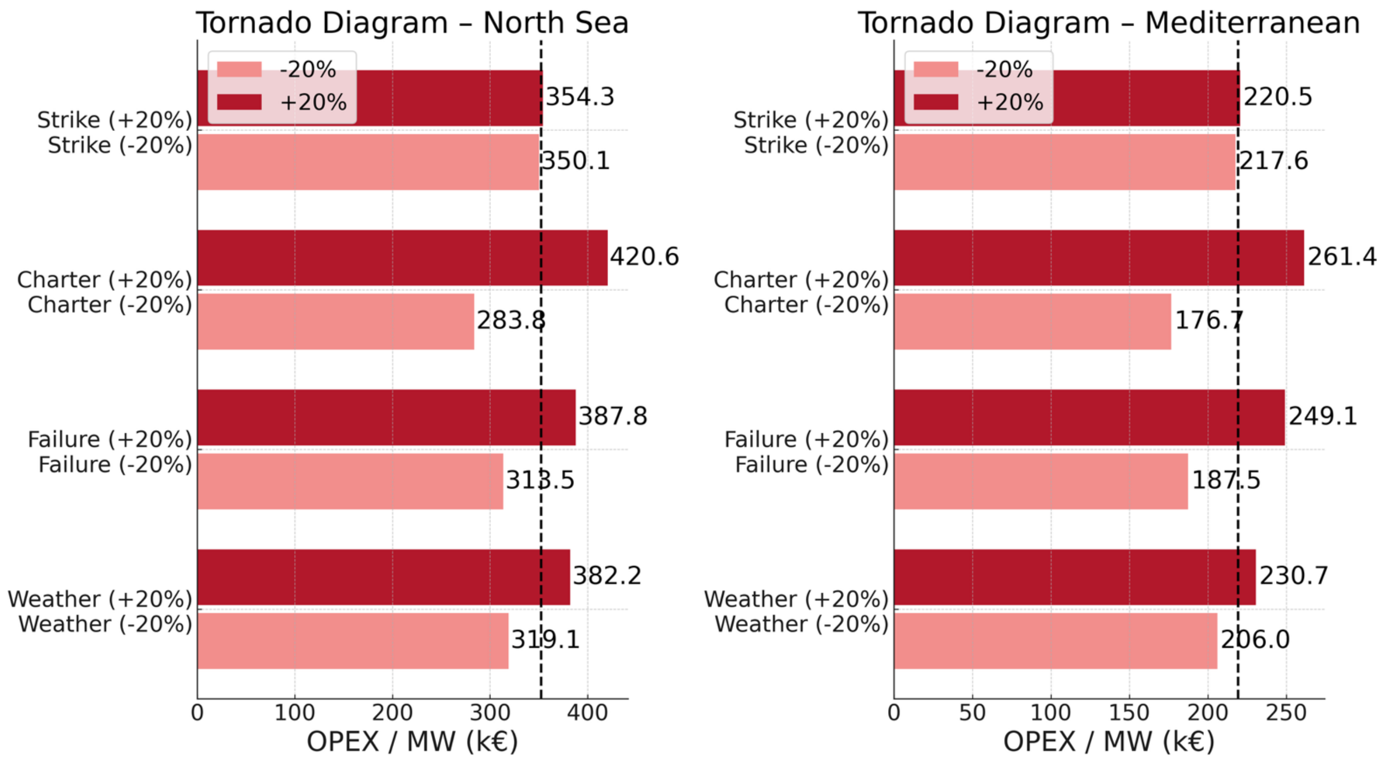


Figure 4.16: Tornado diagram – baseline first order sensitivities

This analysis confirmed that the model behaves almost linearly in the ± 10 % region of perturbation, confirmed by R^2 near unity for all regressions.

For the North Sea, visual ranking of parameters clearly highlights that Charter rates remain the dominant lever (with an impact of approximately +68 k€/MW for a +20% shock), followed by unplanned failure downtime and weather interruptions, Similarly, for the Mediterranean case, Charter remains the primary driver (with an approximate impact of +39k€/MW).

This chart immediately tells managers where to focus negotiations or technology upgrades.

Because weather and failure frequency are not statistically independent during winter storms, they were varied together in a 3 x 3 grid (-20%, 0%, +20% each).

Figure 4.17 shows that only the high-weather / high-failure quadrant pushes OPEX/MW over €400k/MW threshold assumed, defining a practical red-line for operations management. Furthermore, it is clearly highlighted that high-failure / standard-weather and standard-failure / high-weather still pushes OPEX/MW near the threshold, indicating that they are indeed critical drivers also when considered alone.

