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Master's Thesis

A Technology-Informed Accessibility Metric for Site Selection of Offshore Renewable Energy Systems:

A Case Study in Europe

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Abstract

The selection of appropriate offshore renewable energy system sites is essential for their economic viability, given the uncertainties surrounding their potential. While current site selection approaches primarily focus on energy potential, the impact of operation and maintenance (O&M) factors on the site's location is also critical. Traditional accessibility assessment metrics are limited for detailed accessibility evaluations, requiring the development of a novel, technology-informed metric that considers crucial factors such as metocean conditions, visibility, system failures, and O&M logistics. For this study, data on wave heights, wind speed and fog were collected from the European Centre for Medium-Range Weather Forecasts (ECMWF) database for the years 1959 to 2021, and matched with failure rates, vessel types, required repair times and sunrise/sunset times according to predefined criteria. Available time frames were then marked and counted as accessible times. The accessibility metric is calculated as a weighted average, with weights obtained from the downtime characteristics of each O&M activity. The study conducted an accessibility analysis across five different locations in Europe, revealing that limited visibility significantly reduces accessibility, resulting in up to a 60% reduction, while sea fog has less significant impact, contributing only up to a 5% reduction. Intra-annual and inter-annual variability, as well as the impact of different visibility factors, were graphically illustrated. The study also found that accessibility is inversely proportional to energy potential in most locations. Therefore, site selection should consider both energy potential and accessibility assessments, which is feasible with the proposed technology-informed accessibility metric. The metric's specific calculation methodology and weight distribution for each factor were thoroughly explained. The study's findings highlight the importance of accounting for O&M factors and accessibility when selecting offshore renewable energy system sites. Future research should explore additional sources of data and expand the accessibility metric's application to other regions and renewable energy systems. Additionally, more research is needed to validate the proposed metric's effectiveness in guiding site selection decisions.

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1. Introduction

Modern society has changed significantly over the last few centuries, with increased access to and consumption of energy. In the beginning, starting from the industrial revolution, energy production and consumption based solely on fossil fuels increased and diversified as new ways of utilizing energy resources were found.

As seen in Figure 1 based on Vaclav Smil's past estimates of primary energy consumption and updated figures from BP's Statistical Review of World Energy, the search for alternative energy sources starting with nuclear and hydroelectric after fossil fuels have continued in the last few decades with wind, solar, biofuels, and other renewable energy sources, and total energy consumptions has also been increasing [1], [2].

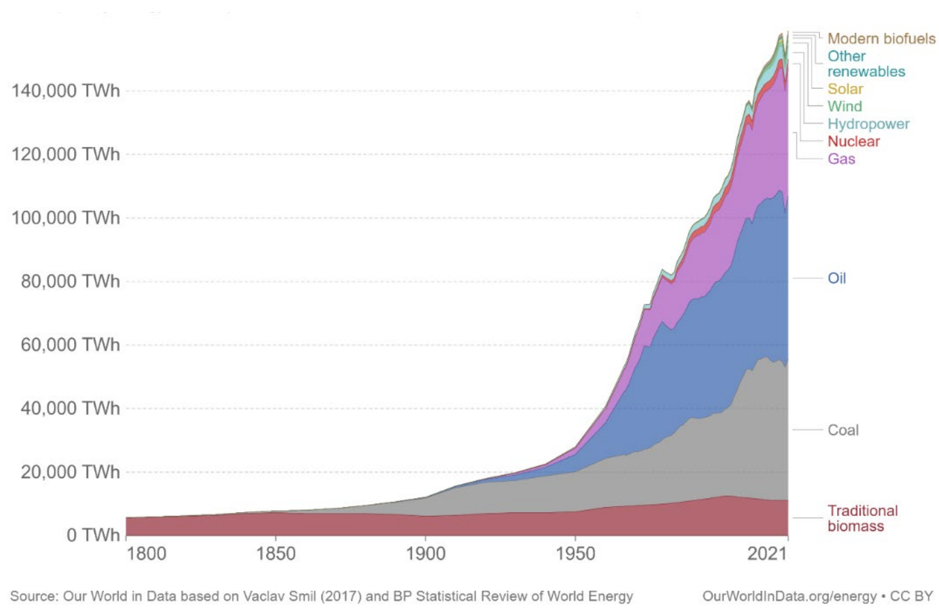


Figure 1. Global direct primary energy consumption [3]

From the Industrial Revolution to the present day, most countries have primarily relied on fossil fuels for their energy, which carries significant implications for the climate and human health. Burning these fuels for energy generates around 75% of global greenhouse gas emissions and contributes to high levels of local air pollution, causing at least 5 million premature deaths each year [4].

