



SPOWIND

Interreg
Euro-MED



Co-funded by
the European Union



October 2025

Techno-economic assessment methods for offshore wind farms

<https://spowind.interreg-euro-med.eu/>



Deliverable Euro-MED0200199

Project acronym	SPOWIND
Project title	Spatial Planning for Offshore Wind Industry Development
Project mission	Strengthening an innovative sustainable economy
Project priority	1 - Smarter MED
Specific objective	RSO1.1 - Developing and enhancing research and innovation capacities and the uptake of advanced technologies
Type of project	Thematic
Project duration	01/01/2024 – 31/03/2026 (27 months)
Deliverable title	Techno-economic assessment methods for offshore wind farms
Deliverable number	D.2.3.1
Deliverable type	Report, study...
Work package number	WP2
Work package title	Spatial planning of offshore wind farms
Activity name	Identification of suitable areas and techno-economic assessment
Activity number	2.3
Partner in charge (author)	POLITO, EDP NEW, UCY
Partners involved	POLITO, UCY, SAP, ICCS, EDP NEW

Document history

Versions	Date	Document status	Delivered by
1.0	31-03-2025	First draft	João Marques, Miguel Chousal, João Formiga, Viola De Clerck, Ermando Petracca, Emiliano Nelson Gorr

Title of the document



2.0

03/06/2025

Second draft

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Abbreviations

ABEX	Abandonment Expenditure
AC	Alternative Current
AEP	Annual Energy Production
AHTS	Anchor Handling Tug Supply
ALF	Average Load Factor
BE	Blue Energy
BEMIP	Baltic Energy Market Interconnection Plan
CAPEX	Capital Expenditure
CF	Capacity Factor
CTV	Crew Transfer Vessels
DC	Direct Current
DEVEX	Development Expenditure
DSS	Decision Support System
EB-MSP	Ecosystem-Based Maritime Spatial Planning
EEZ	Exclusive Economic Zones
EIA	Environmental Impact Assessment
EU	European Union
FSV	Field Service Vessels
HV	High Voltage
IMP	Integrated Maritime Policy
IRR	Internal Rate of Return
JUV	Jack-up Vessel
LCOE	Levelized Cost of Energy
LiDAR	Light Detection and Ranging



LV	Low Voltage
MPA	Marine Protected Areas
MRE	Marine Renewable Energy
MSP	Maritime Spatial Planning
MV	Medium Voltage
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operation Expenditure
R&D	Research and Development
SFOC	Specific Fuel Oil Consumption
SOV	Service Operational Vessels
TIP	Total Installed Power
TLP	Tension Leg Platform
VIA	Visual Impact Assessment



Executive summary

The transition from fossil fuels to sustainable and renewable energy sources is a fundamental challenge to ensure long-term energy security and mitigate environmental impacts linked to greenhouse gas emissions. Among renewable technologies, offshore wind energy is emerging as a promising solution thanks to its high technological maturity, low carbon footprint, and vast resource potential. Offshore wind farms also offer advantages compared to onshore facilities, such as reduced noise and visual impact. However, specific challenges exist for their deployment in the Mediterranean Sea, due to abrupt depth variations close to the shore, which make bottom-fixed turbines less feasible and encourage the adoption of floating technologies.

In this framework, maritime spatial planning represents a crucial element to coordinate offshore renewable developments with existing maritime uses, protecting biodiversity and ensuring compatibility with other economic and social activities. Planning the allocation of marine space is therefore essential to enable an efficient and conflict-free deployment of offshore wind farms.

These deliverable addresses three main topic of offshore wind development in the Mediterranean context. The first concerns the methodology for defining suitable areas for offshore wind deployment, based on an integrated assessment of maritime spatial planning constraints. These include ecological, navigational, socio-economic and technical factors, which together support the identification of areas where offshore wind can be installed with minimum conflicts and maximum sustainability.

The second section relates to the methodology for evaluating the annual energy production of offshore wind farms, both fixed and floating. The approach includes consideration of environmental resources, turbine characteristics, and wake effects through the Jensen model, as well as the evaluation of electrical losses along inter-array cables and export cables. This integrated methodology supports a realistic estimation of production potential, which is fundamental for investment planning and energy system integration.

The third part focuses on the techno-economic assessment of offshore wind solutions. The developed techno-economic model evaluates floating and bottom-fixed configurations by calculating key financial metrics such as the Levelised Cost of Energy, currently ranging from 89 to 107 €/MWh for bottom-fixed turbines in Germany and the UK, with projections down to 48 €/MWh by 2050. Floating turbines today reach approximately 149 €/MWh. The analysis also covers other indicators such as the Net Present Value, which sums the discounted cash flows over the project life, and the Internal Rate of Return, the discount rate at which the NPV is zero. A breakdown of life-cycle costs is provided, including Development Expenditures for site assessments and

licensing, Capital Expenditures for equipment and installation, Operation Expenditures for maintenance and port operations, and Abandonment Expenditures for decommissioning. Maintenance strategies are considered, distinguishing corrective actions for major failures from periodic maintenance for minor issues, with a consequent update of the capacity factor to account for operational and cable losses. Infrastructural aspects, such as port upgrades and service vessels, are also included to support the offshore wind supply chain.

Overall, this work delivers a comprehensive framework to guide offshore wind deployment in the Mediterranean Sea, integrating maritime spatial planning, a robust production evaluation methodology, and a thorough techno-economic analysis. The resulting Levelised Cost of Energy provides a consistent benchmark to assess future competitiveness of both bottom-fixed and floating offshore wind technologies in this region.



1. Maritime spatial planning

1.1. Background on Marine Spatial Planning and offshore wind farms

Marine Spatial Planning (MSP) is one of the cross-cutting tools of the Integrated Maritime Policy (IMP) and contributes to the sustainable development of marine zones and coastal areas. Marine Spatial Planning is a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process. MSP is not an end in itself, but a practical way to create and establish a more rational use of marine space and the interactions among its uses, to balance demands for development with the need to protect the environment, and to deliver social and economic outcomes in an open and planned way.

Offshore wind parks provide a clean and renewable source of electricity, which can help to reduce greenhouse gas emissions and mitigate the impacts of climate change. It can provide significant economic benefits, including job creation, investment opportunities, and revenue generation. Also, they can help to reduce the cost of electricity, as technology becomes more efficient and the cost of production decreases.

While offshore wind parks are a clean energy source, they can impact marine life and ecosystems. The construction and operation of these wind parks can disturb the natural habitats of marine animals and can affect the migration patterns of birds and other wildlife. But this can be mitigated and minimized by appropriate site selection.

It must be admitted that the biggest drawback of an offshore wind park is the higher cost of its construction. Offshore wind parks will also be more expensive to maintain and service due to their location away from land. Wave action, and even very high winds, particularly during heavy storms, can increase the construction costs to be able to withstand those conditions. Also, the installation of power cables under the seafloor to transmit electricity back to land can have significant impact on the financial sustainability of the park. On the other hand, the right choice of location for an offshore wind park is very important, hence it can reduce unnecessary costs and increase social acceptance.

Offshore wind parks have the potential to play an important role in the transition to a low-carbon energy future, providing a clean and renewable source of electricity. While there are challenges associated with the construction and operation of these wind parks, the advantages they offer in

terms of large-scale electricity generation, clean energy, and economic benefits make them an attractive option for many countries. As technology continues to improve and the cost of production decreases, offshore wind parks may become an increasingly important part of the global energy mix.

1.2. Previous Projects and Services

This session provides a brief overview of past projects that have focused on MSP and marine renewables. The goal is to draw insights from these initiatives and use them as a guiding framework for SPOWIND. Several key projects and initiatives have laid the foundation for MSP to support offshore wind development and the sustainable management of marine resources across Europe and the Mediterranean.

1.2.1. Summary of Past MSP Projects Relevant to Offshore Wind

THAL-CHOR I and II: The two projects aimed at developing MSP methodology and its pilot implementation for the preparation of marine spatial plans in selected areas of Cyprus and Greece, through cooperation between the two. The outcome of the latest project was the Marine Spatial Plan of Cyprus which is currently active. The project made a detailed webgis database for all marine uses from different stakeholders, conflict analysis and public consultation for the various areas. The plan defines an area for offshore renewables but also an area for scientific experiments.

BEMIP Offshore Wind Work-program: This program was endorsed by the eight High-Level Group on the Baltic Energy Market Interconnection Plan (BEMIP) Member States and the Commission. It identified offshore wind power as a significant component for economic development and energy transition contributing to renewable energy targets and facilitating carbon neutrality by 2050 (1). The MAESTRALE project aims to lay the basis for a strategy for the deployment of maritime energy in the Mediterranean. The project seeks to enhance the sharing of knowledge on Blue Energy (BE), increase skills of public and private actors at all levels and boost technological and entrepreneurial innovation through the promotion of new industrial clusters. The main goal of the MAESTRALE project is to develop a Decision Support System (DSS) for ecosystem-based maritime spatial planning (EB-MSP) together with a guide on best practices to enhance the effectiveness of spatial conservation and restoration measures for marine biodiversity in European Seas. The project will run for three years (until September 2025). The project contributes to the EU demand for guidance on integrated planning to safeguard biodiversity loss and ecosystem functioning by developing tools and best practice standards. It aligns with the objectives of the European Green Deal.



ORECCA (Offshore Renewable Energy Conversion platforms – Coordination Action) is a project that was dedicated to bringing offshore renewable energy applications closer to the market by creating new infrastructures for both offshore wind and ocean energy converters.

The project combined deep-water engineering experience from European oil & gas developments during the last 40 years, state-of-the-art concepts for offshore wind energy, and the most promising concepts in today's R&D pipeline on wave energy and other marine renewables.

Research in the ORECCA project aimed at establishing a set of equitable and transparent criteria for the evaluation of multi-purpose platforms for marine renewable energy (MRE). Using these criteria, the project produced a novel, whole-system set of design and optimization tools addressing, inter alia, new platform design, component engineering, risk assessment, spatial planning, platform-related grid connection concepts, all focused on system integration and reducing costs

In relation to the EU Marine Spatial Planning Platform, ORECCA contributes to the goal of effectively managing marine resources, balancing multiple uses of the sea, and promoting a sustainable blue economy. It aligns with the objectives of the European Green Deal and the BlueDeal.

The BlueDeal aligns with the objectives of the European Green Deal to ensure that the recovery from the COVID-19 pandemic is ecologically sustainable and inclusive (2). It's part of the EU's commitment to reducing conflicts and creating synergies between different activities, encouraging investment through predictability, transparency, and legal certainty, and increasing cross-border cooperation between EU countries (3).

The BlueDeal aims to manage the use of our seas and oceans coherently and to ensure that human activities take place in an efficient, safe, and sustainable way (2). Many activities take place in Europe's seas. At any given time, fishing, aquaculture, shipping, renewable energy, nature conservation, and other uses compete for maritime space (3).

The Pelagos Forum (4) is an important part of the EU's efforts to promote sustainable use of marine resources and to achieve a sustainable blue economy. It aligns with the objectives of the European Green Deal and the BlueDeal. The Pelagos Forum is an event organized under the umbrella of the European Maritime Spatial Planning Platform which is held to facilitate cross-border cooperation on marine conservation and to provide recommendations.

MarinePlan Project is an EU-funded project aims to develop the science base for ecosystem-based MSP and provide guidance for its practical implementation in European Seas. It will develop a Decision Support System (DSS) for ecosystem-based maritime spatial planning (EB-MSP) together with a guide on best practices to enhance the effectiveness of spatial conservation and restoration measures for marine biodiversity in European Seas² (4).

1.2.2. Insights and Best Practices from EU Marine Spatial Planning Platform

The EU Marine Spatial Planning Platform provides structured and practical information that supports the implementation of MSP across Member States. It serves as a valuable reference point

for accessing existing knowledge, sharing insights, and identifying applicable best practices relevant to ongoing and future MSP initiatives.

- **Availability of Information:** The platform facilitates knowledge exchange among EU Member States by offering access to up-to-date information on MSP approaches and implementation strategies (5).
- **Resources and Tools:** Users can access a variety of resources, including technical studies, planning tools, and best practice examples, which are useful for guiding and enhancing MSP processes.
- **Co-existence and Multi-use of Activities:** A dedicated section explores the multi-use of marine space, providing insights into the combination of different maritime activities, challenges and enablers, as well as concrete case studies illustrating real-life applications.
- **Guiding Principles:** The platform outlines key principles for MSP and highlights important aspects for NGOs and other stakeholders involved in participatory planning processes (5).
- **International Guide:** The “MSPglobal International Guide on Marine/Maritime Spatial Planning,” jointly developed by the Intergovernmental Oceanographic Commission of UNESCO and DG MARE, offers a comprehensive overview of MSP processes. It includes thematic sections, case studies, and practical actions to support governments and practitioners in developing effective spatial plans (5) (6).

This structured framework of insights and tools represents a solid foundation for projects like SPOWIND to build upon, ensuring consistency with EU-level practices and promoting coordinated, ecosystem-based marine spatial planning.

1.3. Current Projects and Synergies

1.3.1. Ongoing MSP Initiatives

In addition to these completed and ongoing projects, several current initiatives continue to advance MSP and offshore wind integration:

- **OCEaN Initiative (7):** An open forum focused on offshore wind and electricity grid infrastructure, emphasizing their role in meeting Europe’s climate goals and energy independence. It gathers knowledge, identifies gaps, and accelerates sustainable offshore wind planning.
- **MarinePlan (ongoing):** Running until 2025, this EU-funded project develops a Decision Support System (DSS) and best practice guide for ecosystem-based MSP in European Seas.
- **MPA Europe (2023-2026):** This project aims to map and prioritize optimal locations for Marine Protected Areas (MPAs) across all European Seas using systematic conservation planning tools.

1.3.2. Possible Collaboration with EU Projects

In the context of offshore wind development and MSP, several ongoing EU initiatives offer valuable opportunities for collaboration, knowledge exchange, and strategic alignment. These projects not only support the implementation of MSP across Member States but also foster innovation in the sustainable use of marine space, which is directly relevant to SPOWIND's objectives.

- **MSP Assistance Mechanism and Blue Forum:** The European Commission initiated the new MSP Assistance Mechanism and Blue Forum, in order to aid the European Commission and EU Member States in executing their MSP strategies and procedures (8) (9) (10).
- **Maritime Spatial Planning** is reaping the benefits of extensive collaboration, numerous communication avenues, and tools that facilitate the exchange of knowledge among stakeholders and institutions. This is largely due to key initiatives such as the MSPglobal Initiative and the International MSPforum (11).
- **FAMOS** (Sustainable, reliable, and socially acceptable modular Floating islands for Multi-use Offshore Spaces) aims to propose and develop innovative modular floating island concepts for offshore sea sites. A layout consists of floating islands with shared mooring solutions. It is envisioned that each island serves one specific need, including the aqua island (fish aquaculture), the wind island (wind energy production), the solar island (solar energy production), and the life island (human activities).

1.4. Offshore Wind Project Planning Considerations

1.4.1. Techno-Economic Factors

The techno-economic constraints are critical for planning an offshore wind farm. Among them, the most important considerations are:

Wind Resource Assessment

In order to have a financially sustainable wind farm, the wind energy potential is among the first criteria to take under consideration. The wind resource assessment directly impacts the feasibility and profitability of the project, as wind speed and consistency determine the energy output and, consequently, the revenue generation. Modern tools can assist in estimating wind energy potential, including:

- **Numerical Models:** These provide high-resolution wind data over large areas and extended time periods, helping to predict the wind resource accurately. Numerical models simulate atmospheric conditions and can forecast wind speeds at various heights.



- **Satellite Observations:** Satellites offer extensive spatial coverage and can provide long-term wind speed data over large areas, including remote offshore locations. These observations are invaluable for initial site screening and assessing the overall wind potential.
- **In-situ Data Collection:** Although less frequent due to higher costs and limited spatial coverage, on-site measurements using anemometers or LiDAR (Light Detection and Ranging) systems offer precise wind speed data specific to the proposed turbine locations. These data are critical for validating model predictions and refining energy yield estimates.