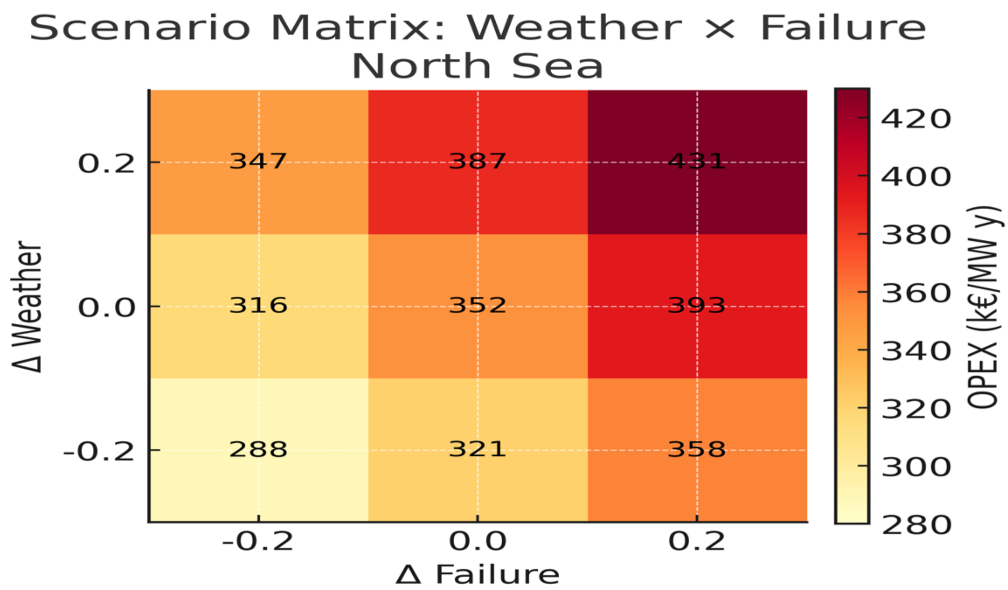


Figure 4.17: Scenario matrix of combined weather and failure stress on OPEX/MW

For each of the nine scenarios in the matrix, the full OPEX model was re-run with the corresponding input values for Weather and Failure drivers scaled by a factor of 0.80, 1.00 or 1.20. This method captures the complete non-linear interactions within the model, providing a more precise result than an approximation based on the β-elasticities.

Using the β-values and triangular ±20% priors, 10000 Latin-Hypercube draws yielded the probability density showed in Figure 4.18, with the following results showed in Table 4.2:

Table 4.3: Monte-Carlo Latin Hypercube Results

Statistic	Mediterranean	North Sea
Mean OPEX/MW	219 k €	**352 k €**
5th–95th percentile range	183 k – 256 k €	**297 k – 408 k €**
Probability (OPEX/MW > 400 k)	0.0 %	**8.7 %**

As Monte-Carlo simulation estimates the output distribution $Y = g(X)$ of the OPEX model by replacing each uncertain driver with many random realization, it is possible that the analysis might randomly land several samples in the same tile (over the 10000 sliced tiles) Hence, the Latin Hypercube was used to force exactly one sample in every tile for every input, with each driver (W, C, F and S) of the 10000 x 4 matrix getting exactly one draw from every stratum, randomly permuting the columns subsequently. This stratified design keeps every marginal uniformly covered and, for smooth models, cuts sampling variance.
Severe metocean conditions inflate both the mean and the right-hand tail of the North Sea cost risk; the calmer Mediterranean site is unlikely to breach €400 k expect under extreme, simultaneous shocks. In simpler words, North Sea cost distribution is much fatter on the right-hand side than the Mediterranean one.
The log-elasticity response is computed as Equation 4.3:

$$OPEX* = OPEX_0 \cdot e^{\beta_W \ln(1+\Delta W)+\beta_F \ln(1+\beta_F)+\beta_C \ln(1+\beta_C)+\ \beta_S \ln(1+\beta_S)\}} \qquad 4.3$$

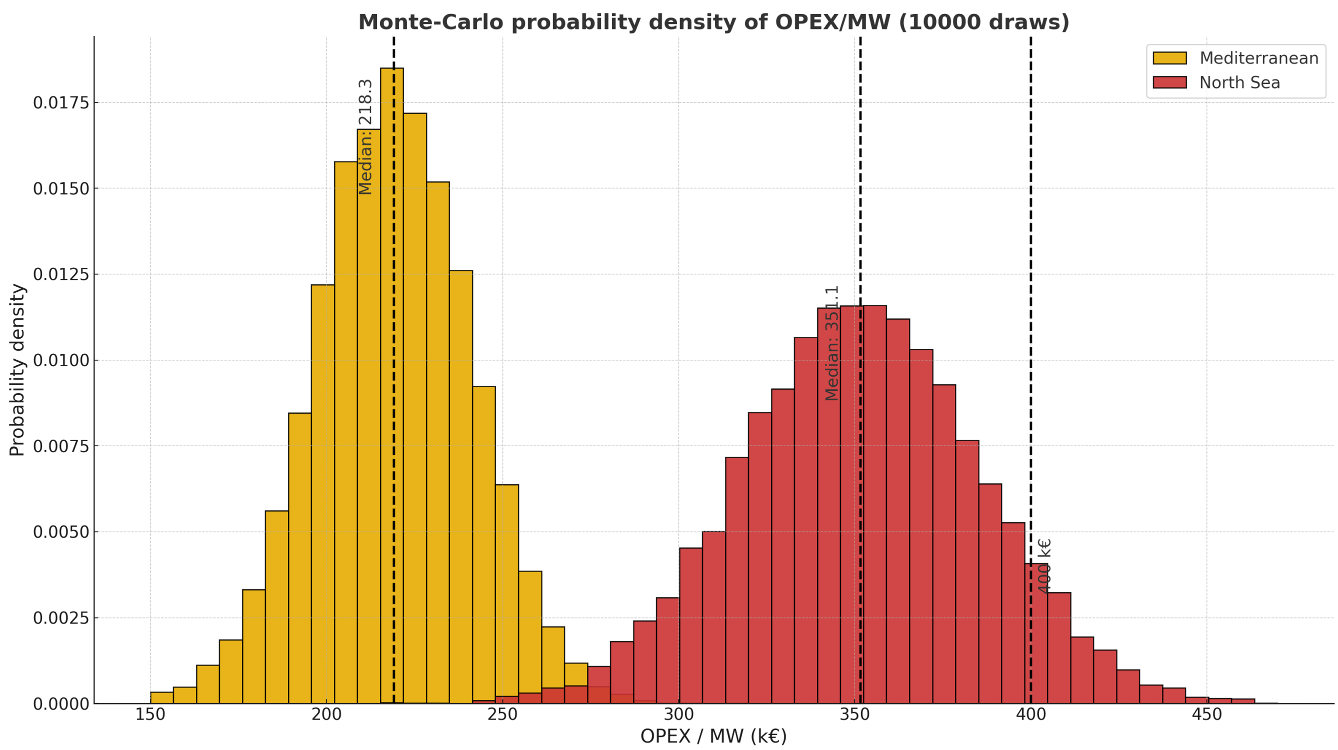


Figure 4.18: Monte-Carlo probability density of OPEX/MW (10000 draws)

The histogram shows the probability distribution of simulated OPEX/MW for the two regions after the 10000 Latin – Hypercube trials. Along the horizontal axis cost level in thousands of euros are represented; on the vertical axis there is a probability-density scale. The tight, high yellow peak centered around 210-230 k€ revealing that Mediterranean costs cluster narrowly, while the North Sea red cloud centers near 330-350 k€ and stretches far to the right, signaling both a higher baseline and much greater volatility. The black dashed line marks the 400k€ threshold: roughly a fifth of the North Sea probability mass lies beyond it, whereas the Mediterranean distribution is virtually entirely below that line.