To mitigate the negative effects and lower CO2 emissions and local air pollution, the world must swiftly shift towards low-carbon energy sources, including nuclear and renewable technologies. Over the next few decades, renewable energy will serve as a critical tool in decarbonizing global energy systems, allowing us to reduce the use of fossil fuels and move towards a cleaner, healthier future.

In 2021, almost 17% (16.9% to be precise) of global primary energy consumption is from low-carbon sources, hydropower and nuclear makeup most of the low-carbon energy produced. For this statistic, low carbon sources are taken as the sum of hydroelectric, wind, solar, bioenergy, geothermal and nuclear energy and renewable energy sources including wave and tidal. 12.6% of this rate came from renewable sources and 4.3% from nuclear. Wind produces only 3% and solar 1.7%, but both sources are growing rapidly [5].

Although more energy is produced from renewable sources each year, coal, oil and gas still dominate the global energy mix. Not only does most of the energy, approximately 83%, come from fossil fuels, although fossil fuels produced each year are declining as a percentage: total production has increased from 124,665 to 136,018 TWh over the past 10 years.

The transition towards a more environmentally friendly and sustainable energy sector is only possible with using the use of offshore renewable energy systems. As the energy demands of the world increase, the need for new and innovative ways of energy production, delivery and distribution also increases. A promising solution for answering the increasing energy demands while reducing the harmful impact of the usage of traditional fossil fuels is offshore renewable energy systems. A couple of opportunities that can be provided with offshore renewable energy systems can be listed:

- Reducing dependence on fossil fuels by introducing alternatives such as wind, wave and tidal power. Particularly, offshore wind power has proven its potential to generate a significant amount of electricity to meet the increasing demand.
- Creating new jobs in a variety of areas such as engineering, manufacturing,

construction and maintenance. For example, to build and maintain an offshore wind farm, lots of workers, engineers, and operators are needed with different backgrounds.

- Lower carbon emissions by not burning fuels in the process of energy production, offshore renewable energy systems as all renewables can help reduce the amount of CO2 and other greenhouse gases that are released into the atmosphere.
- Improve energy security by providing a reliable and sustainable energy source as no country can claim natural resources such as sunlight, ocean waves and wind. Therefore, unlike fossil fuels which have price volatility and can be affected by geopolitical tensions, offshore renewable energy systems are more independent.

The European Commission published a specific EU strategy on offshore renewable energy (COM(2020)741) on November 19, 2020, which suggests concrete steps forward to support the long-term sustainable development of this sector. This strategy is intended to ensure that offshore renewable energy can help the EU achieve its ambitious energy and climate targets for 2030 and 2050. By 2030, the strategy aims to have at least 60 GW of offshore wind capacity installed, along with 1 GW of ocean energy, and by 2050, 300 GW and 40 GW, respectively [6]. To maximize its impact, the EU strategy on offshore renewable energy goes beyond a narrow definition of the factors of energy production and addresses broader issues, such as

- access to sea-space
- regional and international cooperation
- industrial and employment dimensions
- the technological transfer of research projects from the laboratory into practice

The European Green Deal can only be implemented with the use of offshore wind energy. By utilizing the enormous potential of the five EU sea basins, the installed offshore wind capacity in the EU, which was 14.6 GW in 2021, is expected to expand by at least 25 times by 2030 [6].

Although it seems better to benefit from wind energy in places where the potential is higher, the climatic conditions in these locations cause some problems that must be overcome to increase the economic feasibility, in terms of

- Accessibility rates. Since wave height and wind speed are strongly correlated, climatic conditions impact O&M operations by reducing accessibility [7].

- Probability of failure. The rated power of the offshore turbines is typically higher and combined with the higher wind speeds faults on the components become more likely [8], [9].