Wave Activity

The study region is characterized by steep bathymetry, necessitating consideration of foundation options other than solid foundations. These options must be able to withstand the wave activity of the region to avoid any inconvenience. Hence, if possible, areas of low wave activity may be selected, and a detailed assessment of wave activity must be carried out. Key considerations include:

- **Foundation Stability:** The chosen foundation type (e.g., floating platforms) must be able to withstand local wave conditions, which can impact the stability and longevity of the turbines.
- **Wave Data Collection:** Detailed wave activity data, including wave height, period, and direction, should be collected using wave buoys or numerical models. This data is essential for designing foundations that can withstand extreme weather events.
- **Site Selection:** Preferentially selecting areas with lower wave activity can reduce construction and maintenance costs and improve operational reliability.

Bathymetry

The Mediterranean region, especially the eastern part, is characterized by steep bathymetry, presenting unique challenges for offshore wind farm development. Bathymetry is crucial for several reasons such as Cost optimisation and Engineering feasibility

Proximity to the Grid

Efficient grid connectivity is vital for transmitting the generated power to the main grid. Evaluating existing grid capacity and potential upgrades ensures that the infrastructure can handle the additional load. Key considerations include:

- **Submarine Cable Costs:** The distance from the wind farm to the shore and the grid connection point directly affects the length and cost of submarine cables. Longer distances increase capital expenditure and energy losses during transmission.
- **Grid Capacity and Upgrades:** Assessing the existing grid infrastructure is crucial to determine if it can accommodate the additional power generated by the wind farm. Necessary upgrades or reinforcements must be identified and budgeted.

These criteria help in optimizing the design, reducing costs, and mitigating risks, ultimately leading

to successful project implementation.

1.4.2. Environmental Constraints

Avoiding Natura 2000 areas (13), bird passage areas and Marine Protected Areas (MPAs) (12) is crucial for the sustainable development of offshore wind farms in the Mediterranean region. Natura 2000 is a network of protected areas across the European Union aimed at preserving biodiversity by protecting vulnerable and endangered species and habitats. Similarly, MPAs are designated to safeguard marine ecosystems, habitats, and species from potentially harmful human activities. The avoidance of these areas ensures compliance with environmental regulations and contributes to the conservation of biodiversity.

Developing wind farms outside of Natura 2000 and MPAs helps in preserving the ecological integrity of these protected zones. It prevents potential disruptions to critical habitats and species that these areas are meant to protect. This includes avoiding impacts on breeding grounds, feeding areas, and migratory pathways of marine and bird species.

Adhering to regulations and guidelines set forth by environmental protection frameworks is essential for obtaining the necessary permits and licenses. Projects located outside protected areas are more likely to gain approval from regulatory authorities, ensuring smoother and faster project execution.

1.4.3. Human Activities and Regulatory Framework

Human Activity

In planning offshore wind farms, it is crucial to consider the existing and potential uses of marine space by other stakeholders to ensure harmonious and sustainable development. The Mediterranean Sea is a busy area with diverse activities such as commercial shipping, fishing, tourism, military operations, and cultural heritage conservation. These activities must be carefully mapped and assessed to avoid conflicts and ensure the coexistence of multiple marine uses.

- **Shipping and Navigation:** Offshore wind farm locations must avoid major shipping lanes to prevent navigational hazards and ensure the safety of maritime traffic. Collaboration with maritime authorities is essential to align wind farm planning with shipping routes and port operations.
- **Fishing Activities:** Fishing grounds are vital for local economies and food security. Identifying and avoiding significant fishing areas can prevent negative impacts on the fishing industry and marine biodiversity. Engaging with local fishing communities can help mitigate conflicts and find mutually beneficial solutions.
- **Tourism and Recreation:** Coastal and marine tourism is a major economic driver in Mediterranean countries. The visual impact and accessibility of wind farms should be



evaluated to minimize disruptions to tourism and recreational activities, such as sailing and diving.

- **Military Zones:** Certain areas may be restricted due to military operations or exercises. Coordination with defence authorities is necessary to avoid these zones and ensure national security is not compromised.
- **Cultural Heritage Sites:** The Mediterranean is rich in underwater archaeological sites and cultural heritage, such as shipwrecks and submerged ruins. Identifying and protecting these sites is essential to preserve historical and cultural resources. Engaging with heritage conservation authorities ensures that wind farm development does not damage or disturb these invaluable assets.

The above-mentioned factors have a dual impact on setting up an offshore wind farm. Avoiding interaction with human activities and minimizing the visual impact of the wind farm increases the social acceptance of such projects.

Additionally, a robust regulatory framework is essential for the successful planning, development, and operation of offshore wind farms. In the Mediterranean region, various national and international regulations govern marine spatial planning, environmental protection, and energy production.

Each Mediterranean country has its own set of laws and regulations governing offshore wind energy. These include licensing procedures, environmental impact assessments (EIAs), and specific maritime spatial planning guidelines.

EIAs are mandatory for offshore wind projects and involve assessing the potential environmental impacts of the project, including effects on marine ecosystems, wildlife, and water quality. The EIA process ensures that significant environmental effects are identified and mitigated, promoting sustainable development practices. This process often requires engagement with stakeholders, including local communities, industry representatives, and environmental organizations. This engagement ensures that diverse interests are considered and that there is transparency and accountability in the planning process.

By adhering to a comprehensive regulatory framework, offshore wind projects can achieve regulatory compliance, minimize environmental impacts, and foster public trust and acceptance.

1.4.4. Visual Impact Assessment

A Visual Impact Assessment (VIA) evaluates how a proposed project might alter the visual character of a landscape, considering factors like scale, design, and location. Its goal is to minimize negative visual impacts while ensuring harmony with the surrounding environment, a key step for developments in sensitive or scenic areas.

Although the EU doesn't have a directive solely focused on visual impact, several regulations



indirectly address it through environmental assessment procedures. For example, Directives 2000/69/EC (13) and 2024/2881/EU (14), while aimed at air quality monitoring, require transparency in site selection, including maps, visibility considerations, and documentation, reinforcing the importance of visual and contextual fit in project planning. These reflect the EU's broader commitment to landscape and heritage preservation, aligning with UNESCO's recommendations on visual integrity near World Heritage Sites (15).

In terms of methodology, Maslov et al. (2017) (16) developed a GIS-based tool for estimating the visual impact of offshore wind farms without the need for on-site surveys. Their approach combines three indices:

- Horizon Occupation Index, which measures the sea area visually occupied by the turbines from different coastal viewpoints;
- Number of Distinguishable Turbines, refining visual prominence by accounting for which turbines are actually visible from a location;
- Aesthetic Dimension Index, which considers the alignment and arrangement of turbines, influencing the perceived visual order or disruption.

Together, these indices offer a flexible and location-sensitive framework for assessing visual impact, adaptable to different geographies and planning contexts.

The observation points for the visual impact assessment were selected based on the presence of heritage and cultural areas near the coast and regions with high population density. For each country, a maximum of 10 observation points were chosen, focusing on coastal areas and prioritizing cultural sites located in the most densely populated zones.

1.4.5. Potential sites selection criteria

Taking into consideration all the abovementioned factors for site selection it is clearly shown that a complete site selection is not possible within the activities of the project. The engagement of local stakeholders and communities is a process that is lengthy and cannot be implemented for the timeframe of the project.

The consortium decided to the following selection criteria for pre-selecting potential sites that are suitable for offshore wind farms and used as case study areas for the further activities of the project.



Table 1-1 Selection Criteria for offshore wind farm siting

Criteria Name	Description
Marine spatial plan	Countries may have already preselected areas for different activities. Allocation wind energy farms outside those areas may not be feasible
Depth Restriction	For the purposes of the project, shallow areas (< 60 m) will be analyzed for fixed foundations, while floating platforms will be considered only in waters deeper than 60m. The maximum depth limit for applicable technologies will be set at 1000m.
Wind potential	For establishing the financial feasibility of a project, a minimum wind speed of 3 m/s is required.
Marine Protected areas	Areas that are labelled as marine protected areas, natura 2000 and other areas of biodiversity importance will be excluded
Shipping routes	Areas with high shipping density will be excluded (the shipping density is set to 3 ships/hour)
Proximity to shore	The minimum distance from the shore will be 10km to minimize the visual impact and conflict with local human activities
Exclusive Economic Zones (EEZ)	All sites will be located within the EEZ of the participating countries.

The development of offshore wind farms in the Mediterranean region offers significant potential for advancing renewable energy and achieving sustainable development goals. However, it requires meticulous planning and consideration of various factors to ensure success.

Techno-economic considerations, such as wind resource assessment, bathymetry, wave activity, and proximity to the grid, are fundamental in determining the feasibility and financial viability of projects. Accurate assessments and strategic planning can optimize costs and maximize energy output.

Environmental considerations are equally critical. Avoiding Natura 2000 areas and Marine Protected Areas (MPAs) is essential to preserving biodiversity and ensuring regulatory compliance. This approach minimizes environmental impacts and supports the conservation of marine ecosystems.

Human activities and regulations must also be integrated into the planning process. Recognizing and accommodating other marine space uses, such as shipping, fishing, tourism, military operations, and cultural heritage, prevents conflicts and promotes the sustainable coexistence of diverse activities. Adhering to a robust regulatory framework ensures that projects comply with national and international laws, facilitating smooth project approval and implementation.



By addressing these considerations, offshore wind farm developers can create projects that are economically viable, environmentally sustainable, and socially acceptable. This comprehensive approach not only contributes to renewable energy targets but also supports the broader goals of marine spatial planning and sustainable development in the Mediterranean region.



2. State-of-the-art wind technology

2.1. Key components of the system

An offshore wind farm comprises advanced, interconnected systems that convert wind energy into electricity and deliver it to the onshore grid. Its key components include:

- **Support Structures:** In shallow waters (up to 50–60 m), fixed foundations are used. In deeper areas like the Mediterranean, floating platforms anchored by mooring systems are preferred.
- **Mooring System:** Anchors floating platforms to the seabed, stabilizing them against waves and currents. Flexible power cables adapt to platform movement without affecting transmission.
- **Wind Turbines:** Designed for harsh marine conditions, turbines feature lightweight, high-strength blades (often carbon fiber), a nacelle with electromechanical systems, and a tall tower to harness strong winds.
- **Cabling:** Inter-array cables link turbines, forming a medium-voltage network feeding an offshore substation. High-voltage export cables then transmit the power to shore, with strong insulation to withstand marine conditions.
- **Substations:** Offshore substations collect and step up voltage for efficient transmission. Onshore substations convert it for integration into the national grid. HVDC systems are sometimes used for long-distance efficiency.
- **Monitoring & Safety:** Remote systems enable real-time monitoring and ensure operational safety, supported by redundancies like backup generators and sensors.

In the offshore wind energy sector, there are two main types of turbines: fixed-foundation and floating-foundation turbines. Although fixed-foundation turbines are the most economical solution for wind farm development, their applicability is limited to shallow waters, generally less than 60 meters (17). This geographic constraint means that only a limited portion of marine areas can be exploited, considering that about 80 percent of the seas have depths above this threshold (18). Consequently, exclusive reliance on fixed turbines severely limits the potential for wind energy exploitation in many offshore areas. On the other hand, floating turbines offer the possibility of extending offshore wind power to deeper sea basins. These turbines are mounted on floating platforms, which are not anchored directly to the seabed, but instead are secured through advanced mooring systems. This technology makes it possible to develop installations in



deeper waters, opening up new areas for wind energy that would otherwise not be accessible with fixed foundations. However, despite their great potential, floating turbines are still characterized by higher costs.

The following illustration shows the different types of offshore wind platforms, divided into fixed and floating foundations, providing an overview of the available solutions.

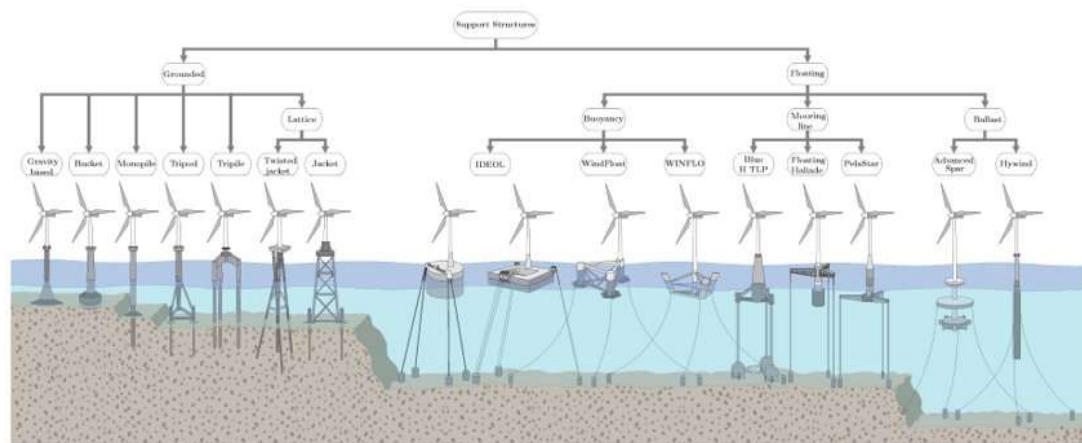


Figure 0-1 Classification of bottom-fixed and floating wind turbines

Fixed foundation

Fixed-foundation turbines are a mature and widely used solution, especially in Europe, where they represent over 99% of installed capacity (18). These turbines are anchored directly to the seabed using different types of foundations, shown in the figure below, such as monopiles (a), jackets (b), gravity bases (c), and tripods (d), each suited to specific seabed and depth conditions. Monopiles are single cylindrical steel piles driven into the seabed, favored for shallow and medium-depth waters due to their simple construction, fast installation, and relatively low cost. Jackets, composed of a lattice steel framework, provide high stability through multiple anchor points and are preferred for deeper waters. Gravity base foundations, typically made of concrete, rely on their own weight for stability and are suitable for rocky or sandy seabeds where pile driving may be impractical. Tripods and tripiles, featuring three-point support structures, offer improved stability compared to monopiles while maintaining a relatively straightforward design.

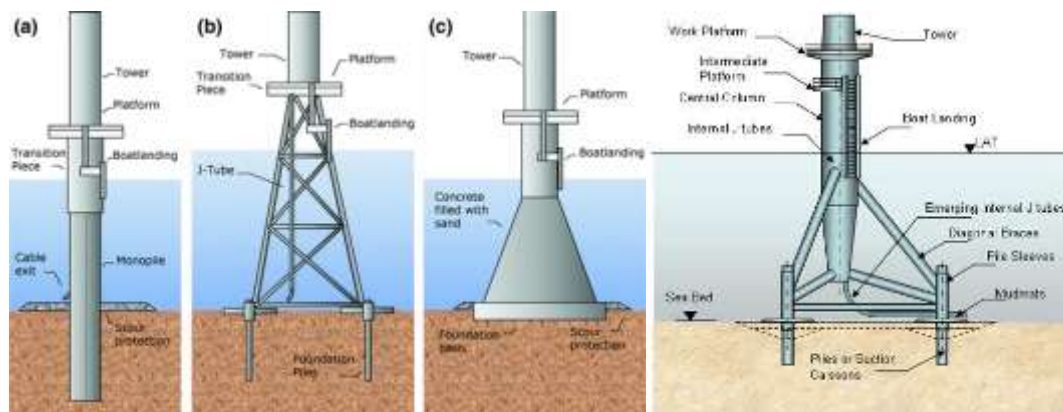


Figure 0-2: Bottom-Fixed foundation types

The market for fixed-foundation offshore turbines has shown an increasing convergence towards the monopile, which accounts for over 78% of total installations in Europe (19), due to its proven efficiency and advantages in terms of cost and operational simplicity. However, alternative technologies such as jacket foundations continue to play a crucial role, especially for projects in deeper waters or particularly challenging environmental conditions.