Using the previously derived β-values, the first-order variance decomposition for North Sea in Figure 4.19 attributes about 66% of the spread to Charter rates, 19% to Failure frequency, 14% to Weather downtime and a negligible share to the Strike price.

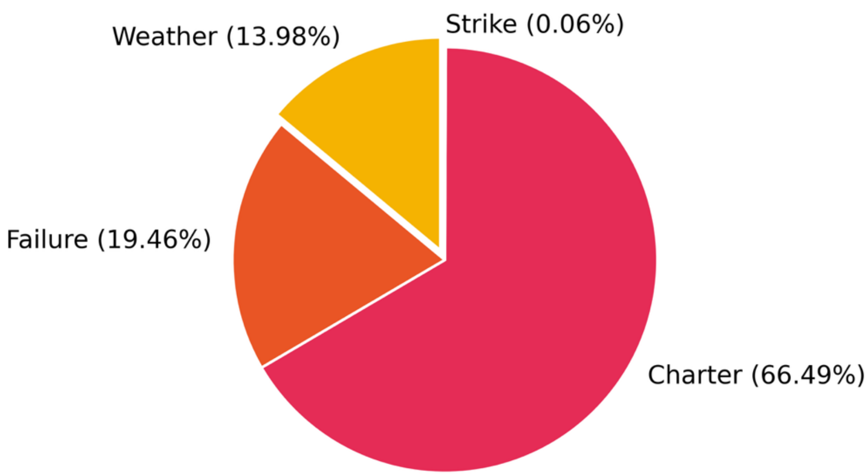


Figure 4.19: Driver contribution to OPEX/MW variance in North Sea

Compared to Mediterranean, which variance values are listed in Table 4.3 along with North Sea ones, it is clearly visible that weather has a greater impact to North Sea variance, confirming the harsher sea conditions of the latter as an important disadvantage in terms of OPEX/MW.

Table 4.4: First-Order Variance Decomposition (%)

	Weather	Failure	Charter	Strike Price
Mediterranean	5.2%	32.7%	62.1%	0.1%
North Sea	13.9%	19.4%	66.5%	0.1%

The fractional variance contribution for each driver was calculated from the squared elasticities β^2 to approximate the first-order shares of the total modeled variance.

Finally, Figure 4.20 answers the practical question "how much extra weather do we have left before the business case collapses?" by plotting the incremental weather downtime required to breach the €400k threshold, holding Charter cost, Failure rate and Strike price at baseline and keep stretching Weather downtime until the cost crosses the limit, using Equation 4.4:

$$OPEX_W = OPEX_0 \cdot (1 + \Delta\mathrm{W})^{\beta_\mathrm{W}} \qquad 4.4$$

A + 33 % in average weather hours is enough, underscoring why winter accessibility strategy is crucial.