The availability of a wind turbine is defined as the percentage of time it can generate electricity [7]. The two parameters given above directly affect availability and are therefore important in determining the productivity of an offshore wind farm. With this definition in mind, we can say that downtime refers to instances when a wind farm or turbine is unavailable and results in a loss of electrical energy production. Although an increase in electrical energy output is expected from a wind turbine in proportion to the wind energy at the location of the wind farm, high wind speeds often mean an increase in failure and a decrease in accessibility which leads to lower availability.

The total efficiency of a wind farm can be increased by increasing the availability values through maintenance and inspections, which are known to be the cause of approximately 30% of the electricity energy price produced by wind turbines [8].

Based on all this, in order to obtain the maximum economic output from a wind farm, it is necessary to achieve high energy potential and availability together.

1.1 Economics of the Offshore Renewable Energies

The high costs associated with offshore technologies have been a major barrier to their widespread use. This cost can be summarized under 3 main categories.

1.1.1 Capital Expenditure (CapEx)

CapEx is short for Capital Expenditure, which refers to the initial investment that a company or organization invests in the purchase or improvement of its assets, such as buildings, equipment, and infrastructure. In the context of offshore renewable energy systems, CapEx refers to the costs required to build, install and commission the necessary infrastructure and equipment to generate energy from renewable sources, such as wind, tidal or wave power [10].

Offshore renewable energy systems require significant investment in both fixed assets and operational costs, such as the construction and installation of offshore wind turbines, underwater cables, substation platforms and other supporting infrastructure. These costs can be quite high due to the logistical challenges of building and maintaining offshore systems in harsh and remote environments.

CapEx in offshore renewable energy systems is generally higher than in onshore systems due to the additional challenges and risks associated with offshore development. These risks include the need for specialized vessels and equipment, unpredictable weather patterns and the potential for natural disasters such as hurricanes. Additionally, the cost of energy storage and transmission infrastructure, such as batteries and subsea cables can add significantly to CapEx. However, as the industry has matured, Capex has decreased, and it is expected to continue to do so in the coming years [11].

1.1.2 Operating Expenditure(OpEx)

Operating Expenditure refers to the ongoing costs associated with running and maintaining an asset or facility, such as salaries, maintenance, repairs, and other operational expenses. Offshore renewable energy systems require ongoing operational costs to ensure that they are functioning efficiently and safely. These costs include routine maintenance, repairs, and replacements of equipment, vessel chartering, logistics and transportation, and monitoring and control systems as well as costs for personnel, insurance and leasing fees. OpEx can also vary depending on the size and location of the wind farm [10].

OpEx in offshore renewable energy systems can be higher than in onshore systems due to the additional costs associated with maintaining infrastructure and equipment in a challenging offshore environment. For example, maintenance and repair costs may be higher due to the need for specialized vessels and equipment, longer travel times to offshore sites, and the potential for more frequent and severe weather events. In addition, the cost of maintenance and repair of underwater cables and substation platforms can increase OpEx.

1.1.3 Decommissioning Expenditure(DecEx)

Decommissioning Expenditure, also known as abandonment costs, refers to the costs associated with dismantling and removing an asset or facility once it has reached the end of its useful life. Offshore renewable energy systems have a finite lifespan, typically between 20-30 years, after which they must be decommissioned and removed. Decommissioning expenditure can include the costs associated with the removal of turbines, underwater cables, substation platforms, and other supporting infrastructure. These costs can be significant due to the logistical challenges of removing infrastructure and equipment from offshore environments [12].

Decommissioning expenditure in offshore renewable energy systems can be affected by factors such as the size and complexity of the installation, the location and accessibility of the site and the environmental and regulatory requirements for decommissioning. For example, the cost of decommissioning an offshore wind farm in a remote location with harsh weather conditions may be higher than a similar installation located closer to shore and in more favorable conditions.

1.1.4 Cost of Offshore Wind

Offshore wind energy is considered one of the most promising renewable energy sources and by now it is the most commercialized offshore energy source. It has immense potential to provide clean and reliable energy to the world. However, despite the potential benefits of ORE technologies, their development process is cautious due to the immaturity of some technologies and the challenging environmental conditions they operate in. The cost of offshore wind energy is decreasing every day. The average cost per kilowatt of electricity from offshore wind energy in 2021 was US$2,858. Considering that this cost was 5,584 US dollars 10 years ago, in 2011, it can be said that the costs have decreased significantly [13].