Floating platform

Although fixed foundations are cost-effective and well-established, they are limited to shallow waters. To overcome this limitation and expand the usable area, floating technology allows wind farms to be installed in deeper waters, unlocking locations that would otherwise be inaccessible. Despite higher costs and greater technical challenges, floating turbines significantly increase the potential for offshore wind energy. Floating platforms generally fall into four main categories, each distinguished by the method used to ensure structural stability.

The Tension Leg Platform (TLP) is a structure consisting of a central column connected to a floating body. This configuration does not provide sufficient stability to balance the turbine-platform system independently. To ensure adequate stability, the TLP requires a mooring system that employs taut lines made of synthetic material or steel cables. The axial stiffness of the pretensioned lines, combined with the weight of the lines, exerts a vertical force on the anchors, thus maintaining platform stability. The use of this technology results in very limited movement overall. However, the installation and maintenance of the tensioned mooring lines incur high costs and involve a complex process with several challenges. The development of TLP platforms has progressed more slowly compared to other floating technologies; to date, only one TLP-based installation, the Provence Grand Large in France, has been deployed (though it has not yet been connected).



Table 0-1: Main existing TLP technologies with patent date, TRL and country

TLP floating platform		
GICON TLP 2018, TRL 5, Germania 	Blue H 2008, TRL 6, Italia 	Provence Grande Large 2019, TRL 7, Francia 

The spar platform is a relatively simple structure, consisting of a single cylinder that can be made of steel or concrete, with the turbine tower installed on top. The platform's stability is ensured by the fact that the center of gravity of the structure is located below the floating point, creating a natural stabilizing effect. This type of platform, the first developed for floating offshore wind energy, was used for the Hywind turbine and currently holds the largest number of installations. However, it has some installation limitations, as it requires a deep dock of over 150 meters, necessitating the use of offshore cranes.

Table 0-2: Main existing SPAR platform technologies with patent date, TRL and country

Spar floating platform			
TetraSpar 2020, TRL 5, Italia 	HyWind 2019, TRL 6, Danimarca 	HexaFloat (semi-spar) 2004, TRL 7, Norway 	WindCrete 2016, TRL 2, Spain 

The barge platform stands out due to its shallow floating plate located beneath the turbine. The stability of this platform can be increased by enlarging the surface area of the plate. Although this technology offers similar advantages to semi-submersible platforms, it also presents comparable disadvantages, particularly regarding its structural limitations and space requirements.

The semi-submersible platform relies on stability through buoyancy, featuring a structure made up of interconnected vertical cylinders (typically three, but sometimes up to five). Stability can be enhanced by either moving the columns away from the center of gravity or lowering the center of gravity itself through the addition of ballast, either solid or liquid, at the base. Current industry trends indicate growing interest in this type of platform, which seems to be gaining wider adoption. The main existing semi-submersible platform are summed up in

Table 0-4: Main existing Semi-Submersible platform technologies with patent date, TRL and country.

Table 0-3: Main existing Barge platform technologies with patent date, TRL and country

Barge floating platform	
Ideol 2015, TRL 6, France 	Blue SATH 2018, TRL 6, Spain 

Table 0-4: Main existing Semi-Submersible platform technologies with patent date, TRL and country

Semi Submersible floating platform			
WindFloat 2013, TRL 7, USA 	V Shape Semi 2016, TRL 7, Japan 	EOLINK 2018, TRL 6, France 	Star Float 2014, TRL 5, Norway 



Nautilus 2020, TRL 3, Spain 	SCD Nezzzy 2019, TRL 3, Germany 	Spider Float 2021, TRL 1, USA 
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Mooring and anchor system

Unlike fixed foundations, floating platforms rely on mooring and anchoring systems to hold their position against waves, wind, and currents. Mooring systems, which connect the platform to the seabed, come in three main types, catenary, taut-leg, and semi-taut, each differing in line configuration and materials, and offering trade-offs in stability, movement, seabed impact, and installation complexity.

Anchors are critical to securing mooring lines to the seabed and must resist the forces acting on them throughout the project's life. Their design varies according to seabed conditions and force directions (horizontal, vertical, or both). The main types are drag-embedded anchors, driven piles, suction piles, and gravity anchors, each suited to different seabeds and installation needs.

Wind turbine size

The offshore wind sector is also defined by a steady increase in turbine size and power. In 2023, the global average turbine capacity reached 9.7 MW (20), with models up to 20 MW already on the market and even larger designs in development (21). Large orders of next-generation turbines confirm this trend, and forecasts predict continued growth in rotor size and power capacity, reinforcing offshore wind's key role in the global energy transition.

Electrical infrastructure

The electrical infrastructure of offshore wind farms is essential for collecting, transmitting, and distributing the energy produced by the turbines to the power grid. The electricity generated at low voltage (around 690 V) is first stepped up to 30 kV by an LV/MV transformer, then transmitted via inter-array cables (up to 66 kV) to the offshore substation. To reduce losses, the energy is then converted to high voltage (220 kV) and sent through the export cable to shore (18).

Submarine cables are built to resist marine conditions, with protections against seabed abrasion and floating platform movements. Inter-array AC cables typically have three cores (one per phase), while HVDC cables are used for long distances, offering lower losses, especially effective beyond



80–100 km.

The offshore substation collects and transforms the energy, which is then sent to the onshore substation for final conversion and integration into the grid. The onshore substation includes transformers and protection systems to ensure safe and reliable operation. Overall, the design of offshore electrical infrastructure must consider marine challenges like movement and corrosion, while adapting to specific transmission needs.

2.2. Offshore wind farms productivity model

The estimation of the Annual Energy Production (AEP) follows the methodology proposed by E. Faraggiana et al. (22), combining detailed wind farm modelling with long-term wind resource data. The objective is to assess the technical floating offshore wind potential of available areas in the Mediterranean Sea by identifying the optimal wind farm characteristics across various configurations. The methodology is applied to two wind turbine models (DTU-10MW and IEA-15MW), three layout configurations (radial, star, and double ring), and three wind farm sizes (900 MW, 1.5 GW, and 3 GW). Each configuration is evaluated across several inter-turbine spacings, ranging from 5 to 18 times the rotor diameter.

A productivity look-up table is first constructed by calculating the wind farm power output over a finely discretized set of operating conditions, covering 1001 wind speed intervals (from 0 to 100 m/s) and 361 wind directions (from 0° to 360°). The productivity is derived from the turbine power curve, corrected for wake losses using the Jensen model, and further reduced by internal electrical losses. These losses are evaluated assuming MVAC transmission, after determining the optimal size of each inter-array cable based on its required nominal power capacity and length, as described in (22).

Once the look-up table is generated, the actual wind farm power output is estimated by coupling it with the 20-year wind resource time series from the CERRA dataset (23). Wind data are sampled on a predefined spatial grid of 0.01° × 0.01°, with a temporal resolution of 3 hours, enabling a detailed reconstruction of energy production under realistic atmospheric conditions.

For each grid point, the distance between the wind farm's central location and the nearest onshore substation is calculated to estimate export cable losses. Two transmission technologies are considered: HVAC and HVDC. For each location, the most suitable option is selected based on a trade-off between cost and transmission losses. Typically, HVDC becomes more advantageous for higher distances.

Thus, the annual energy production is done with the following expression, where η_{avail} is an average availability factor of the offshore wind turbine of 95% (24), $P_{iT}(\theta(t), v(t))$ is the time series productivity, resulted from the interpolation of the look-up-table and the resource data, and P_{EL}

is the transmission electrical losses.

$$AEP\left(\frac{GWh}{year}\right) = \left(\sum_{i_t}^{N_{time}} \eta_{avail} \sum_{i_T}^{N_{Tub}} P_{iT}(\theta(t), v(t)) - P_{EL}(t) \right) \cdot \frac{\Delta t}{8760} \quad 2.1$$

2.2.1. Floating AEP

While the reference power curve provided in (25) can be directly used for bottom-fixed wind turbines, specifically, the 10 MW DTU turbine selected for this study; the evaluation of AEP for floating wind turbines requires a modified power curve that accounts for wave-induced motions. To model these effects, the MOST tool (26) is used.

MOST is a non-linear, time-domain simulation tool specifically designed for floating wind turbines, and it allows for the integration of complex dynamic systems, such as hybrid wind-wave platforms. Within MOST, the various floating platform configurations considered in this study have been implemented as follows:

Table 0-5 Floating offshore wind turbine and platform used in the model

Platform	Nautilus	VoltturnUS	SPAR	TLP
Power	10 MW	15 MW	10MW / 15 MW	15MW
Mooring	Catenary (4 lines)	Catenary (3 lines)	Catenary (3 lines)	Taut-Leg
TRL	4	6	9	5

As results, it's possible to evidence the difference between the power curves. So, by considering the effect of the wave motion, and so the dynamic features of the wind turbine, the power curve goes down, with respect the reference one, with a consequence on minor annual energy production.

The figure below shows the resulted power curves on comparison for the 15MW wind turbines for the three-case analysed in this work: spar, semi-sumbersible, TLP.

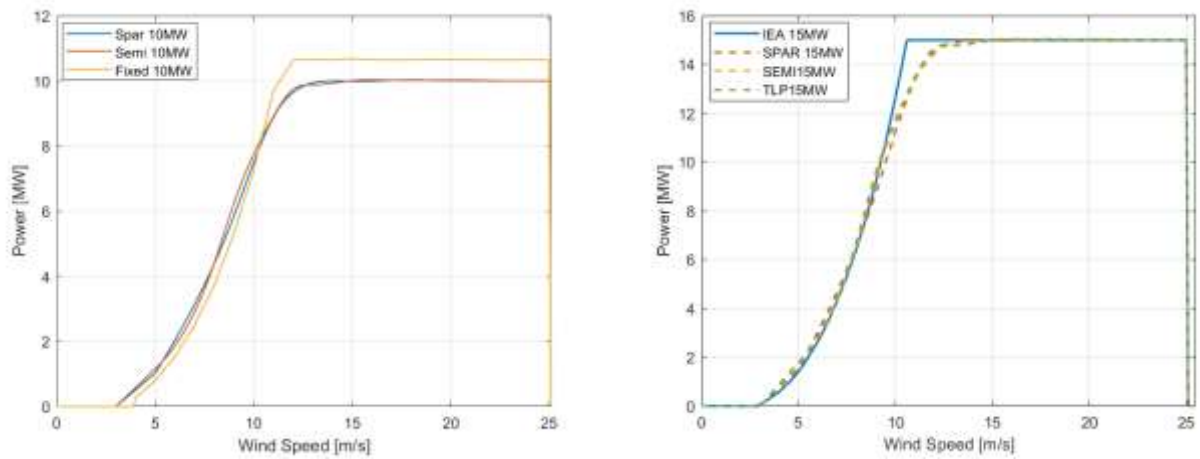


Figure 0-3 Comparison of 10 MW and 15 MW power curves

In the MOST tool, besides accounting for the effect of waves on the power curve, the dynamic behaviour of nacelle acceleration and the maximum blade pitch angle are also calculated.

3. State-of-the-art techno-economic assessment method for offshore wind farm

3.1. Economic metrics

This chapter focuses on the techno-economic evaluation of offshore wind energy solutions, both bottom-fixed and floating, in the Mediterranean context. The objective is to quantify relevant financial and technical indicators that support decision-making and investment prioritisation.

The present report focuses on 4 techno-economic metrics that must be produced by the tool to be shown in the WebGIS tool. Starting with the Levelized Cost of Energy (LCOE), it represents the net present value of the quotient between the costs of operating that specific technology over the lifetime by the total amount of energy produced and it is given by Equation 3.1 below:

$$LCOE = \frac{I_0 + \sum_{y=1}^{OY} \frac{A_y}{(1+r)^y}}{\sum_{y=1}^{OY} \frac{E_y}{(1+r)^y}} \quad 3.1$$

Where I_0 represents the capital investment, OY is the expected operational years of the project, Y is the current year in operation, A_y is the activity costs associated with the year Y, E_y is the energy produced in year Y, and r is the discount rate.

The Net Present Value is the sum of the discounted cash flows associated with a specific investment. The formula for NPV is given by the following equation:

$$NPV = \sum_{t=0}^n \frac{[\text{cash flow}]_t}{(1-k)^t} - [\text{initial investment}] \quad 3.2$$

where n is the number of years of the project, t is the year of analysis and k is the discount rate of the project. This metric helps determine the value of a project after a series of cash flows, adjusted for a specified discount rate. The discount rate is crucial as it reflects the project's risk—the higher the discount rate, the greater the risk associated. It also accounts for inflation over the project's duration. Conversely, the Internal Rate of Return (IRR) is the discount rate at which the Net Present Value (NPV) equals zero. It represents the compound annual return that an investor expects to earn throughout the investment's life. To create value, a project's NPV must be positive by the end



of its expected lifetime. Ideally, the IRR should exceed the discount rate; if the IRR is lower than the discount rate, it suggests that the project may not be profitable enough to justify the investment. (36).

Finally, there is the Capacity Factor (CF), which is the ratio between the amount of electricity produced by the wind farm, $E_{produced}$, and the electricity that would have been theoretically produced if the farm was always operating at maximum power (rated power output), $E_{maximum}$, and it is given by Equation 3.3 (37):

$$Capacity\ Factor = \frac{E_{produced}}{E_{maximum}} \quad 3.3$$

Initially, the capacity factor is computed as direct function of the wind farm energy production, after considerations of wake effect, cable losses and wave motion in the farm. Then, this parameter will be updated with information regarding O&M activities, where the availability of the farm plays a key role in determining which locations are. Availability is defined as the share of the time when the system is operating and/or able to operate, compared to the total time (37) and is given by the following formula:

$$Availability = \frac{T_{available}}{T_{available} + T_{unavailable}} \quad 3.4$$

Considering production losses in O&M activities, the true capacity factor of a farm is computed, giving accurate electricity production values that would be injected into the grid.

3.2. Life cycle costs of offshore wind farms

The life cycle expenditures of an OWF consists of four main stages: development expenditures (DEVEX), which are the processes prior to the installation of the farm, such as site resource evaluation and licensing procedures; capital expenditures (CAPEX), the costs associated with the implementation activities, namely the equipment, cost of capital, insurance and installation; operation expenditures (OPEX), the costs referent to the operation, maintenance, port activities, and licensing fees for the OWF operation (38); and abandonment expenditures (ABEX), which are the costs associated with the decommissioning of the structures in the farm (39). In the present work, Euro to US Dollar and Euro to British Pound conversions were based on the average of the last 10 years, where €1 is equal to \$1,1239 (40) and €1 equals to £0,8403 (41)



3.3. O&M activities overview

For offshore wind farms, O&M activities can be responsible for 20 to 37% of the overall costs, regardless if it is bottom-fixed or floating (39) (42) (43). As such, an effective maintenance strategy is essential for the operating life of the turbines, as electricity production is necessary to make the farm economically viable. The challenge is increasing, not only because more and more farms are being commissioned, but also because the turbines are getting larger, and farms are being put into commission further from the coast (28).

Effective maintenance strategies are crucial for the profitability of a farm. It is a balance between availability and costs, where if too few interventions are performed, less money is spent over the operating lifetime however, the availability will also decrease, reducing revenues substantially. On the other side of the spectrum, if too many maintenance operations are performed, the costs increase and turbines have to be stopped more often, potentially increasing the LCOE (28). Figure 0-1 illustrates such balance. O&M models indicate that depending on the frequency of inspections and if there are health monitoring systems in place, the strategy that minimizes LCOE is not

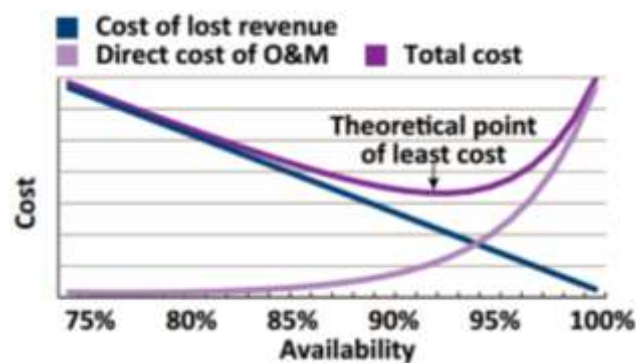


Figure 0-1 Balance between cost and availability in an offshore wind farm. Source: (46)

necessarily the cheapest O&M option, however, repairing small failures frequently will reduce the number of replacements, which reduces the total downtime of a farm and, consequently, reduce the LCOE (39) (44).