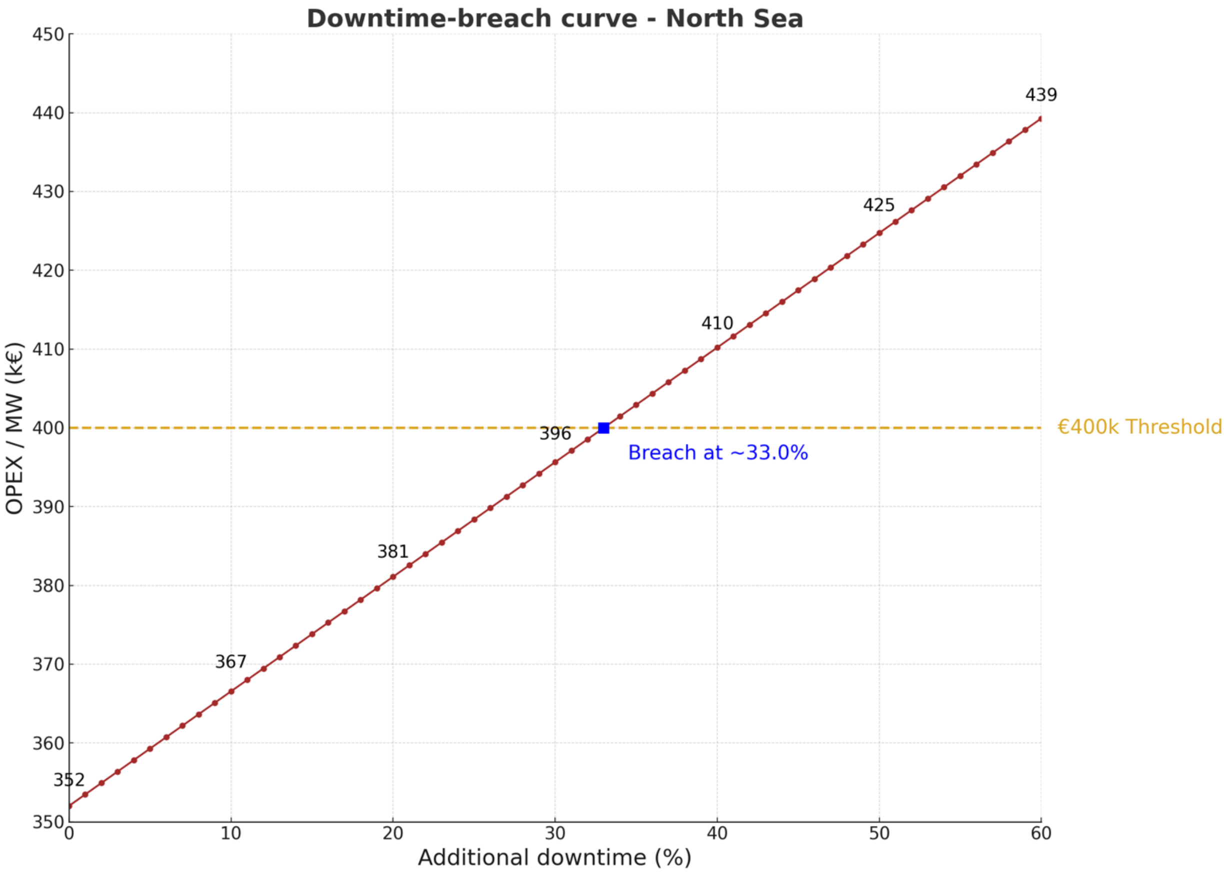


Figure 4.20: Downtime-breach curve to the €400k/MWy threshold

The sensitivity analysis highlights four practical conclusions: first, charter contracts emerge as the single most effective lever for risk control, with roughly 65% of total cost variance tied to daily rate swings. Hedging escalation clauses or pooling vessel capacity cuts first-order exposure mor than any engineering action.

Second, weather-related downtime remains an inherent structural risk on North Sea, as a +27% increase in average weather hours would tip OPEX above the threshold, underscoring the value of faster-access solutions but also the higher dependence on weather conditions with respect to Mediterranean Sea.

Third, while the frequency of corrective failures is certainly meaningful, its economic weight is distinctly secondary, explaining only about one-fifth of the spread; raising turbine reliability therefore yields a smaller payoff than improving logistics or charter terms.

In the end, strike price shocks contribute less than one percent to overall cost variance and can be addressed adequately with standard power-purchase agreements floors rather than bespoke operational measures.

By layering deterministic sweeps, paired-driver grids and probabilistic sampling, quantifying "what could go wrong, by how much and how often", this section converts a complex cost engine into a management dashboard:

- Developers see which contract clauses (charter escalation caps) and site-choice criteria (milder weather) most affect financial close;
- Operators obtain quantitative justification for access-technology CAPEX or weather-buffer days in schedules;
- Stakeholders receive a probability distribution, not just a point estimate, that OPEX crosses a threshold fatal to project cash flows, against which to size debt and contingency.

4.4 OPEX Benchmarking

Our cost outcomes sit noticeably above widely published European benchmarks. The BVGA Guide quotes an indicative OPEX ≈ €82K/MWy for a 450 MW reference farm [74].
Against that yardstick, the Mediterranean case (≈ €219k/MWy) is about +167%, while the North Sea case (≈ €352k/MWy) is roughly +329%.
Turning to PEAK-Wind's 2022 survey of sixty European assets, the mean fixed-bottom OPEX is €135 k/MWy and the "worst performer" band begins at ≥ €253k [75]. On that scale, the Mediterranean project still sits +62% above the fleet average, whereas the North Sea occupies the uppermost cost band, consistent with its harsher metocean climate and smaller farm size.
Finally, PEAK-Wind observes that 45-55% of lifetime OPEX typically lies in logistics, insurance and shared services [76], hence confirming the modeled cost allocation matches the pattern almost exactly: 46% fixed for the Mediterranean case and 55% for the North Sea

case. The structural similarity lends credibility to the model, even though absolute totals are elevated by early-stage floating premiums and severe weather exposure.

4.5 *Discussion*

The case study confirms that regional metocean conditions and technology maturity dominate floating wind O&M economics. The Mediterranean farm, larger and located in calmer seas, achieves a substantially lower OPEX/MW and availability losses below 1%, whereas the smaller North Sea farm endures a higher cost and 3% loss.
Component-level results show that major replacements of DIAC and Pitch System assemblies account for >70% of variable cost disparity, amplified by approximately 55% longer weather-waiting windows in the North Sea.

Sensitivity analysis confirms that logistics remains the dominant lever: charter alone accounts for 66.5% of North Sea cost variance, while weather downtime adds another 14%. Together they explain about 80% of the spread. Monte-Carlo results with the ± 20% envelope give a 5^{th}-95^{th} percentile band of € 297 k - € 408 k per MW, quantifying the upside risk that those two drivers place on the business case.

Benchmarking puts these findings in context, highlighting a gap which is largely methodological:

- first, the model charges the opportunity cost of lost production for every downtime hour, while BVGA and PEAK-Wind averages publish only cash outlay, omitting this significant lost-energy component from their figures;
- second, PEAK-Wind costs are referred to FBWTs, hence an actual precise comparison cannot be made between two different technologies;
- third, the model's charter logic bills daily rate on a per-event basis. This contrasts with BVGA, which amortizes a permanent SOV (at representative cost of 2200 £/MW/year), and PEAK-Wind, whose fleet spreads JUVs and CTVs across more than 550 MW on average. This methodological difference does not align with the one-vessel usage and component-specific charter daily costs considered in this study;

- fourth, fixed overheads (admin/legal and insurance) are applied per turbine, while in the benchmarks they are spread over far larger capacities.

In other words, higher results from the model with respect to benchmarking could be explained by these factors.

Chapter 5: Conclusions and Future Prospects

The rapid evolution and deployment of FOWTs represent a pivotal advancement in the renewable energy sector, and are particularly crucial as nations strive to meet decarbonization goals. The aim of this work was to contribute significantly to the understanding and practical assessment of OPEX associated with floating offshore wind farms, with a particular emphasis on site-specific analysis for the current logistic and infrastructure state of the Mediterranean Sea.