The primary focus of developers currently is to reduce the cost of energy (CoE) associated with these technologies. CoE is calculated based on Capital Expenditure (CapEx), Operational Expenditure (OpEx), and Decommissioning Expenditure (DecEx) as follows,

$$CoE = \frac{CapEx+OpEx+DecEx}{E_{gen}}, \quad (1)$$

where Egen determines the energy generation of the ORE farm. Therefore, to lower the CoE, it is necessary to reduce the Capital Expenditure, Operating Expenditure and/or DecEx and/or increase the Egen. This metric is also used in all other energy production technologies. However, aspects that are often neglected in onshore power generation technologies become important due to adverse offshore environmental conditions. In this sense, accessibility is the most critical element. Accessibility is the approachability of an ORE group and is defined as the normalized time during which access to a device is possible.

Situations, where environmental conditions do not allow to physically approach to the ORE farm, are called inaccessible. While the ORE farm is inaccessible, any possible commissioning, maintenance, or decommissioning tasks on the farm cannot be performed, which affects CapEx, the OpEx and the DecEx, respectively. Also, if one or more devices on the farm stop working due to a failure in any of its critical components, the inability to reach the farm can significantly increase system downtime and reduce availability and ultimately energy production. As a result of all these, the CoE will decrease. Figure 2 shows a schematic diagram of the main considerations regarding accessibility and impact.

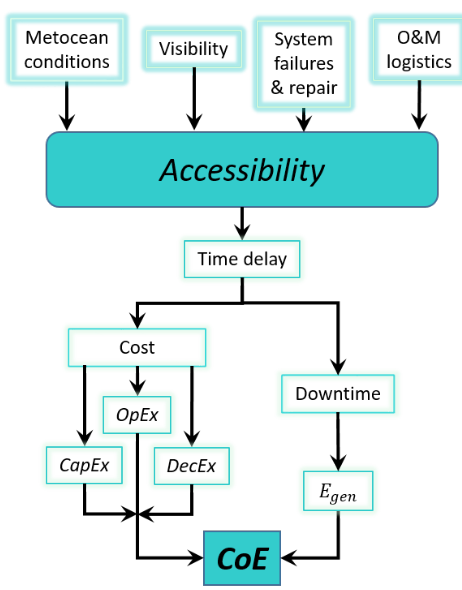


Figure 2. Visual Representation of the Relationship between Accessibility and Cost of Energy (CoE)

1.2 Critical Accessibility Aspects

Offshore Renewable Energy (ORE) farms are subject to varying environmental and weather conditions throughout their operational lifetime and assessing their accessibility is crucial for ensuring optimal performance. Accessibility is determined by converting temporal quantities into operational parameters, which is achieved through the use of weather windows (WWs). WWs refer to periods of time during which it is feasible to access the ORE farm. As shown in Figure 2, identifying WWs involves taking into account four critical factors: metocean conditions, visibility, system failures and repairs, and operations and maintenance logistics.

- Metocean conditions refer to the meteorological and oceanographic conditions that impact the accessibility of the ORE farm [14]. These may include wave height, wind speed and direction, and sea state. These conditions need to be favorable for accessing the farm, and safe working conditions should be ensured for workers [15].
- Visibility is another important factor to consider when identifying WWs. Reduced visibility due to fog, mist or other weather conditions can lead to unsafe working conditions and can impact the accuracy of equipment and data collection. Thus, WWs need to be identified when visibility is adequate for accessing and working on the farm.
- System failures and repairs also affect the accessibility of ORE farms. WWs need to be identified when the risk of system failures is low, and when repairs can be carried out effectively. Identifying WWs when the risk of system failure is high, or during periods when repairs cannot be carried out, can result in reduced accessibility.
- Finally, operations and maintenance logistics should also be considered when identifying WWs. This includes the availability of personnel and equipment needed to carry out operations and maintenance, as well as transportation to and from the ORE farm.