Maintenance is the work that is done to keep something repaired and in good condition (45) and throughout the literature, maintenance strategies are categorized in various ways. Z. Ren *et al.* (28) provided an overview that classifies these strategies into three major groups: corrective, opportunistic, and proactive. Corrective maintenance is performed after a fault is recognized, aiming to restore an item to a state where it can fulfil its required function. On the other hand, proactive maintenance is a more intricate procedure, focusing on inspections and replacements before failures occur. This last approach helps reduce downtimes and prevents minor issues from escalating into major failures. Proactive maintenance can be sub-categorized in 3 different ways: preventive maintenance (scheduled maintenance), condition-based maintenance, and predictive

maintenance. When a combination of proactive maintenance and corrective maintenance is applied, it is called opportunistic maintenance.

3.4. Supporting infrastructure

3.4.1. Foundations

In offshore wind, foundations can be classified by the depth they are installed, with shallow waters classified as being up to 30 meters, transitional waters between 30 and 60 meters, and deep waters as more than 60 meters, as seen in Figure 0-2. For shallow waters and transitional waters, bottom fixed foundations are the main choice in the industry and their respective costs are expected to increase the deeper the location is. For open waters, where more wind resources are available, floating foundations are currently the only solution available, and the development knowledge mostly comes from the oil industry (39). Regarding foundations, a more detailed analysis is provided in Deliverable 2.2. In the present work, it is considered that bottom-fixed foundations go to a maximum of 60 meters of depth and use a monopile structure and floating foundations are applied when depths are between 60 and 500 meters, where Tension Leg Platform (TLP), Semi-Submersible Platform (both with Nautilus and VoltturnUS platforms), and Spar Buoy are considered.

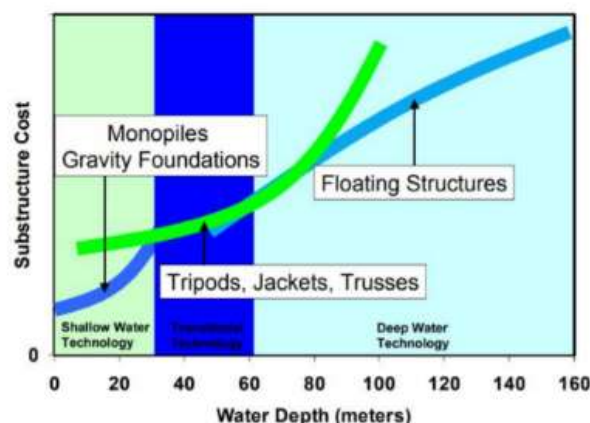


Figure 0-2 Infrastructure required depending on the depth of the farm and respective expected costs. Source: (39).

The depth maps analysed are from the European Marine Observation and Data Network (30), where the shapefile with the depth of the Mediterranean Sea was obtained and used on every computation for floating wind's costs estimation.



3.4.2. Vessels

Depending on the foundation and type of O&M strategies employed, different vessels may be used. While smaller interventions only require small components and few technicians, vessels used in replacements can carry large components or have to transport the turbine to a port's facility. Thus, throughout the literature, 4 vessels stand out as being the most used in maintenance: Crew Transfer Vessels (CTV); Service Operational Vessels (SOV), also known as Field Service Vessels (FSV) depending on the source; Jack-up Vessels (JUV) for replacements in bottom fixed turbines; and Anchor Handling Tug Supply (AHTS) to drag floating turbines to shore for replacements (28) (37) (46) (47) (48) (49).

Starting with the CTVs, the most used kind of vessels in O&M activities for offshore wind farms. As they are small, the main purpose is to transport operators to and from turbines, as well as small equipment to perform inspections and maintenance. Usually, these vessels are catamarans, up to 30 meters in length and capable of accommodating 12 to 16 technicians and must stay connected to the wind turbine while technicians move to and from the foundations (28) (46) (50) (51). An example of a CTV can be seen in Figure 0-3.

SOVs or FSV are offshore support vessels capable of accommodating up to 60 crew members for long periods of time at sea and can be used for a wider variety of operations, from repairs to replacements. SOVs are also usually equipped with gangways and helipads and have excellent stability characteristics to handle sea conditions (28) (42) (46) (51) (52). Figure 0-4 shows an example of a SOV in action.



Figure 0-3 Example of a crew transfer vessel. Source: (50)



Figure 0-4 Example of a service operational vessel. Source: (52)

On the replacements side, JUVs are large heavy-duty vessels cable of elevating themselves from the seafloor to perform maintenance activities. The stabilization is key, as they employ a large crane for operations, and can operate up to a depth of 65 meters (28) (53) (49). If the platform is



floating, the alternative solution for replacements is to have them in port facilities and, in that scenario, AHTS are the solution (49) (54). Examples of these two vessels in operation can be seen in Figure 0-5 and Figure 0-6.



Figure 0-5 Jack-Up Vessel in operation. Source: (28).



Figure 0-6 Anchor Handling Tug Supply. Source: (81).

Another point of consideration is the limitations of the use of each vessel. Failures determine if and when operators must go to the farm, however, sea conditions may not allow O&M when needed, just when it is possible to perform it. Thus, wind speed, current speed and wave height limit vessel use and, consequently, increase downtimes and OPEX costs, and reduce the revenue of a farm. In the case of AHTS, there are added considerations when the turbines are being transported (28) (37) (49). Table 0-1 provides the maximum wind speed and wave height each vessel can operate.

Table 0-1 Limits of the vessels used for O&M. Adjusted from: (49).

Name of the vessel	CTV	SOV	JUV	AHTS
Wave limit [m]	2.5	1.8	1.5	3
Wind limit [m/s]	30	30	25	30
Current limit [m/s]	5	5	4	4
Wave limit with the device [m]	-	-	-	2.1
Wind limit with device [m/s]	-	-	-	21
Current limit with device [m/s]	-	-	-	2.8



3.4.3. Ports and connecting grid substations

Offshore wind requires existing inland infrastructure to be upgraded, or even created, to accommodate its needs. Ports are very common along countries' coastlines and are the starting ground for the deployment of this technology. However, only a very small number of them are capable of meeting the installation and O&M demands, and even already large industrial ports require upgrades to existing infrastructure if a country decides to have offshore wind. They are the middle point between the supply chain and the project. Currently, ports can be divided into 4 categories: small oceanic ports for survey vessels, manufacturing ports, marshalling ports, and O&M ports (47). Small oceanic survey ports are the easier and cheaper to create or adapt, as plenty of ports already accommodate this infrastructure for launching survey vessels used for wildlife surveys, seafloor scans, and geotechnical analysis. Manufacturing ports can have areas up to 25 ha and are responsible for building the turbine's components and enabling the transport of large components. Sea transport is quicker and easier than land transportation due to the large size of turbine's parts. Blades for offshore wind turbines can measure more than 100 meters and subsystems such as foundations, nacelles and generators can easily exceed road and train limits for transportation. Thus, ship transport is the better alternative for offshore wind. Marshaling ports are where components are collected, stored, and made ready for installation. An analysis made by Parkinson S. and Kempton W. (47) concluded that for a 1 GW farm, with 12 to 14 MW turbines would occupy 22 ha of land of an already existing port during the construction phase. Lastly, there are O&M ports, typically smaller than Marshaling ports, at 2 ha, however, the trend is to increase in size, as projects are getting located further from shore, turbines are getting larger in size, and farms have more turbines. These O&M ports can be developed by upgrading existing ports, with investments starting at 10 million euros.

Inland substations allow the farm to be connected to the regional grid and are an area of heavy investment in the sector, because current grids are not designed to accommodate the size of projected farms, making reinforcements a priority (55). Even though investments in grid reinforcement are outside the scope of the project, they are important to mention, and the techno-economic model must at least incorporate a layer of decision on which substation the farm can be connected to an estimate the export cable costs and losses.

3.4.4. Insurance

The low initial maturity of these technologies presents significant risks during both installation and operation stages. Operational risks include equipment damage or malfunction, business interruptions, worker liability, and environmental liability. Additionally, insurance companies may require owners to maintain real-time condition monitoring of components and have replacement parts readily available to address potential unexpected faults. According to a survey conducted by

Vieira M. (39), insurance costs can range from €10 thousand to €15 thousand per MW of installed capacity per year of operation. Implementing health monitoring systems may help reduce insurance costs in some company contracts.

3.5. Market trends and learning curves

Current electricity markets work on an hourly basis and are composed of electricity suppliers, consumers, transmission system operators, distribution network operators and regulators. Markets also depend on geography, as they may be at a country level, a region level, or, in the case of Portugal and Spain, they are shared between two countries. Electricity suppliers must deploy equal energy demands at all times, balancing supply and demand, and the prices are bided differently for every hour, meaning that whenever energy supply is high and demand is low, prices are low (in some cases even negative) while if the demand is high, electricity prices will also increase, based on the resources available. Renewable energies are inherently unstable, as they depend on weather conditions, and good weather predictions are of utmost importance to deliver competitive prices. On the other hand, traditional fossil fuels have good grid flexibility, as they can be deployed quickly to support energy demands, however, they are more expensive than renewable energies. Inflation in 2022 due to the Russia-Ukraine war led to energy prices increasing to levels never seen before, especially in countries dependent on natural gas. In the Iberian Peninsula, average yearly grid prices were previously around 50 €/MWh until 2021, reached approximately 167 €/MWh in 2022, and then 63 €/MWh in 2024, while in Italy, they were about 55 €/MWh in 2021, 320 €/MWh in 2022 and 130 €/MWh in 2024. Future market trends point to a gradual decrease in electricity prices, especially in countries where there is more installed capacity of renewable energy sources, and by 2035 Portugal, Spain, The Netherlands, and the United Kingdom should have market prices at 60 to 70 €/MWh, France at 70 to 80 €/MWh and Italy at 100 €/MWh (35) (56) (57) (58).

Regarding learning rates, the present work will use the work from the EU-SCORES project (59) as a baseline for possible cost reductions in the offshore wind industry. The yearly cost reduction in bottom-fixed offshore wind, based on industry data, is present in Figure 0-7, with the respective learning rates in Table 0-2. Using the same learning rates of 14.1% for floating offshore wind, Figure 0-8 is produced, with the growth model and the doubling model. The present learning rates will be used to give better estimates of future LCOE figures of the developed model, using current industry prices.



Table 0-2 Learning rate for floating offshore wind from public sources. Source: (59).

Learning Rate	On item	Reference
14.1%	LCOE	Rabobank 2023 & DNV 2022. Energy Transition Outlook
14.1%	LCOE	DNV 2023. Energy Transition Outlook
5.9% - 9.5%	CAPEX	2021, ORE Catapult. Floating Offshore Wind: Cost Reduction Pathway to Subsidy Free.
8.7% - 14.3% (avg 11.5%)	CAPEX	2022, NREL. A Systematic Framework for Projecting the Future Cost of Offshore Wind Energy
2.8% - 12.8% (avg 7.8%)	CAPEX	2022, University of Edinburgh. Deriving Current Cost Requirements from Future Targets.

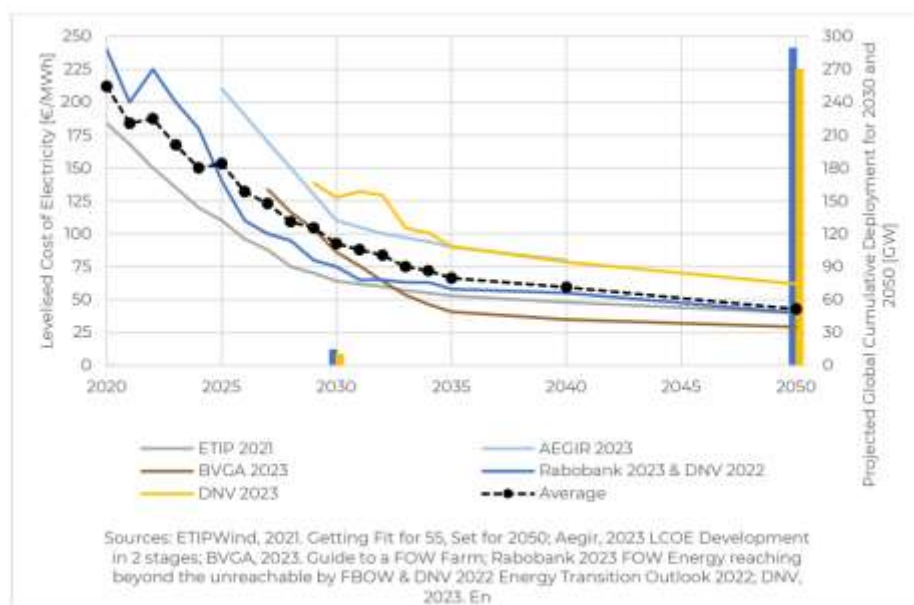


Figure 0-7 LCOE curves from different sources to 2050, along with the projected deployment in 2030 and 2050. Sources in the figure and the compilation study is from (59).

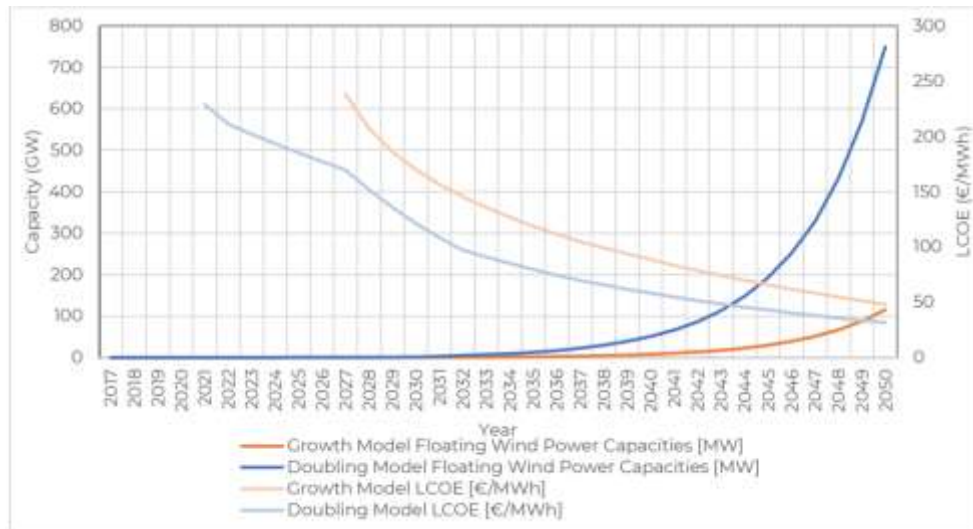


Figure 0-8 Projected floating offshore wind capacities and corresponding LCOE using reference technology fixed offshore wind, growth, and doubling models. Source: (59).



4. Techno-economic analysis: DEVEX, CAPEX and Decommissioning

4.1. DEVEX

The development of an offshore wind farm requires a preliminary phase that includes the activities necessary to obtain authorisations and define the feasibility of the project. This phase, known as Development Expenditure (DEVEX), includes environmental and impact studies, geotechnical and meteorological-oceanographic analyses, economic and technical assessments, including engineering and consulting, as well as the bureaucratic process to obtain the necessary licences and permits.