Through an extensive literature review, detailed numerical modeling and comparative analysis, the work has demonstrated how OPEX varies substantially between different geographical regions, largely driven by metocean conditions, infrastructure readiness and logistical constraints. The Mediterranean Sea, characterized by relatively milder wave and wind climates compared to the North Sea, offers significantly enhanced accessibility, reducing downtime and overall operational costs. Specifically, the OPEX/MW in the North Sea was found to be approximately 60.7% higher compared to the Mediterranean scenario, primarily due to high weather-induced downtime and increased intervention cost.

The MATLAB-based simulation model developed effectively integrated turbine specs, detailed failure rate distributions, cost parameters and region-specific weather data. This model not only enabled quantification of maintenance strategies but also facilitated rigorous sensitivity analysis, crucially highlighting the most influential cost drivers.

Sensitivity analysis provided further critical insights, explicitly identifying charter vessel costs and weather downtime as the two dominant factors affecting the economic viability of floating offshore wind projects. Notably, the model demonstrated that even minor variations in these parameters could substantially affect overall OPEX. The rigorous Monte-Carlo simulations emphasized the necessity of strategic investments in logistical enhancements,

such as securing favorable vessel charter agreements and adopting advance weather forecasting and access technologies, thereby significantly mitigating financial risks.
In essence, this thesis work has bridged complex technical modeling with actionable managerial insights, significantly contributing to lowering the LCOE for floating offshore wind farms.

Although this research provided insights and practical guidance, several opportunities exist for model enhancement and expansion to improve its applicability and accuracy: first and foremost, future iterations of the model should incorporate predictive maintenance strategies based on real-time monitoring and condition-based maintenance analytics. Integrating machine learning algorithms to analyze sensor data and predict component failures that could significantly optimize maintenance scheduling, thus further reducing downtime and operational costs. Also, the possibility of considering multiple turbines and vessels in a single maintenance operation could help by aggregating costs.
Secondly, expanding weather modeling capabilities to integrate high-resolution weather forecasts and advanced accessibility models could enhance prediction accuracy, particularly in challenging sea states. As the model is built with the support of ESOX tool, a future enhancement could regard the integration of a weather-window computation device to better estimate the metocean conditions. Coupling these with digital twin technologies could enable scenario testing and operational planning with very high precision, further optimizing cost efficiency.
Thirdly, incorporating modules for broader economic and environmental impact assessments would enhance the models' value. Evaluating factors such as job creation, carbon footprint reduction and broader socioeconomic impacts would support strategic decision-making and improve stakeholder communication and public acceptance.
Finally, to maximize practical utility, future model developments should emphasize scalability and adaptability across diverse global sites, not limited to the Mediterranean or North Sea regions. Including a broader range of metocean datasets and regional cost parameters and expanding the cost voices contributing in the OPEX would significantly broaden the model's applicability, supporting global deployment strategies.

Floating offshore wind energy stands at the crossroads of technological innovation and environmental responsibility. The work conducted in this thesis was not only intended to enrich the understanding of operational complexities and cost dynamics, but also to lay robust foundations for future advancements. This is especially true in the Mediterranean region, where it can foster its current early-stage support infrastructure to achieve a greater potential.

As Marcus Aurelius wisely remarked with the citation in the opening of this thesis “If a thing is humanly possible, consider it within your reach”. Indeed, achieving sustainable, economically viable floating offshore wind power is not just possible, it is well within our collective reach, provided that insightful research continues to guide and inform industry practices and policy developments.

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Appendix A

Layer	Material	Function	Relevance for FOWTs
Conductor	Copper or Aluminum	Transmits electrical power	Copper preferred for high flexibility and conductivity
Conductor Screen	Semi-conductive polymer (e.g., XLPE-based)	Ensures smooth voltage gradient and reduces stress	Essential for electrical reliability under dynamic loading
Insulation	XLPE (Cross-linked Polyethylene) or EPR (Ethylene Propylene Rubber)	Electrically isolates conductor from ground	EPR preferred for better flexibility and fatigue resistance
Insulation Screen	Semi-conductive polymer	Maintains uniform electric field	Protects against partial discharge under movement
Metallic Shield / Screen	Copper tape or wire	Provides fault current path and EMI shielding	Important for safety and SCADA signal integrity
Water Blocking Layer	Swellable tapes or powders	Prevents moisture ingress into insulation layers	Protects integrity in case of outer sheath damage
Bedding Layer	Polypropylene or rubber-based material	Protects inner layers from armor abrasion	Buffers dynamic mechanical loads from armor
Armoring	Galvanized steel wires (single or double helix)	Provides mechanical protection from tension, impact, and torsion	Crucial for fatigue resistance in dynamic, moving environments
Outer Sheath	Polyethylene (PE) or Polyurethane (PUR)	Outer environmental protection from seawater, UV, and mechanical damage	PUR is often used for abrasion and hydrocarbon resistance
Optional Fiber Optics	Glass fibers with protective coating	Enables real-time data and condition monitoring (e.g., DTS, DSS)	Vital for predictive O&M and SCADA systems
Buoyancy Modules (External)	Foam or syntactic material	Shapes cable into lazy-wave or steep-wave form	Manages motion and reduces stress at hang-off and touchdown points