These factors will be discussed in more detail below.

1.2.1 Metocean conditions

The specific variables of a location such as wind, wave and climatic are referred to as the metocean conditions [14]. These conditions play a crucial role in assessing the potential for deploying Offshore Renewable Energy (ORE) farms. In particular, wave and wind conditions are two main factors that are commonly considered when analyzing both the accessibility and energy yield of an offshore wind farm. These conditions may affect the economic viability of offshore wind energy as a source of renewable electricity by reducing or increasing the energy yield and accessibility, thus affecting the income generated by offshore wind farms.

Some of the main concerns related to wave and wind conditions include:

- The limit of significant wave height (H_s) for transferring technicians and material from vessels to turbines;
- The limit of H_s for performing operation and maintenance (O&M) interventions using jack-up barges;
- The limit of wind speed (U_w) for performing O&M operations, especially for lifting operations during major repairs and replacements;
- The impact of $U_w$on power production.

1.2.2 Visibility

Visibility is a critical factor that can significantly limit O&M operations in offshore renewable energy (ORE) farms. However, it is a complex phenomenon with various characteristics and nonlinear relationships between them, making it challenging to include it in studies.

Visibility refers to the distance at which an object can be distinguished from its background, and different factors can limit it during O&M interventions, such as daylight, meteorological conditions, air quality, direct obstruction of the view, and poor design of O&M vessels [16]. Defining visibility in a determined location and time becomes a complex task, and the most relevant factors are daylight hours and meteorological conditions [17]. Daylight hours are the number of hours when natural light enables correct visibility without artificial light, and the geographical location and season of the year are the main drivers of daylight hours [7], [17].

Meteorological conditions, including heavy rain and sea fog, which produce situations with a visibility of less than 1 km, are important hazards in offshore and maritime industries [18]. The combination of daylight and sea fog is used to define the weather windows in which operators could access the ORE farm and perform the required O&M task.

1.2.3 System failures and repair

The final cost of energy (CoE) for wind farms is greatly affected by the frequency of breakdowns and the expenses incurred for repairs, including material costs and labor. To minimize these costs, offshore wind farms are established with turbines that have low failure rates and are easy to maintain [8]. However, offshore wind turbines are more prone to failures compared to onshore turbines due to several additional factors. For instance, offshore locations usually experience higher winds, leading to a higher probability of failure. Also, offshore turbines have higher-rated power and larger size, which are known to increase failure rates. The harsher offshore environment is another factor that contributes to the higher failure rate [8], [9], [19].

Accessibility and failure rate are two concepts that are commonly studied separately, but it's crucial to consider them together as they are interdependent. For instance, failure rates can decrease if accessibility is high and routine maintenance tasks are performed on time. In this regard, accessibility can be calculated depending on when it is required to prioritize turbines that have lower failure rates. The duration of the weather window (WW) is defined based on the onsite repair time, which varies for each component and type of failure. Therefore, it's essential to have a comprehensive accessibility metric that articulates failure and maintenance information for effective wind farm management.

1.2.4 O&M Logistics

The success of O&M operations in offshore wind farms is closely related to the accessibility of the farms. The O&M logistics depends on several factors, including the type and availability of O&M vessels, the labor crew, the surrounding ports' geographical location and capabilities, and the availability of spare parts. The operational limits of the vessels, the trip time to the ports, and the availability of the crew and spare parts are all factors that determine whether an O&M intervention can be performed or not.

The distance between the offshore wind farms and the port also affects the accessibility values, as sites that are farther away require longer weather windows for safe travel to the turbines, completing maintenance, and returning to shore. Of two different wind turbines with the same parameters except for the distance from the shore, a higher accessibility value can be expected in the one closer to the shore.

The type of vessel to be used for O&M operations depends on the type and size of the job to be done. For example, smaller repair jobs may require a catamaran-type CTV, while more comprehensive maintenance jobs that involve larger parts may require different types of vessels with cranes. However, each vessel type has its wave and wind limits to transport technicians and work equipment to the desired region, which restricts accessibility according to these thresholds.