DEVEX represents a significant investment, which is essential to reduce risks in the subsequent construction (CAPEX) and operation (OPEX) phases. Careful planning at this stage optimises costs, minimises environmental impacts and ensures the financial sustainability of the project.

The costs associated with DEVEX, listed below, show a difference between bottom-fixed (18) and floating (42) technologies, with the latter characterised by higher costs. A more detailed breakdown for both technologies is provided in Annex 1.

$$DEVEX_{fixed} = 142800 \cdot PWF [MW] \quad 4.1$$

$$DEVEX_{floating} = 173918.5 \cdot PWF [MW] \quad 4.2$$

4.2. CAPEX

After the development phase, the project moves into the capital investment stage, known as CAPEX (Capital Expenditure). This phase represents the most significant portion of the investment, covering all costs required for the construction of the plant. Specifically, CAPEX includes the costs of manufacturing and purchasing the turbine and foundation, expenses related to the electrical infrastructure, such as internal connection cables, export cables to the grid, and both onshore and offshore substations. It also encompasses the installation costs of the entire structure, contingency reserves to account for unforeseen risks, and, in the case of a floating structure, additional costs associated with mooring and anchoring. Additionally, a cost reduction factor λ is considered for the turbine, platform, and mooring costs to reflect the savings from series



production of N_T wind turbines:

$$C_R = \left(\frac{2}{3} + \frac{1}{3} e^{-0.00174 \cdot N_T^2} \right) \quad 4.3$$

4.2.1. Turbine and substructure

In our model two different wind turbine size are considered, the DTU 10MW and the IEA 15MW. The cost considered for those two wind turbines are in Table 0-1:

Table 0-1 Costs of wind turbines of 10 MW and 15 MW.

Wind Turbine size	Cost	Reference
10 MW	€ 7 118 071	(60)
	€ 11 900 000	(18)
	€ 13 781 475	(61)
	Average of the values: € 10 933 182	
15 MW	1 547 000 €/MW	(42)

For the computation of the foundation cost, it's necessary to consider specific parameters related to each foundation type, by distinguishing between bottom-fixed and floating solutions.

For the floating foundations employed in deeper waters, the cost per MW is generally higher due to structure complexity and the mooring system. Also, a difference for the three platform types is considered in Table 0-2.

Table 0-2 Costs of the different foundations used in the study.

Foundation	Cost	Units	Reference
Bottom-Fixed (10MW)	3 873 108	€	(61)
	3 332 000	€	(42)
	Average of the values: € 3 601 003		
Semi-Submersible (concrete)	496 429	€/MW	(62)
Semi-Submersible (steel)	750 000	€/MW	(62)
SPAR (concrete)	247 285	€/MW	(62)
SPAR (steel)	374 000	€/MW	(62)
TLP (concrete)	66 775	€/MW	(62)
TLP (steel)	93 450	€/MW	(62)



4.2.2. Mooring cost

For the mooring cost evaluation, it was first computed the mooring length for a range of sea depths, to afterwards select the mooring length in each grid position based on specific bathymetry.

The mooring cost is calculated as:

$$C_{Moor} = n_M \cdot (C_{Anchor} + C_{Mline}) \cdot N_T \cdot C_R \quad 4.4$$

where n_M is the number of mooring lines, C_{Anchor} is the anchor cost, and C_{Mline} is the mooring line cost.

Mooring line cost of the chain is calculated as:

$$C_{Mline_c} = c_{Mw} \cdot c_{Mc} \cdot L_m \quad 4.5$$

where c_{Mw} (kg/m) and c_{Mc} (€/kg) are respectively the mooring chain specific weight and the mooring chain specific costs, L_m is the mooring line length (m).

The mooring chain specific cost depends on mooring diameter, d_m (mm), is evaluated by taking as reference (63):

$$c_{Mw} = 0.02 \cdot d_m^2 \quad 4.6$$

Table 0-3 reports all the details considered for the three different floating platforms (58), (59), (60):

Table 0-3 Mooring lines characteristics for the different foundation in study.

	Spar	Semi-sub	TLP
Lines number	3	3	4
Mooring chain specific cost	2.75	2.75	-
Mooring Type	Catenary, chain	Catenary, chain	Taut, wire

4.2.3. Electrical infrastructure cost

Grid connection cost is composed by cable connection cost, which are subdivided in inter-array and export cable costs, and cost of the offshore and onshore substations:

Title of the document



$$C_{Grid} = C_{int_i} + C_{ex} + C_{Offsub} + C_{Onsub} \quad 4.7$$

Inter array cable cost

The inter-array cable cost model are defined based on (60):

$$C_{int_i} = Cable_{length} * 303\,500 \text{ €/km} \quad 4.8$$

Export cable cost

Regarding the export of energy to the grid, two distinct approaches were considered: high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) transmission. A 220 kV current was considered for both voltage levels. The choice between the two systems depends mainly on the distance from the nearest onshore substation: HVAC is more suitable for shorter distances, while HVDC becomes cost-effective for longer distances. The cost functions for each technology, depending on the distance from the coast, are presented below (62).

$$C_{HVAC} = 1016000 * Distance, \text{ for } D < 110km \quad 4.9$$

$$C_{HVAC} = 2800000 \left(\frac{V_{HVAC}}{320kV} \right) * Distance, \text{ for } D > 110km \quad 4.10$$

$$C_{HVDC} = 1200000 * Distance, \text{ for } D > 110km \quad 4.11$$

Finally, the offshore and onshore substation costs are estimated as the sum of the transformer and switchgear costs. The transformer cost is obtained as:

$$C_{tr} = c_{tr1} \cdot P_{farm} \quad 4.12$$

where c_{tr1} is assumed as 150.9 k€/MW and 21.56 k€/MW for the offshore and onshore transformer respectively (65) and P_{farm} is the farm rated power (MW). The switchgear cost is estimated as:

$$C_{switch} = c_{s1} \cdot V_{HVAC} + c_{s2} \quad 4.13$$

where c_{s1} and c_{s2} are respectively 0.668 €/V and 36000 € (66).



4.2.4. Installation

The installation cost is related to the distance to shore and water depth, it includes substructure, wind turbine installation, cost related to ports facilities, offshore logistics, cable installations and for the floating platform case also the mooring installation. Table 0-4 presents the installation costs of mooring lines, export cables and offshore logistics.

Table 0-4 Installation costs of some elements of the farm.

	Cost	Unit	Reference
Mooring Installation	80920	€/MW	(42)
Offshore logistics	2618	€/MW	(42)
Export cable installation	$513375 \cdot D_{shore}$	€	(62)

For the platform cost a detailed cost function for each different type are considered; by including substructure, turbine and ports cost associated to installations. In the following equations DCF is distance to port (km), WD is the water depth (m) and WFC is the wind farm capacity (MW).

- Semi-submersible:

$$Semi\ sub_{structure} = \frac{(23658000 + 11625 \cdot WD + 35450 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.14$$

$$Semi\ sub_{turbine} = \frac{(59608000 + 120833 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.15$$

$$Semi\ sub_{port} = \frac{(15896470 + 2975 \cdot WD + 28266 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.16$$

- Spar:

$$Spar_{substructure} = \frac{(94577688 + 9850 \cdot WD + 175081 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.17$$

$$Spar_{turbine} = \frac{(175000000 + 363916 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.18$$

$$Spar_{port} = \frac{(28101577 + 28266 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.19$$

- Tension Leg Platform:



$$TLP_{substructure} = \frac{(99746000 + 21625 \cdot WD + 75650 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.20$$

$$TLP_{turbine} = \frac{(230000000 + 452861 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.21$$

$$TLP_{port} = \frac{(34151022 + 55231 \cdot DCF)}{600000} \cdot WFC \cdot 1000 \quad 4.22$$

- Bottom-Fixed foundation:

Unique parameter is considered for the bottom-fixed offshore wind turbine installation, which is:

$$Fixed = 434945 \cdot WFC \quad 4.23$$

4.2.5. Contingencies

Contingency costs are accounted for by allocating a budget reserve to cover any unforeseen events or changes in costs during the construction phase of the installation. Given the higher overall costs associated with floating offshore wind farms, the contingency budget for floating installations is also higher than for bottom-fixed facilities. The contingency figures used are present in Table 0-5.

Table 0-5 Contingencies considered in the project.

Foundation	Cost	Reference
Bottom-Fixed	325 652 €/MW	(67)
Floating	137 500 €/MW	(62)
	321300 €/MW	(42)
	368360	(67)
	Average of the values: 2750 €/MW	

4.3. Decommissioning

As with installation costs, the decommissioning costs of a wind farm depend on the distance from shore and the depth. To estimate these costs, a reverse installation process is used, as described in (65). However, this process is assumed to be simpler and faster, resulting in lower decommissioning costs, typically considered a fraction of the installation costs. The percentages used to compute them based on installation costs are provided in Table 0-6.



Table 0-6 Decommissioning costs of systems in the wind farm.

Description	% of Installation cost
Wind turbine (Fixed)	80
Wind turbine (Floating)	70
Subsea cables	10
Substation	90
Mooring	90

OPEX

The main goal of the present chapter is to demonstrate the cost function developed for the techno-economic model, clarify the inputs and databases used for failure data and repair costs and describe the assumptions taken. The OPEX model is tailor-made for each configuration in the study: turbine power, total farm's capacity, type of foundation and internal cable array. There are two main divisions within the OPEX model, as maintenance for bottom fixed turbines and for floating turbines require different vessels and have different subsystems.

5.1. Failure data and availability data

Failure rates are necessary to estimate the number of visits to the farm over its lifetime and the respective vessels needed. The mathematical failure cumulative distribution function is defined below as:

$$F(t) = 1 - R(t) \quad 5.1$$

where $F(t)$ denotes the cumulative distribution function, t the time, and $R(t)$ the reliability, which is the probability that the system will perform its tasks (68). Reliability is also defined by Equation 3.2 by:

$$R(t) = e^{-\lambda t} \quad 5.2$$

Here, λ is the constant failure rate, and it gives the average amount of failures expected per period of time. It can be written in the following form:

$$\lambda = \frac{1}{\text{mean time between failures}} \quad 5.3$$

5.1.1. Bottom-fixed

One of the most cited sources in the literature for failure rates in offshore wind farms is the analysis performed by J. Carroll et al. (69). For bottom-fixed turbines, the O&M model developed uses the data shown in Table 0-1, where all subsystems are listed along with the respective



maintenance operations. Failures are also classified in 4 different categories, depending on the repair cost: no cost failures, which, as the name suggests, have no repair cost associated on the database; minor repairs, which are failures which repair cost is less than €1000; major repairs, which repair cost is between €1000 and €10 000; and when the repair cost of a failure is larger than €10 000 it is classified as major replacement. The costs are only based on material costs, excluding factors such as transportation, crew salaries, travel times, and assembly costs.

In the developed model, the “no cost data” class of repairs is not included in the analysis, as its cost is referenced as non-existent and it is assumed that crews are large enough to fix failures in the wind turbine at the same time when they are deployed. Failures in both bottom-fixed and floating turbines are assumed not to evolve into more serious types, are independent from each other and, since the model has to run for thousands of points, the most efficient way to perform the computations is to have average failure rates for each point.

Table 0-1 Failure rates for every subsystem of a wind turbine blade and different maintenance types. The failure rates are shown in failures per turbine per year of operation. Source. (69).

Subsystem	Minor Repair	Major repair	Major Replacement
Pitch/Hyd	0.824	0.179	0.001
Other components	0.812	0.042	0.001
Generator	0.485	0.321	0.095
Gearbox	0.395	0.038	0.154
Blades	0.456	0.01	0.001
Grease/oil/cooling Liq	0.407	0.006	0
Electrical Components	0.358	0.016	0.002
Contactors/circuit breaker/ Relay	0.326	0.054	0.002
Controls	0.355	0.054	0.001
Safety	0.373	0.004	0
Sensors	0.247	0.07	0
Pumps/Motors	0.278	0.043	0
Hub	0.182	0.038	0.001
Heaters/coolers	0.19	0.007	0
Yaw System	0.162	0.006	0.001
Tower/foundation	0.092	0.089	0
Power Supply/converter	0.076	0.081	0.005



Service Items	0.108	0.001	0
Considered to be Transformer	0.052	0.003	0.001

5.1.2. Floating turbines

If finding failure rate data for bottom-fixed wind turbines is complicated, as farm owners don't want to share publicly that information due to competitive reasons, compiling data for floating offshore wind turbines is even harder, as not only just a few projects exist (by February 2025, there are only the Hywind Scotland farm, Wind Float Atlantic, Kincardine Offshore Wind Farm, and Hywind Tampen (70)), and all of them are quite recent, leading to even smaller data available. Studies performed by Rinaldi G. *et al.* (49), Zhang X. *et al.* (71) and Elusakin T. *et al.* (72) gathered data relative to floating wind turbines' failure data and costs for maintenance activities and are the basis for this analysis.

For the present techno-economic analysis, the subsystems of the turbine are considered the same for both bottom-fixed and floating. However, floating platforms are considered to have added subsystems, present on Table 0-2. Due to inconsistent data regarding floating platforms in the studies listed above, it is considered that every 5 years, floaters need maintenance in a port, and the cost of maintenance is 1% of the floaters' cost.

Table 0-2 Failure rates of floating platforms. Maintenance costs of floaters are equal to 1% cost of the floater per maintenance.

Subsystem	Failure rate
Floating platform (Semi-Sub SPAR Tension Leg Platform)	0.21
Mooring lines	0.12
Anchors	0.107

The availability of the farm is the time-based ratio of the amount of time a wind turbine/farm is ready to operate in each time divided by the total time in that time (73), and it is computed based on the study performed by Carroll J. *et al.* (73). Since the Mediterranean Sea is calmer than the North Sea (74), it was considered the upper curve from Figure 0-1 and the availability of the site is interpolated with the distance the farm is to the port.

For distances greater than 100 km from port, it is considered that for every km further from shore, it is lost 0.08% of availability, which is the same slope as from 90 to 100 km from the port.

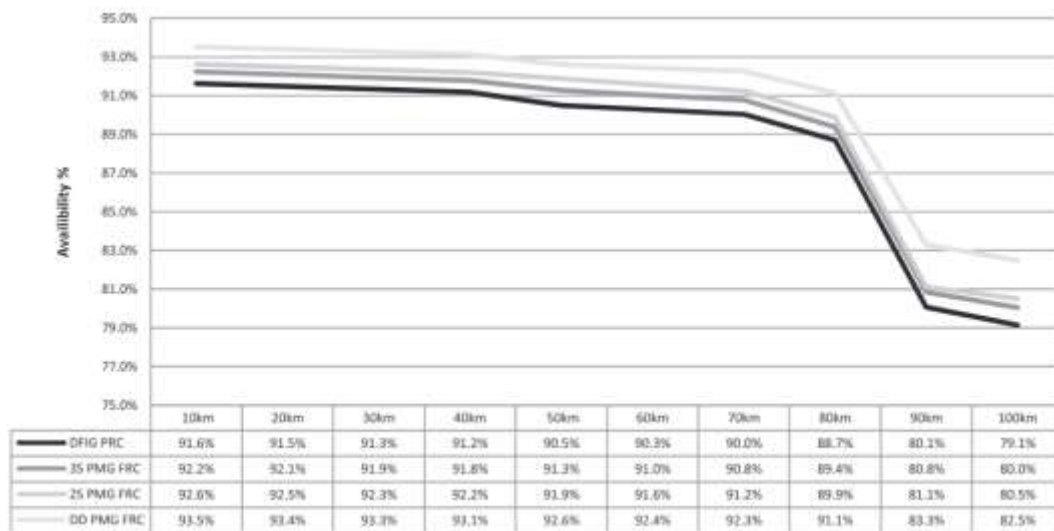


Figure 0-1 Availability of wind farms showing all drive train types at sites varying distances from shore. In this study, it is considered the upper curve of this analysis. Source: (73).