Appendix B

Section	Function & Conditions	Material Type	Key Characteristics	Considerations
Upper Section	Connects to substructure; exposed to splash zone; highest load region	Steel chain	- Typically larger diameter (e.g., 220 mm) - High mass (700 kg+ per link) - High strength grades (R4, R5)	- Stud-link chain preferred for load and tangle resistance - Must resist corrosion and dynamic fatigue - Suitable mainly for <200 m water depths
		Synthetic rope	- Nylon: highly elastic, helps absorb dynamic loads - Polyester: moderate compliance and durability - HMPE: stiffer, high load capacity	- Jacketed for abrasion and sand protection - Requires skilled termination (spliced eyelets + steel thimbles)
		Wire rope	- Lightweight and easier to handle - Higher strength-to-weight ratio than chain - Typically jacketed	- Prone to structural degradation near splash zone - Less stiffness than chain in upper dynamic sections
Middle Section	Free-hanging in the water column; less exposed to harsh environment	Steel chain	- Reduced diameter possible vs upper section - May use stud-less chain to reduce cost and fatigue	- Less fatigue loading; design based on weight distribution and damping
		Synthetic rope	- Significant weight savings - Buoyancy modules may be used to reduce tension	- Critical for managing dynamic motion - Polyester is most common for long-term performance
		Wire rope	- Suitable for deeper sites due to low mass - Requires jacket for corrosion and damage protection	- Buoyant section designs help reduce load variation
Ground Section	Rests on seabed; subject to abrasion in "thrash zone"; connects to anchor	Steel chain	- High resistance to abrasion - High static mass anchors line position - Rugged and well-understood	- Ideal for drag embedment and suction anchors - Limits use in deep water due to weight

Section	Function & Conditions	Material Type	Key Characteristics	Considerations
		Synthetic rope	- Jacketed with HDPE/PU for abrasion and sand resistance - Lightweight; may need weighting or hybrid with chain	- Risk of abrasion from seabed contact; rarely used alone in seabed sections
		Wire rope	- Must be protected against mechanical wear and corrosion - Generally not favored in seabed-contact areas	- Only used with additional seabed protection elements

Appendix C

VESSEL TYPES AND DATA							
Type of vessel	Total Fleet	Mediterranean Availability	Drougth	Speed	Max Hs	Max Wind speed	Other characteristics
JUV (Jack-Up Vessel)	100-150	VERY LOW	5-8 m before jacked up legs	10 kn	2.5-4 m	30-40 kn	\
HLV (Heavy Lift Vessel)	50-80	LOW	10-15 m	12-14 kn	1.8 m	25-30 kn	1001 to 5000 tons crane capacity, extensive deck space, DP
CTV (Crew Transfer Vessel)	200-300	LOW	1.5-3 m	20-30 kn	Up to 1.5 m	20-25 kn	Accomodate 12-24 passengers
SOV (Service Operation Vessel)	30-50	VERY LOW	5-6.5 m	12-14 kn	2.5-3.5 m	30-35 kn	DP, 60-90 people capacity, motion compensated gangways for transfer
SFV (Specialist Field Vessel)	150-250	LOW	3-6 m	25-30 kn	2 m	20-30 kn	DP, ROV and other specialized tools
AHTSV (Ancor Handling Tug Supply Vessel)	400-600	MEDIUM	5-8 m	12-15 kn	2 m	35-40 kn	80-150 tonnes bollard pull, 500-800 m2 deck area for equipment transport
Tug Vessel	1000-1500	HIGH	3-6 m	10-13 kn	1-1.65 m	30-40 kn	30 to 80 tons bollard pull
Cable Lying Vessel (CLV)	50-100	LOW	4-8 m	10-13 kn	1-1.65 m	25-30 kn	31 to 80 tons bollard pull

Appendix D

AVAILABLE PORTS					
Port	**Country**	**Quay Length (m)**	**Maximum Draft (m)**	**Warehouses (m2)**	**Cranes Presence**
Port La-Nouvelle	France	650, currently expanding to 1000	10.5	7480	F, M, FL (E)
Marseille - Fos sur mer *	France	2600	22.25	614000	F, M, FL
Genoa	Italy	30000	14.4	500000 (E)	F, M, FL
Livorno	Italy	3000 (E)	12	350000 (E)	F, M, FL
Palermo	Italy	3700	14	200000 (E)	F, M, FL
Augusta	Italy	5600	20.36	300000 (E)	F, M, FL
Valencia	Spain	12000	16	400000 (E)	F, M, FL
Almèria	Spain	3000	11.7	100000 (E)	F, M
Barcelona	Spain	22238	16	600000 (E)	F, M, FL
Tarragona	Spain	1435	17-19	300000 (E)	F, FL
Castellon de la Plana	Spain	1500 (E)	14	250000 (E)	F, M
Piraeus	Greece	4500 (E)	12.5	600000 (E)	FL
Chalkis Shipyard	Greece	1200 (E)	6.4	50000 (E)	F, M (E)
Cemre Shipyard	Turkey	1500 (E)	8-10	75000 (E)	F, M (E)
Izmir	Turkey	656	20	12000	M
Istanbul	Turkey	3500 (E)	18.28	500000 (E)	F, M, FL
Valletta	Malta	2000 (E)	13.7	200000 (E)	F, M (E)

*DEOS project aims at estabilishing a platform for the construction and assembly of floating turbines starting in 2028

Where an (E) is present, the data was estimated due to limited informations availability. The rationale behind these estimation is based upon comparisons with similar ports, and logical assumptions based on port capacity and function

Appendix E

WEATHER DATA FILE NAME	n36.25_e15.25.csv
WEATHER DATA COORDINATES	n36.25_e15.25
LINK TO ESOX MAP	https://esox.lautec.com/map/?location=36.25/