1.3 Literature Review

Various studies in the literature have presented site selection studies for different offshore wind turbine(OWT) technologies and farms. These studies typically use techno-economic models that take into account both the energy potential and the different factors related to the CapEx across a predefined area, but they often neglect or only partially consider O&M aspects [20]–[23]. Alternative metrics, such as the exploitability index, have also been suggested for identifying promising locations, but they too neglect the O&M aspect [24]. Despite the acknowledged importance of availability and accessibility to OWT farms, existing studies have been shown to overlook them when assessing potential deployment locations. For a proper assessment of possible installation sites, the study should at least include an estimation of both accessibility and the power density of the area or location under study. However, there is currently no comprehensive metric that effectively incorporates a surrogate indicator for accessibility.

Among the studies available in the literature, those focusing on accessibility can be divided into two groups: technology-agnostic and technology-informed studies. Technology-agnostic studies evaluate a broad range of metocean conditions, but they do not take into account technology-specific information, such as the type of O&M interventions, their duration, the type of vessels, and their operational limitations [25]–[29]. In contrast, technology-informed studies consider specific technology-related information [7], [30]–[33]. Table 1 summarizes the main characteristics of the different approaches suggested in the literature.

Table 1. Overview of Key Features in Accessibility Assessment Studies from the Literature

			[29]	[25]	[26]	[27]	[28]	[7]	[30]	[31]	[17]	[32], [33]		Present Study
# O&M interv. [a]	Isolated	Single	N/A[c]					mr/Mr[a]	Mr[a]	-	-	-		-
		multiple						-	-	mr/Mr/MR	mr/Mr/MR	mr/Mr/MR		
	Combined		-					-	-	-	-	-		mr/Mr/MR
Critical access. aspects	Metocean conditions	H_s	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
		U_w	✓	✗	✗	✓	✗	✓	✓	✓	✗	✗		✓
		Combined	✓	✗	✗	✓	✗	✓	✓	✓	✗	✗		✓
	Visibility	Daylight	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗		✓
		Fog	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗		✓
	O&M logistics	CTV-like	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓		✓
		FSV-like	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓		✓
		HLV-like	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓		✓
Geog. Area	Number of isolated deployment site(s)		Two sites (North Sea - UK)	Two sites (North Sea - UK)	Two sites (West Ireland - UK)	Three sites (Portugal)	One site (South England - UK)	-	Three sites (UK)	NL7 site (Dutch coast)	15 sites (North Sea - UK)	Three sites (Portugal & Adriatic & North Sea - UK)		Five sites (Section 3.1)
	Spatial area		-	-	-	-	-	North Sea	-	-	-	-	-	-
Temporal range	Short-term[b]		-	1992-93 2006-08	2003-05	2000-09	-	-	-	9 years	-	-	2000-09	-
	Long-term[b]		1989-2010	-	-	-	1989-2011	1990-2012	19-21-34 years	-	1990-2019	2000-19	1995-2019	1959-2021
	Intra-annual analysis		✓	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓

[a] *mr, Mr and MR refer to minor repair (2h to 7 h), medium repair (7h to 24h) and major repair (>24h), respectively* [17]

[b] *Short- and long-term refer to temporal ranges that are below and above 10 years, respectively*

[c] *No specific information is reported with respect to O&M interventions, but a wide range of different possibilities are studied instead*

Studies that focus on accessibility in a technology-agnostic manner fail to provide a comprehensive perspective because they overlook at least one of the three important environmental factors: wave height (H_s), wind speed (U_w), and visibility. Some studies [25], [26], [28] solely examine Hs, while others [27], [29] evaluate both H_s and U_w, but none of them take into account visibility. These studies generalize accessibility for various metocean conditions, O&M intervention duration and operational limits, but fail to relate this information to any technology-specific aspect, resulting in a lack of specific characterization.