The availability of the farm, is then multiplied by the capacity factor initially computed without maintenance activities, to have the real capacity factor of the farm over 25 years of operations:

$$\text{Real CF} = \text{CF} \times \text{Availability}(\text{Distance})$$

5.4

5.2. Periodic maintenance

Preventive maintenance is considered to occur every 6 months and is responsible for fixing minor failures. This module is also responsible for giving an average number of the vessels needed for the task and performs the same regardless of the type of foundation.

Table 0-3 presents the following considerations for periodic maintenance. It is assumed that inspection time per turbine is able to inspect and fix all minor failures present and that it takes 7.5 h to do so, based on the study from Carrol J. *et al.* (69). The travel time between turbines, the interval between inspection and the type of vessel used are assumed, based on the literature reviewed. Thus, the total number of farm visits is:



$$\text{Total number of farm visit} = \text{annual number of inspections} \times \text{years of operation} \times \text{number of CTV}$$

5.5

Table 0-3 Periodic Maintenance considerations.

Inspection time per turbine (h)	7.5
Travel time between turbines (h)	0.5
Interval between inspections (months)	6
Vessel used	CTV
Number of vessels per inspection	1 vessel per 50 turbines

With the information above it is possible to estimate the time needed for periodic maintenance of the farm and thus, estimate the vessel and personnel costs, which are present in section 5.5. However, to compute the material cost of repairs, it is used data from Carrol J. (69). Table 0-4 presents the average annual failure rate of each subsystem and the respective repair price. By multiplying the factors over 25 years, it is possible to obtain the total average repair cost for minor repairs per turbine in the farm.

Table 0-4 Average material cost for minor repairs over 25 years. Source: (69).

Subsystem	failure rate	repair price	cost over 25 years
Pitch/Hyd	0.824	210	4326
Other components	0.812	110	2233
Generator	0.485	160	1940
Gearbox	0.395	125	1234.375
Blades	0.456	170	1938
Grease/oil/cooling Liq	0.407	160	1628
Electrical Components	0.358	100	895
Contactora/circuit breaker/ Relay	0.326	260	2119
Controls	0.355	200	1775
Safety	0.373	130	1212.25
Sensors	0.247	150	926.25
Pumps/Motors	0.278	330	2293.5
Hub	0.182	160	728
Heaters/coolers	0.19	465	2208.75
Yaw System	0.162	140	567
Tower/foundation	0.092	140	322
Power Supply/converter	0.076	240	456



Service Items	0.108	80	216
Transformer	0.052	95	123.5
Total cost (€) per turbine			27141.625

5.3. Corrective maintenance

The corrective maintenance part of the model is responsible for fixing major failures and performing replacements in the turbines. In here, there are a few vessels that can be used, depending on the type of the foundation and the type of failure to be fixed. More information regarding vessel use is provided in the following sections.

5.3.1. Bottom-fixed turbines

The first step to compute the corrective maintenance costs is to assess which vessels are used for each maintenance task. Based on the information from section 3.4, Table 0-5 was created, assigning each vessel type to the respective maintenance task and subsystem of the turbine.

Table 0-5 Vessels are assigned for each maintenance task in corrective maintenance for bottom-fixed turbines. Cells in the table where no vessel is assigned are a consequence of their failure rate for Replacements in that subsystem being null.

Subsystem	Vessel	
	Major repairs	Replacements
Pitch/Hyd	SOV/FSV	JUV
Other components	SOV/FSV	SOV/FSV
Generator	SOV/FSV	JUV
Gearbox	SOV/FSV	JUV
Blades	SOV/FSV	JUV
Grease/oil/cooling Liq	SOV/FSV	-
Electrical Components	SOV/FSV	JUV
Contactors/circuit breaker/ Relay	SOV/FSV	JUV
Controls	SOV/FSV	SOV/FSV
Safety	SOV/FSV	-
Sensors	SOV/FSV	-
Pumps/Motors	SOV/FSV	-
Hub	SOV/FSV	JUV
Heaters/coolers	SOV/FSV	-
Yaw System	SOV/FSV	JUV
Tower/foundation	SOV/FSV	-



Power Supply/converter	SOV/FSV	JUV
Service Items	SOV/FSV	-
Transformer	SOV/FSV	JUV

Following the vessel allocation, it is necessary to know, on average, how many deployments are needed, how long they will take for vessel and personnel costs computations and the average material cost of the maintenance activity. Applying the same logic from periodic maintenance here, it is possible to produce Table 0-6 and Table 0-7, as seen bellow:

Table 0-6 Average material cost, hours of operation and number of site visits for major repairs over 25 years. Source: (69).

Subsystem	Major repair					
	failure rate	repair price	repair time	cost per turbine over 25 years	hours of operation over 25 years	number of site visits over 25 years
Pitch/Hyd	0.179	1900	19	8502.5	85.025	4.475
Other components	0.042	2400	21	2520	22.05	1.05
Generator	0.321	3500	24	28087.5	192.6	8.025
Gearbox	0.038	2500	22	2375	20.9	0.95
Blades	0.01	1500	21	375	5.25	0.25
Grease/oil/cooling Liq	0.006	2000	18	300	2.7	0.15
Electrical Components	0.016	2000	14	800	5.6	0.4
Contactactor/circuit breaker/ Relay	0.054	2300	19	3105	25.65	1.35
Controls	0.054	2000	14	2700	18.9	1.35
Safety	0.004	2400	7	240	0.7	0.1
Sensors	0.07	2500	6	4375	10.5	1.75
Pumps/Motors	0.043	2000	10	2150	10.75	1.075
Hub	0.038	1500	40	1425	38	0.95
Heaters/coolers	0.007	1300	14	227.5	2.45	0.175
Yaw System	0.006	3000	20	450	3	0.15
Tower/foundation	0.089	1100	2	2447.5	4.45	2.225
Power Supply/converter	0.081	5300	14	10732.5	28.35	2.025
Service Items	0.001	1200	0	30	0	0.025
Transformer	0.003	2300	26	172.5	1.95	0.075
	Totals per turbine			71015 €	478.825 h	26.55



Table 0-7 Average material cost, hours of operation and number of site visits for replacements of 10 MW and 15 MW bottom-fixed turbines over 25 years. Source: (69), (61), (75).

Replacements bottom-fixed turbines								
	failure rate	repair price (10 MW)	repair price (15 MW)	repair time	cost per turbine over 25 years (10 MW)	cost per turbine over 25 years (15 MW)	hours of replacemen ts over 25 years	number of site visits over 25 years
Pitch / Hyd	0.001	591244.77	1248999.02	24	14781.12	31224.8	0.6	0.025
Other component s	0.001	10000	10000	24	250	250	0.6	0.025
Generator	0.095	708337.04	1062505.56	20	1682300.47	2523450.71	47.5	2.375
Gearbox	0.154	1855147.26	3131951.24	24	7142316.93	12058012.28	92.4	3.85
Blades	0.001	734021.41	13076771.36	16	18350.53	326919.28	0.4	0.025
Grease/ oil/ cooling Liq	0	0	0	0	0	0	0	0
Electrical Component s	0.002	549604.06	824450.57	18	27480.20	41222.53	0.9	0.05
Contacto r/ circuit breaker/ Relay	0.002	13500	13500	24	675	675	1.2	0.05
Controls	0.001	13000	13000	12	325	325	0.3	0.025
Safety	0	0	0	0	0	0	0	0
Sensors	0	0	0	0	0	0	0	0
Pumps/ Motors	0	0	0	0	0	0	0	0
Hub	0.001	288459.83	605792.33	24	7211.50	15144.81	0.6	0.025
Heaters/ coolers	0	0	0	0	0	0	0	0
Yaw System	0.001	401459.2	941676.30	24	10036.48	23541.91	0.6	0.025
Tower/ foundation	0	0	0	0	0	0	0	0
Power Supply / converter	0.005	699706.38	1049559.57	24	87463.30	131194.95	3	0.125
Service Items	0	0	0	0	0	0	0	0
Transformer	0.001	70000	70000	24	1750	1750	0.6	0.025
Total per turbine					8,992,940,53€	15,153,711,44 €	148.7 h	6.625

From the previous 2 tables, the repair time comes from (75), which is an update of (69), the failure rates from (69), and the costs of each subsystem are from (69) and (61). The costs of each subsystem had to be updated for larger turbines, as the report from Carroll J. (69) is only for older turbines between 2 and 4 MW, and to complement that gap, a study performed by Ashuri T. et al. (61) allows to update the costs for 10 MW and 20 MW turbines in some subsystems. Both analyses



only consider the cost of materials and do not include labour costs or compensation costs for downtimes. Finally, for 15MW turbine costs, a linear interpolation of the values from Ashuri T. *et al.* (61) was used and then converted the costs from US Dollars do Euros.

5.3.2. Floating turbines

For maintenance in floating wind turbines, different vessels are used. The main difference is that replacements are done in port, which means that instead of using JUVs, operators must drag the turbines to and back from the port with AHTS. Table 0-8 shows the vessel chosen for each maintenance activity. It is important to minimize the travel needed for replacements, thus, as said previously, on average, it is considered that every 5 years, floaters need maintenance in a port, and the cost of maintenance is 1% of the floaters' cost. The costs, repair times and number of site visits for major repairs are also similar to Table 0-6, as is the same vessel performing such maintenance activities.

Table 0-8 Vessels assigned for each maintenance task in corrective maintenance for floating turbines. Cells in the table where no vessel is assigned are a consequence of their failure rate for Major Failures or Replacements in that subsystem being null.

	Vessel	
	Major repairs	Replacements
Pitch/Hyd	SOV/FSV	SOV/FSV
Other components	SOV/FSV	SOV/FSV
Generator	SOV/FSV	AHTS
Gearbox	SOV/FSV	AHTS
Blades	SOV/FSV	AHTS
Grease/oil/cooling Liq	SOV/FSV	-
Electrical Components	SOV/FSV	SOV/FSV
Contactor/circuit breaker/ Relay	SOV/FSV	SOV/FSV
Controls	SOV/FSV	SOV/FSV
Safety	SOV/FSV	-
Sensors	SOV/FSV	-
Pumps/Motors	SOV/FSV	-
Hub	SOV/FSV	SOV/FSV
Heaters/coolers	SOV/FSV	-
Yaw System	SOV/FSV	SOV/FSV
Tower/foundation	SOV/FSV	-
Power Supply/converter	SOV/FSV	SOV/FSV
Service Items	SOV/FSV	-
Transformer	SOV/FSV	SOV/FSV



Floating platform (semi-sub)	-	AHTS
Mooring lines	-	SOV/FSV
Anchors	-	SOV/FSV
Power cable (interarray)	-	SOV/FSV
Export cable	-	SOV/FSV

The data regarding replacements is provided in Table 0-9, which has a similar logic to Table 0-7 with additional considerations due to the floater.

*Table 0-9 Average material cost, hours of operation and number of site visits for replacements of 10 MW and 15 MW floating turbines over 25 years. Source: (49), (69), (72), (61), (75). Label: * i) equals to 1% cost of the floater per maintenance; * i i) already considered in Table 0-10; *iii) uses AHTS vessels and not SOV. The values of the last column in the table are for site visits (SOVs) and not drag to shore operations.*

Replacements floating turbines								
	failure rate	repair price (10 MW)	repair price (15MW)	repair time	cost per turbine over 25 years (10MW)	cost per turbine over 25 years (15MW)	Hours of operation over 25 years	Number of site visits over 25 years
Pitch / Hyd	0.001	591244.77	1248999.02	24	14781.12	31224.98	0.6	0.025
Other components	0.001	10000	10000	24	250	250	0.6	0.025
Generator	0.095	708337.04	1062505.56	20	1682300.47	2523450.71	47.5	*iii
Gearbox	0.154	1855147.26	3131951.24	24	7142316.93	12058012.28	92.4	*iii
Blades	0.001	734021.41	13076771.36	16	18350.53	326919.28	0.4	*iii
Grease/ oil/ cooling Liq	0	0	0	0	0	0	0	0
Electrical Components	0.002	549604.06	824450.57	18	27480.20	41222.53	0.9	0.05
Contacto/ circuit breaker/ Relay	0.002	13500	13500	24	675	675	1.2	0.05
Controls	0.001	13000	13000	12	325	325	0.3	0.025
Safety	0	0	0	0	0	0	0	0
Sensors	0	0	0	0	0	0	0	0
Pumps/Motor s	0	0	0	0	0	0	0	0
Hub	0.001	288459.83	605792.33	24	7211.50	15144.81	0.6	0.025
Heaters / coolers	0	0	0	0	0	0	0	0
Yaw System	0.001	401459.2	941676.30	24	10036.48	23541.91	0.6	0.025
Tower / foundation	0	0	0	0	0	0	0	0
Power Supply / converter	0.005	699706.38	1049559.57	24	87463.30	131194.95	3	0.125
Service Items	0	0	0	0	0	0	0	0
Transformer	0.001	70000	70000	24	1750	1750	0.6	0.025
Floating platform	0.21	* i	* i	12	* i	* i	63	*iii

Title of the document



Mooring lines	0.12	30000	45000	12	90036.01	135054.02	36.01	3.00
Anchors	0.107	55000	82500	12	146588.49	219882.73	31.98	2.67
Power cable (interarray)	0.0000323	* i i	* i i	12	* i i	* i i	* i i	* i i
Export cable	0.167	* i i	* i i	24	* i i	* i i	* i i	* i i
Total per turbine							279,70h	6,041

The cost structure is similar between Table 0-7 and Table 0-9 where the components are the same. The differences arise in the floater's subsystems, where to know the maintenance cost of the respective floater it is required to know the cost of the floater in this approximation (maintenance in floaters equals to 1% cost of the floater per maintenance) (49), meaning that every floater combination produces different OPEX figures, regardless of the type used. The mooring and anchors data come from the work of Elusakin T. *et al.* (72), with the conversion for 15 MW being an interpolation (1.5x increase in value). Table 0-9 also considers site visits from SOVs, and the replacements that require AHTS are considered to happen every 5 years. Thus, every turbine has to go to the port on average 5 times during the 25 years of life of the farm. The time estimates for that are present in section 5.5.

5.4. Maintenance support infrastructure considerations

Although realistically, not all costs referenced in this subsection are constant in an OWF O&M phase, they are considered non-variable in this analysis, due to a lack of available information. All these costs are available in Table 0-10 and include port spendings, maintenance in other components of the farm besides the turbines, scour and structural surveys, costs related to monitoring systems, weather forecasting costs, management and coordination activity costs, administration costs, and insurance costs. The costs are also presented in Euros per year per MW of installed power to account for different farm sizes and are the same for floating and bottom-fixed farms.

Table 0-10 Maintenance support infrastructure costs considered in the simulation tool in Euros per year per MW of power.