DATE	HOUR	WIND 10	WIND 100	Hs	Tp	PROGRESS	POSITION IN PROGRESS	CYCLE IN PROGRESS
10/03/19	00:00	2,73	2,83	0,5	5,16	Failure reception	-	1
10/03/19	01:00	2,57	3,08	0,5	5,15	Failure reception	-	1
10/03/19	02:00	2,59	3,12	0,5	5,14	Failure reception	-	1
10/03/19	03:00	2,31	2,8	0,51	5,12	Sail from Port to site	-	1
10/03/19	04:00	1,75	2,04	0,51	5,11	Sail from Port to site	-	1
10/03/19	05:00	1,14	1,33	0,57	5,28	Sail from Port to site	-	1
10/03/19	06:00	0,54	0,77	0,56	5,26	Minor replacement	1	1
10/03/19	07:00	1,25	1,53	0,56	5,24	Minor replacement	1	1
10/03/19	08:00	1,73	2,08	0,55	5,21	Minor replacement	1	1
10/03/19	09:00	2,02	2,33	0,54	5,19	Minor replacement	1	1
10/03/19	10:00	1,06	1,33	0,53	5,16	Minor replacement	1	1
10/03/19	11:00	1,25	1,44	0,53	5,13	Minor replacement	1	1
10/03/19	12:00	1,74	1,88	0,52	5,11	Minor replacement	1	1
10/03/19	13:00	2,29	2,45	0,52	5,08	Minor replacement	1	1
10/03/19	14:00	3	3,23	0,52	5,05	Minor replacement	1	1
10/03/19	15:00	3,8	4,23	0,51	5,02	Minor replacement	1	1
10/03/19	16:00	4,5	5,31	0,52	4,99	Minor replacement	1	1
10/03/19	17:00	5,03	6,05	0,53	4,95	Minor replacement	1	1
10/03/19	18:00	5,55	6,61	0,54	4,91	Minor replacement	1	1
10/03/19	19:00	6,36	7,46	0,56	4,86	Minor replacement	1	1
10/03/19	20:00	7,14	8,34	0,6	4,75	Minor replacement	1	1
10/03/19	21:00	7,3	8,53	0,65	3,62	Minor replacement	1	1
10/03/19	22:00	7,33	8,48	0,69	3,95	Minor replacement	1	1
10/03/19	23:00	7,54	8,71	0,72	4,1	Minor replacement	1	1
11/03/19	00:00	7,59	8,73	0,74	4,29	Minor replacement	1	1
11/03/19	01:00	7,81	8,99	0,77	4,35	Minor replacement	1	1
11/03/19	02:00	8,17	9,4	0,8	4,4	Minor replacement	1	1
11/03/19	03:00	8,18	9,42	0,83	4,51	Minor replacement	1	1
11/03/19	04:00	8,02	9,27	0,84	4,65	Minor replacement	1	1
11/03/19	05:00	7,8	9,08	0,82	4,71	Minor replacement	1	1
11/03/19	06:00	7,22	8,42	0,8	4,73	Minor replacement	1	1
11/03/19	07:00	7,15	8,33	0,79	4,73	Minor replacement	1	1
11/03/19	08:00	7,73	9,04	0,78	4,71	Minor replacement	1	1
11/03/19	09:00	8,23	9,76	0,78	4,69	Minor replacement	1	1
11/03/19	10:00	8,19	9,95	0,81	4,65	Minor replacement	1	1
11/03/19	11:00	8,51	10,36	0,84	4,64	Minor replacement	1	1
11/03/19	12:00	8,49	10,49	0,87	4,64	Minor replacement	1	1
11/03/19	13:00	8,61	10,68	0,89	4,67	Minor replacement	1	1
11/03/19	14:00	8,64	10,79	0,93	4,72	Minor replacement	1	1
11/03/19	15:00	8,83	11,06	0,97	4,76	Minor replacement	1	1
11/03/19	16:00	8,94	11,14	1,01	4,82	Minor replacement	1	1
11/03/19	17:00	8,97	11,22	1,05	4,94	Minor replacement	1	1
11/03/19	18:00	9,32	12,15	1,1	5,08	Minor replacement	1	1
11/03/19	19:00	9,54	12,93	1,17	5,15	Minor replacement	1	1
11/03/19	20:00	9,73	12,77	1,24	5,22	Minor replacement	1	1
11/03/19	21:00	9,92	12,98	1,3	5,35	Minor replacement	1	1
11/03/19	22:00	10,67	13,86	1,39	5,61	Minor replacement	1	1
11/03/19	23:00	11,22	14,3	1,52	5,74	Downtime: WIND 10, Hs,	1	1
12/03/19	00:00	11,85	15,71	1,69	5,87	Downtime: WIND 10, Hs,	1	1
12/03/19	01:00	11,44	14,42	1,83	6,14	Downtime: WIND 10, Hs,	1	1
12/03/19	02:00	12,2	14,76	1,96	6,31	Downtime: WIND 10, Hs,	1	1
12/03/19	03:00	14,87	18,17	2,28	6,45	Downtime: WIND 10, Hs,	1	1
12/03/19	04:00	14,98	18,51	2,7	6,84	Downtime: WIND 10, Hs,	1	1
12/03/19	05:00	15,54	19,29	3,06	7,06	Downtime: WIND 10, Hs,	1	1
12/03/19	06:00	15,55	19,26	3,37	7,54	Downtime: WIND 10, Hs,	1	1
12/03/19	07:00	15,92	19,49	3,68	7,79	Downtime: WIND 10, Hs,	1	1
12/03/19	08:00	17,08	21,12	3,94	8,27	Downtime: WIND 10, Hs,	1	1
12/03/19	09:00	15,85	19,57	4,07	8,46	Downtime: WIND 10, Hs,	1	1
12/03/19	10:00	14,94	18,1	3,98	8,67	Downtime: WIND 10, Hs,	1	1
12/03/19	11:00	14,33	17,19	3,82	9,01	Downtime: WIND 10, Hs,	1	1
12/03/19	12:00	13,64	16,1	3,62	9,15	Downtime: WIND 10, Hs,	1	1
12/03/19	13:00	12,32	14,34	3,42	9,21	Downtime: WIND 10, Hs,	1	1
12/03/19	14:00	12,25	14,14	3,27	9,23	Downtime: WIND 10, Hs,	1	1
12/03/19	15:00	13,12	15,14	3,18	9,24	Downtime: WIND 10, Hs,	1	1
12/03/19	16:00	13,4	15,59	3,15	9,2	Downtime: WIND 10, Hs,	1	1
12/03/19	17:00	13,62	15,88	3,14	9,12	Downtime: WIND 10, Hs,	1	1
12/03/19	18:00	13,42	15,64	3,18	8,95	Downtime: WIND 10, Hs,	1	1
12/03/19	19:00	12,42	14,36	3,12	8,37	Downtime: Hs,	1	1
12/03/19	20:00	12,11	13,83	3,03	8,33	Downtime: Hs,	1	1
12/03/19	21:00	12,39	14,16	2,94	8,43	Downtime: Hs,	1	1
12/03/19	22:00	12,49	14,35	2,86	8,51	Downtime: Hs,	1	1
12/03/19	23:00	11,86	13,57	2,79	8,57	Downtime: Hs,	1	1
13/03/19	00:00	11,44	12,99	2,72	8,64	Downtime: Hs,	1	1
13/03/19	01:00	11,29	12,76	2,66	8,71	Downtime: Hs,	1	1
13/03/19	02:00	11,41	12,91	2,62	8,76	Downtime: Hs,	1	1
13/03/19	03:00	11,38	12,9	2,6	8,77	Downtime: Hs,	1	1
13/03/19	04:00	10,78	12,22	2,56	8,75	Downtime: Hs,	1	1