Component	Value [€/ (year*MW)]	Reference
Ports Onshore Logistics	1309	(46)
Substation Maintenance	297.5	(46)
Export Cable Surveys and Repairs	297.5	(46)
Array Cable Surveys and Repairs	833	(46)
Scour and Structural Surveys	952	(46)
Lifting, Climbing and Safety Equipment	357	(46)



Inspections		
SCADA and Condition Monitoring	1428	(46)
SAP and Marine Co-ordination	1428	(46)
Weather Forecasting	154.7	(46)
Administration	833	(46)
Insurance	15000	(39)
Total [€/ (year*MW)]	22889.7	-

5.5. Cost Structure

The cost computation is a complex subject that combines information from all maintenance systems. In the present work, the costs are a sum of the average material used for repairs, listed in the previous section, from all subsystems over 25 years, the vessels and technicians' costs based on the time needed in operations, and the extra expenses listed in section 5.4, as seen in Equation 3.6.

$$C_{total} = C_{material} + C_{operation} + C_{support\ infrastructure} \quad 5.6$$

To compute the costs of operations, the times of operations, costs of different maintenance components and the number of items (turbines, vessels, inspections) required. In periodic maintenance, it was to be multiplied the number of CTVs used by the salary of the crew, charter cost of each vessel and the fuel that it consumes per hour, as seen in Equations 3.7 and 3.8:

$$C_{PM} = (t_{CTV\ operations\ over\ 25\ years\ per\ vessel} \times (C_{CTV\ crew\ hourly\ salary} + C_{CTV\ charter} + C_{CTV\ fuel}) \times N_{vessels}) \quad 5.7$$

With:

$$t_{CTV\ operations\ over\ 25\ years\ per\ vessel} = ((N_{turbines}/N_{vessels}) \times (t_{travel\ between\ turbines} + t_{inspection\ per\ turbine}) + 2 \times d_{port}/CTV_{speed}) \times N_{inspections} \quad 5.8$$

Regarding corrective maintenance, it has to be divided into 2 approaches, one for bottom-fixed turbines where defects are fixed in the farm and replacements require a JUV, and another for floating turbines, where major failures are also fixed in the farm with SOVs, however some replacements require AHTS to perform replacement in the ports:



$$C_{CM \text{ bottom-fixed turbines}} = (t_{SOV \text{ operations over 25 years per vessel}} \times (C_{SOV \text{ crew hourly salary}} + C_{SOV \text{ charter}} + C_{SOV \text{ fuel}})) + (t_{JUV \text{ operations over 25 years per vessel}} \times (C_{JUV \text{ crew hourly salary}} + C_{JUV \text{ charter}} + C_{JUV \text{ fuel}})) \quad 5.9$$

$$C_{CM \text{ floating turbines}} = (t_{SOV \text{ operations over 25 years per vessel}} \times (C_{SOV \text{ crew hourly salary}} + C_{SOV \text{ charter}} + C_{SOV \text{ fuel}})) + t_{AHTS \text{ operations over 25 years per vessel}} \times (C_{AHTS \text{ crew hourly salary}} + C_{AHTS \text{ charter}}) + (N_{turbines} \times N_{AHTS \text{ interventions}} \times (2 \times d_{port} / AHTS_{speed}) \times C_{AHTS \text{ fuel without load}}) + (N_{turbines} \times N_{AHTS \text{ interventions}} \times (2 \times d_{port} / AHTS_{speed}) \times C_{AHTS \text{ fuel with load}}) + (t_{AHTS \text{ total replacement in port}} \times N_{turbines} \times C_{AHTS \text{ crew hourly salary}}) \quad 5.10$$

With:

$$t_{SOV \text{ operations over 25 years per vessel}} = N_{turbines} \times N_{SOV \text{ interventions}} \times \left(2 \times \frac{d_{port}}{SOV_{speed}} \right) + N_{turbines} \times t_{SOV \text{ repair per turbine}} \quad 5.11$$

$$t_{JUV \text{ operations over 25 years per vessel}} = N_{turbines} \times N_{JUV \text{ interventions}} \times \left(2 \times \frac{d_{port}}{JUV_{speed}} \right) + N_{turbines} \times t_{JUV \text{ repair per turbine}} \quad 5.12$$

$$t_{AHTS \text{ operations over 25 years per vessel}} = N_{turbines} \times N_{AHTS \text{ interventions}} \times \left(2 \times \frac{d_{port}}{AHTS_{speed \text{ with load}}} \right) + N_{turbines} \times N_{AHTS \text{ interventions}} \times \left(2 \times \frac{d_{port}}{AHTS_{speed \text{ without load}}} \right) \quad 5.13$$

where C are the costs, N the number of times an event happened, d the distance, and t the time of an event. The term $t_{SOV \text{ repair per turbine}}$ refers to the time an SOV is used in major repairs and replacements operations offshore and comes from Table 0-6, Table 0-7 and Table 0-9.

The costs of the support infrastructure are present in Table 0-10 while the costs of material are in Table 0-6, Table 0-7 and Table 0-9.

Regarding the cost parameters of the vessels used, the information can be seen in Table 0-11. It is important to keep in mind that different vessels also have different charter agreements, based on the expected duration of operations (48), and thus, some simplifications have to be made to some of the contracts. Based on the maintenance needs and the literature review performed, the number of technicians needed is assumed to be the values below. Furthermore, the salary of each



technician is assumed to be the same at 82886 Euros per year (72) and the analysis only considers that technicians are paid every time they are mobilized, as a part of an active service contract. The charter costs and fuel consumptions of CTVs, SOVs and JUVs is based on the analysis of Fonseca F. *et al.* (43) where it is introduced, the following considerations using data from the vessel market: CTV's length is 25 meters (46), the SOV has less than 60 passengers, and the JUV has a lift capacity of 1500 tones (73). The final results introduced in the model are in Euros per hour, as vessels are chartered for the number of hours they are needed. The fuel costs can be estimated based on Equation 5.14:

$$C_{fuel} = f_{cs} \times p_{fuel} \quad 5.14$$

where f_{cs} is the average fuel consumption of the vessel per day and p_{fuel} the fuel costs. Furthermore, the average fuel consumption per day (tons/day) is also dependent of a number of variables, namely the vessel's total installed power (TIP), in kW, the average load factor (ALF), and the specific fuel oil consumption (SFOC), in g/kWh, which are presented in Equation 5.15 (48):

$$f_{cs} = TIP \times ALF \times SFOC \times 24 \left(\frac{1}{1000^2} \right) \quad 5.15$$

According to Fonseca F. *et al.* (48), the referenced average load factor is 80% and the specific fuel oil consumption is 210 g/kWh, and the fuel cost considered is 515 Euros per tonne, taken from the port of Rotterdam. The final parameter, the vessel's total installed power, is specific for each vessel in the study. Regarding CTVs, the TIP considered is 1790 kW (78), the SOVs' TIP is 2200 kW (79) and the JUVs' TIP is considered to be 10400 kW (77). In the case of AHTS, the fuel costs and charter costs are based on the work of Rinaldi G. *et al.* (49).

Table 0-11 Cost parameters of the vessels used. Sources:

Parameter	CTV	SOV/FSV	JUV	AHTS
Number of technicians	15	20	40	30
Cost per technician (€/h)	9.46	9.46	9.46	9.46
Charter cost (€/h)	150.25	1000	7047.38	928.9
Fuel consumption (€/h)	154.87	190.34	899.81	538,69
Fuel consumption with load (€/h)	-	-	-	1000.13

6. First results

The analysis first focused on identifying the areas suitable for offshore wind deployment in the Mediterranean, distinguishing between bottom-fixed and floating technologies. After applying all technical, environmental, and maritime-use constraints, a clear difference emerged between the two approaches. As expected, the areas available for bottom-fixed turbines are extremely limited due to depth restrictions between 20 and 60 meters, which are incompatible with most of the Mediterranean seabed. Conversely, floating turbines can be deployed in much wider portions of the basin, confirming their role as the dominant and most promising solution for future offshore wind development in the region.

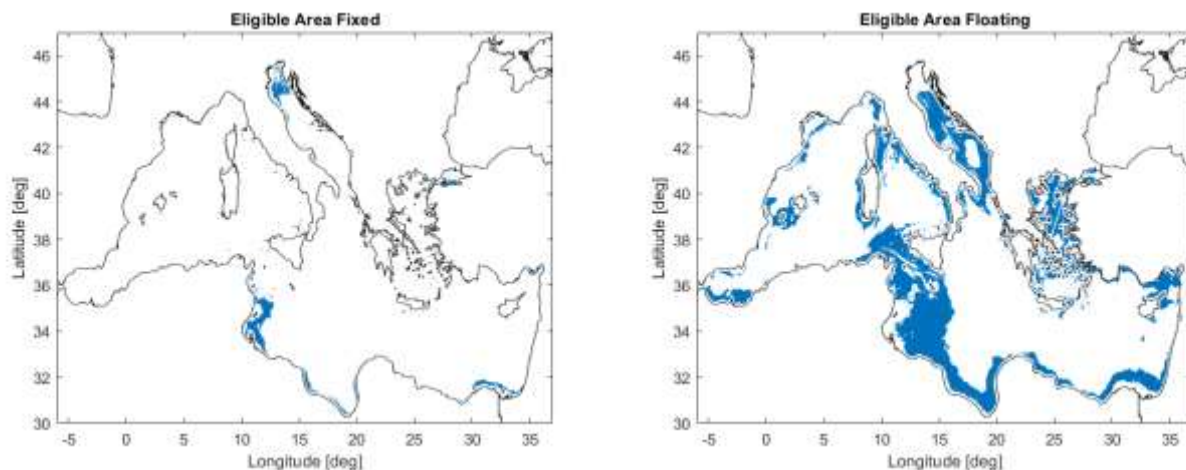


Figure 0-1 Eligible area for bottom-fixed (left) and floating platform (right)

Subsequently, for each layout configuration – radial, d-ring, and star – the optimal results were calculated based on the minimum LCOE. In the case of radial and d-ring, the outcomes are very similar because the d-ring can be considered a specific case of the radial layout, characterized by slightly higher losses due to the introduction of redundancy cables, which result in a modest increase in costs. The figures for AEP and LCOE for these two layouts show a slight difference in energy production, with the d-ring presenting lower AEP values and, consequently, slightly higher LCOE compared to the radial. The maps of the optimal farm size and platform selection (Figure 0-4) indicate that, for both configurations, the preferred option is predominantly the smallest size,

0.99 GW. Only a few remote areas are associated with the 3 GW option, while the most productive zones correspond to 1.5 GW, always associated with the selection of monopile wind turbine. In both layouts, the optimal spacing consistently corresponds to the maximum available value, confirming the preference for wide turbine spacing in both radial and d-ring.

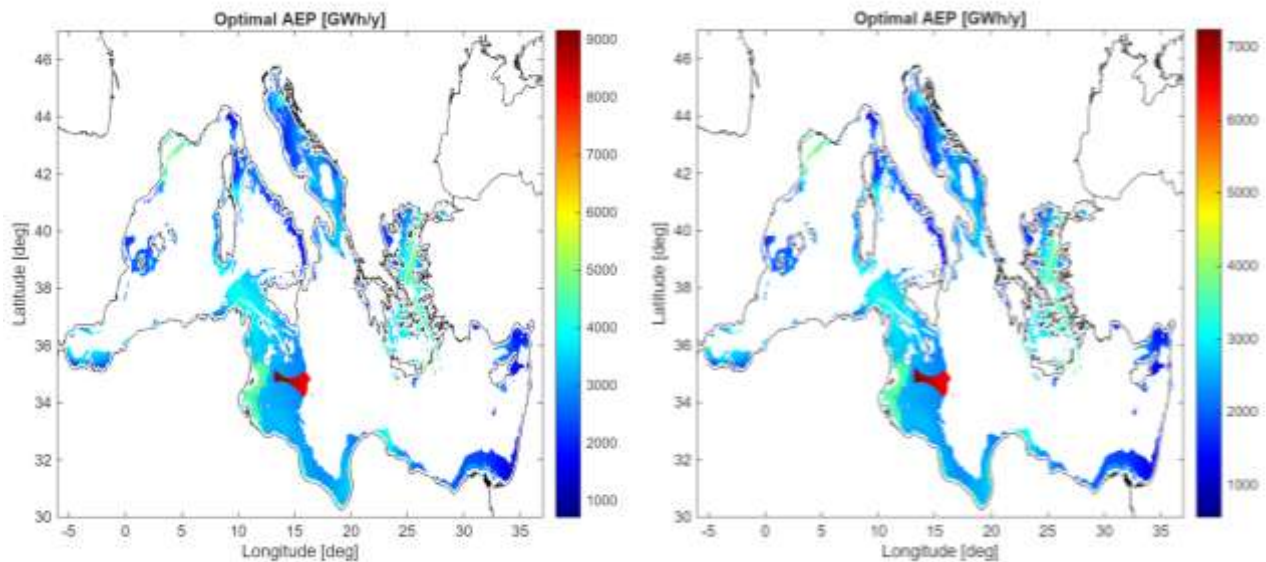


Figure 0-2 Optimal annual energy production for radial (left) and double ring (right) layout.

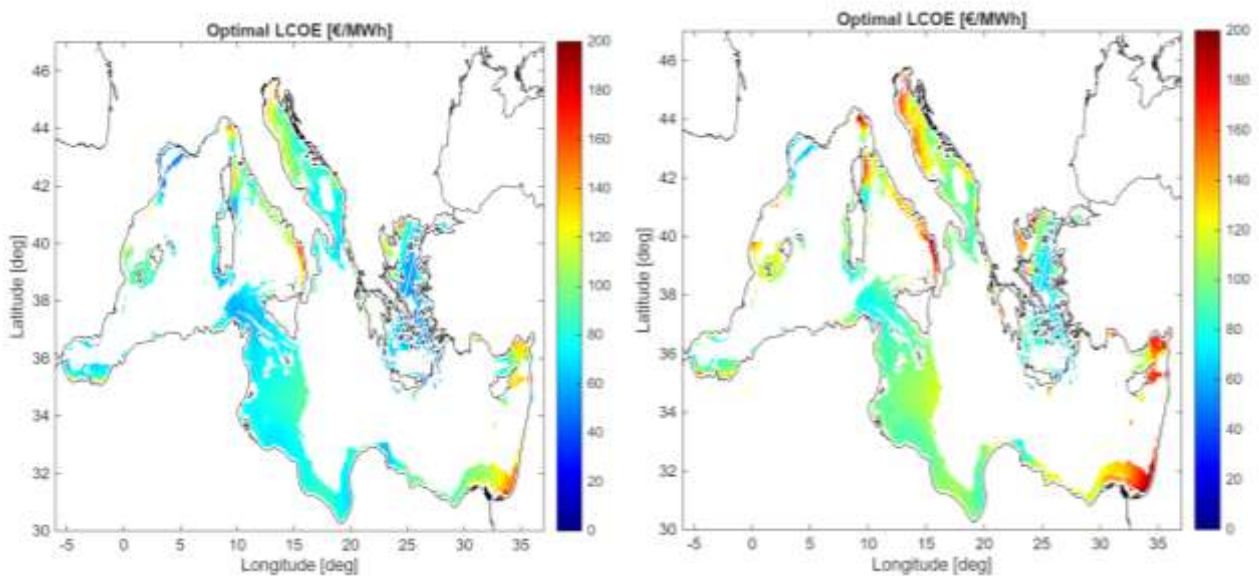


Figure 0-3 Optimal levelized cost of energy for radial (left) and double ring (right) layout.

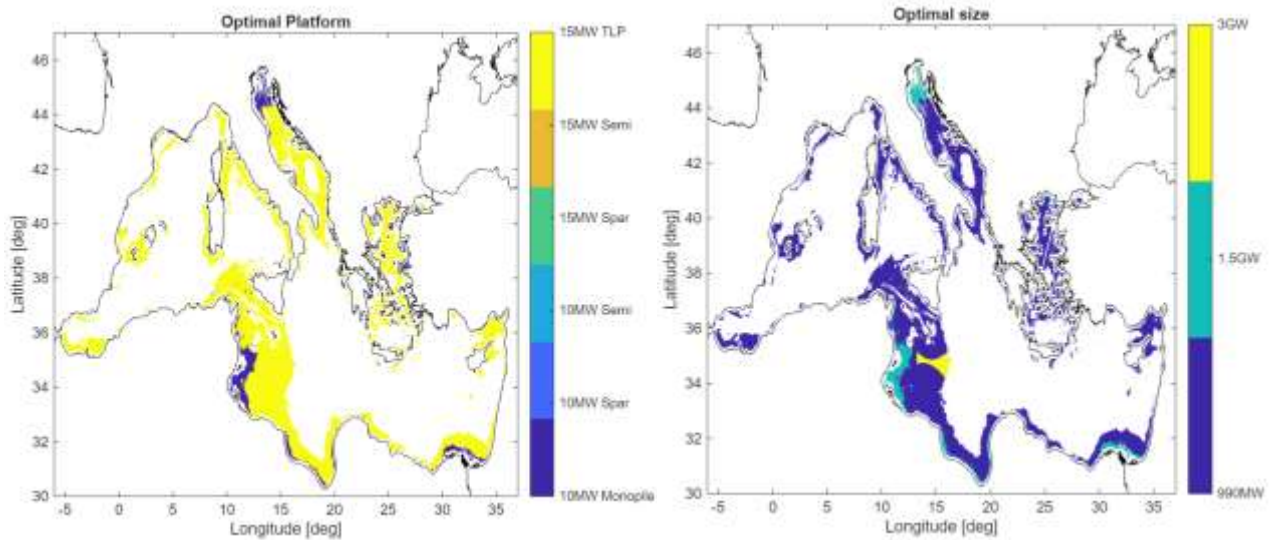


Figure 0-4 Platform (left) and size (right) corresponding to the minimum LCOE values for the radial layout.

For the star layout, the optimal results show lower AEP and higher LCOE compared to the radial, but with greater variability in the selection of farm size and turbine spacing. The maps (Figure 0-6) show that the optimal farm size is predominantly the largest option, 3 GW, while the selected spacing is mainly concentrated in the smaller values of 7 and 11 rotor diameters. This indicates that the star layout behaves less uniformly and is more sensitive to site-specific characteristics than radial or d-ring.

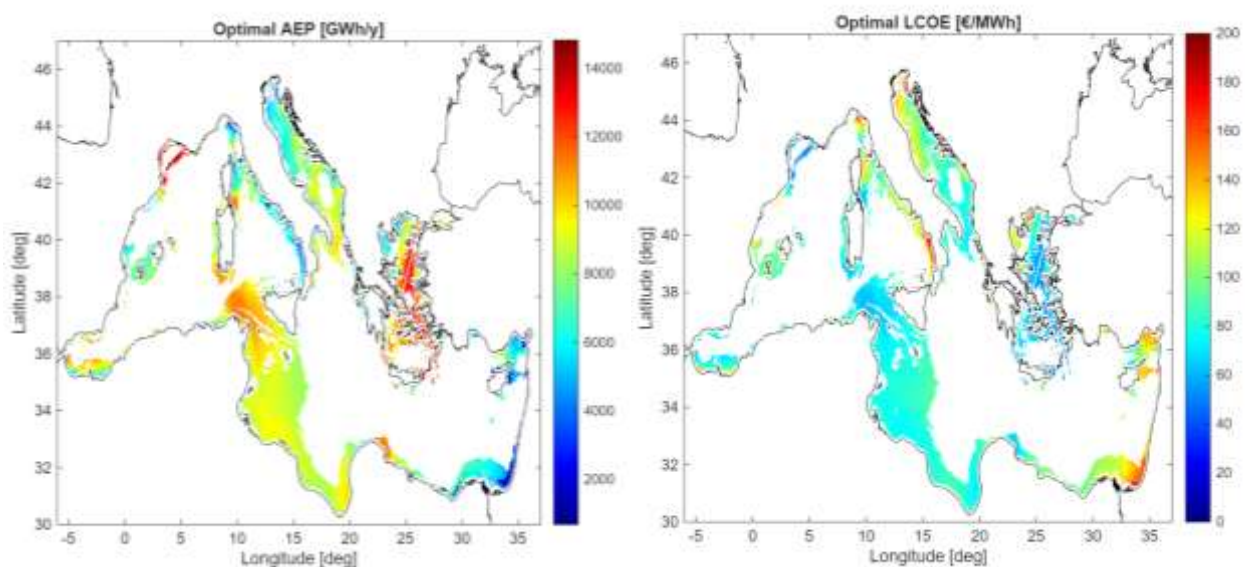


Figure 0-5 Optimal annual energy production (left) and levelized cost of energy (right) for star layout.

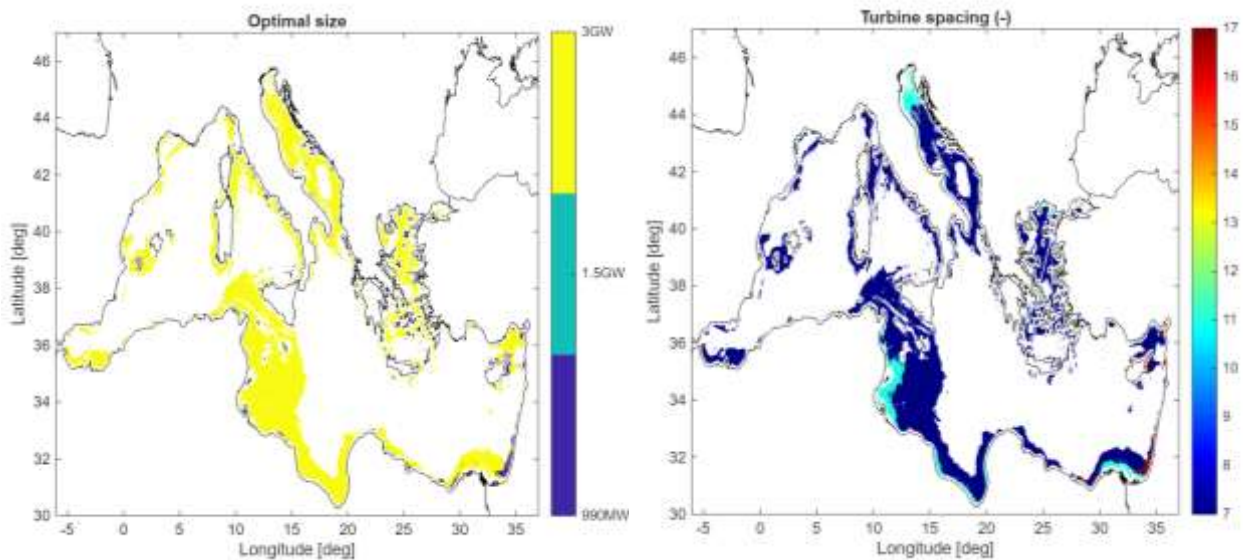


Figure 0-6 Size (left) and spacing (right) corresponding to the minimum LCOE values for the star layout.

Considering all configurations, the overall optimal results confirm that the radial layout is the most advantageous solution economically, consistently outperforming d-ring and star across all analysed points.

In parallel, an alternative analysis was conducted focusing on the maximization of the capacity factor. In this case, the results converge for the radial layout, with the platform distribution similar to that observed in the LCOE-based selection and maximum spacing chosen at each point. However, compared to the cost-based selection, the farm size is limited to 0.99 and 1.5 GW, excluding the 3 GW option. The associated figures show the maximum CF values, the LCOE corresponding to the CF-optimal configuration, and the selection of the optimal farm size, demonstrating that the radial remains the most robust layout even when the objective is to maximize energy yield.

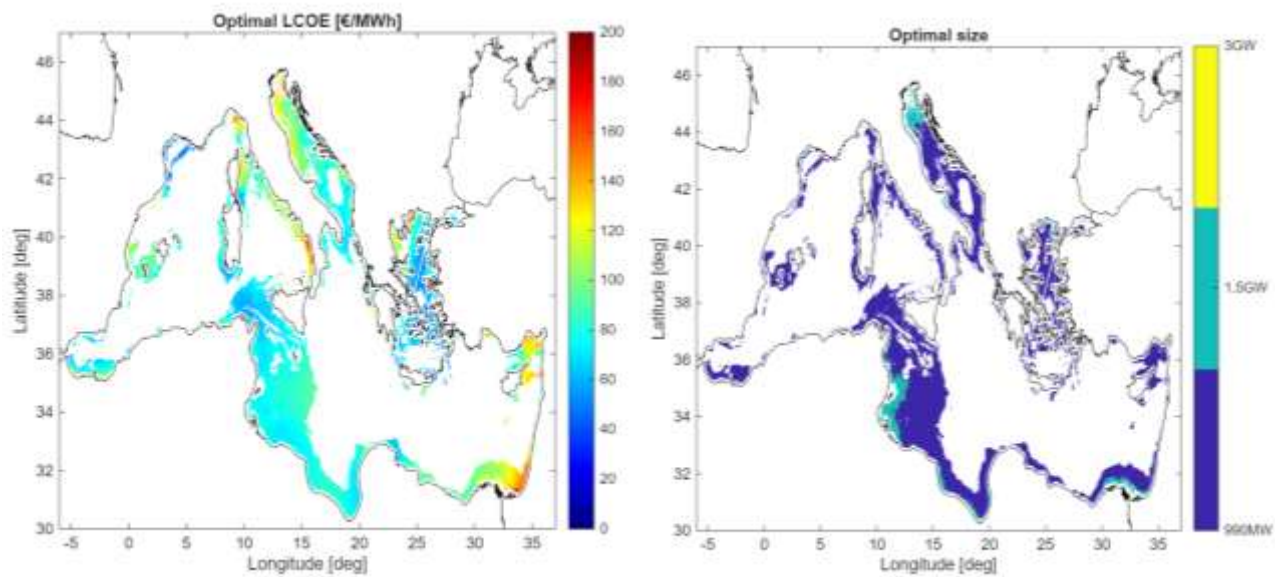


Figure 0-7 Levelized cost of energy (left) and optimal size (right) corresponding to the highest capacity factor.

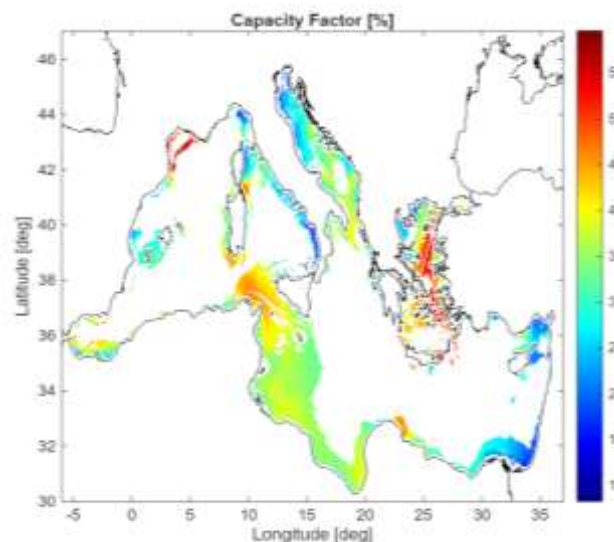


Figure 0-8 Maximum capacity factor obtained among all configurations.

In summary, the analysis confirms the central role of floating turbines for offshore wind development in the Mediterranean and identifies the radial layout as the optimal solution in terms of both economics and productivity. The star layout can offer localized advantages in terms of maximum energy output, but shows greater variability in design choices, while the d-ring represents a slightly less efficient variant of radial due to the additional costs of redundancy cables. The combination of LCOE-based and CF-maximization analyses provides a comprehensive overview of development opportunities, highlighting the areas and configurations most promising for future offshore wind farms in the Mediterranean.

Conclusions

The research and development of a techno-economic assessment tool for offshore wind farms has provided significant insights into the feasibility and economic viability of deploying offshore wind energy in the Mediterranean Sea. The transition from fossil fuels to renewable energy sources is imperative, and offshore wind energy presents a viable solution due to its technological readiness, low environmental impact, and abundant availability.

The methodology developed for the application of Maritime Spatial Planning constraints ensures a coherent and transparent approach to identifying suitable areas for offshore wind deployment, balancing energy production goals with environmental and societal priorities. This first analytical framework lays the groundwork for future spatial planning initiatives in the Mediterranean context.

In addition, the systematic definition of the Annual Energy Production and capacity factor, as presented in the second part of this work, offers robust metrics to evaluate energy performance. By integrating resource availability, wake effects, and operational constraints, the model ensures a realistic estimation of wind farm outputs.

The techno-economic model, explored in detail in the third section, evaluates both bottom-fixed and floating offshore wind solutions, providing key metrics such as the Levelized Cost of Energy and Capacity Factor. The life cycle costs of offshore wind farms, including Development Expenditures, Capital Expenditures, Operation Expenditures, and Abandonment Expenditures, have been thoroughly analyzed, with a compilation of all values and metrics provided. The capacity factor will require updates to reflect the availability of O&M operations and cable losses.

Supporting infrastructure, such as foundations, vessels, ports, and substations, plays a critical role in the successful deployment and operation of offshore wind farms. Insurance costs and market trends have also been considered, highlighting the importance of risk management and the potential for future cost reductions through learning rates.

Finally, a synthesis of the main results demonstrates the effectiveness of this comprehensive framework, supporting informed decision-making for offshore wind development in the Mediterranean Sea. By leveraging both bottom-fixed and floating turbine technologies, this tool aims to facilitate the transition to renewable energy and contribute to a sustainable energy future.

To conclude, recommendations for future work include:

- Developing a Monte-Carlo method for better availability accuracy of the O&M results, recognizing that the areas analyzed are vast and would require greater computational resources to achieve accurate averages across the mesh.



- Including industry data, which would increase the accuracy of CAPEX figures, current failure rates, and a better understanding of the actual differences among the foundation solutions. As floating substructures mature, more reliable data on their long-term performance will become available.
- Exploring O&M strategies incorporating robotics and autonomous vehicles, aligning with industry trends that aim to enable safer and more efficient maintenance, even under harsher weather conditions.
- Implementing a more detailed learning curve approach, not only applied to the resulting LCOE but directly embedded within the cost functions of the main economic parameters (CAPEX, OPEX, DECEX). This would allow a more granular estimation of cost reduction potential across the full life cycle of offshore wind projects.



Annexes

Annex 1 – DEVEX costs breakdown

Development and project management (FIXED)	142800	€/MW
Development and consenting services	59500	€/MW
Environmental impact assessments	9520	€/MW
Other (includes developer staff hours and other subcontract work)	49980	€/MW
Environmental surveys	4760	€/MW
Benthic environmental surveys	535,5	€/MW
Fish and shellfish surveys	476	€/MW
Ornithological environmental surveys	1190	€/MW
Marine mammal environmental surveys	1190	€/MW
Onshore environmental surveys	654,5	€/MW
Human impact studies	416,5	€/MW
Resource and metocean assessment	4760	€/MW
Structure	3570	€/MW
Sensors	773,5	€/MW
Maintenance	357	€/MW
Geological and hydrological surveys	4760	€/MW
Geophysical surveys	833	€/MW
Geotechnical surveys	2975	€/MW
Hydrographic surveys	952	€/MW
Engineering and consultancy	4760	€/MW
Other (includes lost projects that incur development expenditure)	64260	€/MW
Development and project management (FLOATING)	173918,5	€/MW
Environmental impact assessments	11900	€/MW
Development activities and other consenting services	69020	€/MW
Offshore species and habitat surveys	8330	€/MW
Onshore environmental surveys	1309	€/MW
Human impact studies	833	€/MW
Structure	3927	€/MW



<i>Sensors</i>	3213	€/MW
<i>Maintenance</i>	773,5	€/MW
<i>Geophysical surveys</i>	2856	€/MW
<i>Geotechnical surveys</i>	5593	€/MW
<i>Hydrographic surveys</i>	2142	€/MW
<i>Engineering and consultancy</i>	10472	€/MW
<i>Project management</i>	53550	€/MW

Annex 2 – Task description

Activity 2.3) Suitable areas in the Med basin for offshore wind farms will be selected based on the WebGIS developed and stakeholder interest. The WebGIS will provide a methodology and layers to identify the most suitable areas. The identification will be based on the constraints implemented, energy and technoeconomic scenarios, considering the distance to ports and electrical infrastructure. Offshore wind developers will also be consulted to identify key areas of interest and available technologies in the offshore wind market. Offshore wind turbines will be compared in terms of their performance and suitability for different bathymetry and metocean conditions. The feasibility of an offshore wind farm project will be investigated calculating key performance indicators such as the Levelised Cost Of Energy, Internal Rate of Return, capacity factor and Net Present Values. Therefore, a technoeconomic assessment is carried out to compare different offshore wind technologies. EDP will lead the activity.



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