Appendix F

Blades

Small replacement						Small repair						Major repair					
Phase	Description	Time (h)	Vessel uses	Max Hs lim (m)	Notes	Phase	Description	Time (h)	Vessel uses	Max Hs lim (m)	Notes	Phase	Description	Time (h)	Vessel used	Max Hs lim (m)	Notes
Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/
Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	HLV	1.8	/
Repair Window	Blade bolt replacement, minor surface repair	8-16	CTV	1.5	Include access time	Repair Window	Blade bolt replacement, minor surface repair	4-8	CTV	1.5	Include access time	Repair Window	Disconnect and Tow to port, full replacement	8-16 to disconnect, towing to port depends on distance 24-72 for full replacement	HLV	1.8	/
Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	Tow from site to closest port, reconnect	Depends on the port, 8-16 to recconnect	HLV	1.8	/
TOTAL TIME																	

Gearbox

Small replacement						Small repair						Major repair					
Phase	Description	Time (h)	Vessel uses	Max Hs lim (m)	Notes	Phase	Description	Time (h)	Vessel uses	Max Hs lim (m)	Notes	Phase	Description	Time (h)	Vessel used	Max Hs lim (m)	Notes
Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/
Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	HLV	1.8	/
Repair Window	Sensor replacement, minor part replacement	6-12	CTV	1.5	/	Repair Window	Oil leak repair, mechanical adjustment	8-16	CTV	1.5	Include access time	Repair Window	Disconnect and Tow to port, full replacement	8-16 to disconnect, towing to port depends on distance 48-168+ for full replacement	HLV	1.8	/
Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	Tow from site to closest port, reconnect	Depends on the port, 8-16 to recconnect	HLV	1.8	/
TOTAL TIME																	

Generator

Small replacement						Small repair						Major repair					
Phase	Description	Time (h)	Vessel uses	Max Hs lim (m)	Notes	Phase	Description	Time (h)	Vessel uses	Max Hs lim (m)	Notes	Phase	Description	Time (h)	Vessel used	Max Hs lim (m)	Notes
Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	8-16	/	/	Includes weather window planning
Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	HLV	1.8	/
Repair Window	Gangway installation, vessel to platform, replacement	16-30	CTV	1.5	/	Repair Window	Adjusting tension, repairing connectors	nov-16	CTV	1.5	/	Repair Window	Disconnect and Tow to port, full replacement	82-104+	HLV	1.8	/
Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	Tow from site to closest port, reconnect	Depends on the port, 8-16 to recconnect	HLV	1.8	/
TOTAL TIME																	

Dynamic Inter Array Cables

Small replacement						Small repair						Major repair					
Phase	**Description**	**Time (h)**	**Vessel uses**	**Max Hs lim (m)**	**Notes**	**Phase**	**Description**	**Time (h)**	**Vessel uses**	**Max Hs lim (m)**	**Notes**	**Phase**	**Description**	**Time (h)**	**Vessel used**	**Max Hs lim (m)**	**Notes**
Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	Disconnect mooring, prepare for Tow	8-16	/	/	Includes weather window planning
Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	CLV	1.65	/
Repair Window	ROV inspection, Small Replacement	94-113	CTV	1.5	/	Repair Window	ROV inspection, Small Repair	18-24	CTV	1.5	/	Repair Window	ROV inspection, Major Repair	122-145	CLV	1.66	/
Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	Tow from site to closest port, reconnect	Depends on the port, 8-16 to recconnect	CLV	1.67	/
TOTAL TIME																	

Pitch System

Small replacement						Small repair						Major repair					
Phase	**Description**	**Time (h)**	**Vessel uses**	**Max Hs lim (m)**	**Notes**	**Phase**	**Description**	**Time (h)**	**Vessel uses**	**Max Hs lim (m)**	**Notes**	**Phase**	**Description**	**Time (h)**	**Vessel used**	**Max Hs lim (m)**	**Notes**
Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	SCADA alarm, communication, repair scheduling	1-3	/	/	/	Failure reception	Disconnect mooring, prepare for Tow	8-16	/	/	Includes weather window planning
Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	CTV	1.5	/	Mobilization	From closest port to the site	Depends on the port	HLV	1.8	/
Repair Window	Gangway installation, vessel to platform, replacement	23-28	CTV	1.5	/	Repair Window	Gangway installation, vessel to platform, replacement	15-18	CTV	1.5	/	Repair Window	Disconnect and Tow to port, full replacement	200-240	HLV	1.8	/
Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	From site to closest port	Depends on the port	CTV	1.5	/	Return	Tow from site to closest port, reconnect	Depends on the port, 8-16 to recconnect	HLV	1.8	/
TOTAL TIME																	