On the other hand, technology-informed accessibility studies incorporate specific information about O&M interventions into the analysis. These interventions are categorized as minor repairs (2 to 7 hours), medium repairs (7 to 24 hours), and major repairs (over 24 hours), as suggested by [17]. The most comprehensive accessibility assessment among these studies is presented in [7], where all critical aspects except sea fog are considered in the assessment of accessibility across a large area in the North Sea. However, this study is limited because the two types of O&M interventions included in the analysis are characterized by an 8-hour weather window, and no interplay is assumed between them. As a result, no comprehensive accessibility metric is provided that considers either the overall offshore wind turbine (OWT) or the OWT farm. A simplified version of such an approach is presented in [30], where the accessibility assessment is exclusively focused on a single O&M intervention without considering visibility aspects. Minor, medium, and major repair interventions are evaluated in [17], [31], although, as in [30], visibility aspects are ignored. Some studies [17], [30], [31] assess the same O&M logistics features related to Crew Transfer Vessel (CTV)-like vessels, which are not appropriate for medium and major repair interventions. Thus, none of these studies provides a holistic perspective required to properly assess the accessibility of a potential deployment site.

Other studies consider failure and repair characteristics of critical components, but the techno-economic models employed for such analyses are computationally prohibitive for a site selection study [34]. However, an alternative analytic model with similar precision but a significantly lower computational cost is presented in [33], which has the potential to be used in a site-selection process. Yet, only Hs is considered among all the critical accessibility aspects. In any case, the preliminary analysis undertaken in [32] demonstrates that availability can have a significant impact on the final energy generation, with energy losses of up to 35%.

1.4 Motivation

Developing a comprehensive accessibility assessment methodology is critical during the site-selection process for Offshore Wind Turbine (OWT) farms. High accessibility, estimated to be around 80% according to literature, is crucial in achieving a wind farm availability of 90%, as failures are inevitable [31]. In addition, O&M costs in Offshore Renewable Energy (ORE) farms represent up to 30% of the final cost [8], [35]. Despite this, there has been no precise metric suggested in the literature to assess accessibility comprehensively.

Recent research has focused on developing a technology-agnostic methodology that provides accessibility information based only on metocean data. However, this methodology is insufficient as the required infrastructure for each O&M task highly depends on the specific characteristics of each technology. To address this issue, a MATLAB code was developed to calculate a single accessibility metric for any area in the world, considering different vessels and failure types.

This new calculation method offers valuable information that can be used to strategically develop offshore wind farms, guiding location, logistics, O&M planning, and the assessment of climatic variables specific to the chosen region. The code takes into account visibility, failure type, and vessel type, factors that were not collectively considered in previous studies. As an example, the northern seas, which have a significant share in the offshore wind energy sector, are often affected by fog, which significantly affects visibility. Additionally, the previously used fixed time intervals for weather windows (WW) are variable, depending on the nature of the work to be done. In conclusion, the MATLAB code developed in this study offers a comprehensive and accurate accessibility assessment methodology for OWT farms, providing a reliable guide in strategic decision-making.

2 Methodology

The technology-informed approach involves significant difficulties in synthesizing different components and their maintenance requirements, including failure and repair characteristics, in a single metric. Regardless, this study suggests a comprehensive single metric that is a combination of the overall set of critical accessibility aspects and O&M operations, as seen in Table 1.

This novel metric will enable assessing a site with respect to the energy potential and accessibility characteristics, thus assisting the corresponding planners and decision makers in the site selection process. The standard method for quantifying accessibility in ORE farms involves calculating an approachability parameter, which is the ratio of the time that the farm can be accessed to the total amount of time. Typically, the total time corresponds to the farm's lifetime (T_m), and the accessibility is expressed as a percentage of the lifetime when it is possible to access the farm.

$$A_{ta_j} = \frac{\sum_{i=1}^{N_i} t_{WW_i}}{T_m}, \quad (2)$$

where N_i is the number of valid WWs. However, the requirements of the valid WW are defined using specific operational limits (H_s^{lim}, U_w^{lim}, v_f^{lim} and v_s^{lim}) and repair and trip times. Only if all these conditions are fulfilled along the considered time frame (t_i), the WW is considered as a window in which accessing the farm is feasible (WW_i). Otherwise, the farm results inaccessible, meaning that the O&M personnel needs to wait until all conditions are fulfilled, so the time frame is considered as a waiting time (WT_i). However, each type of component and/or fault requires different operational limits and repair/trip times, meaning that the accessibility metric obtained for each combination of these parameters will be different. Therefore, the traditional accessibility metric is referred to as the technology-agnostic metric (A_{ta_j}), and is not capable of providing a single comprehensive metric for a specific technology and location.

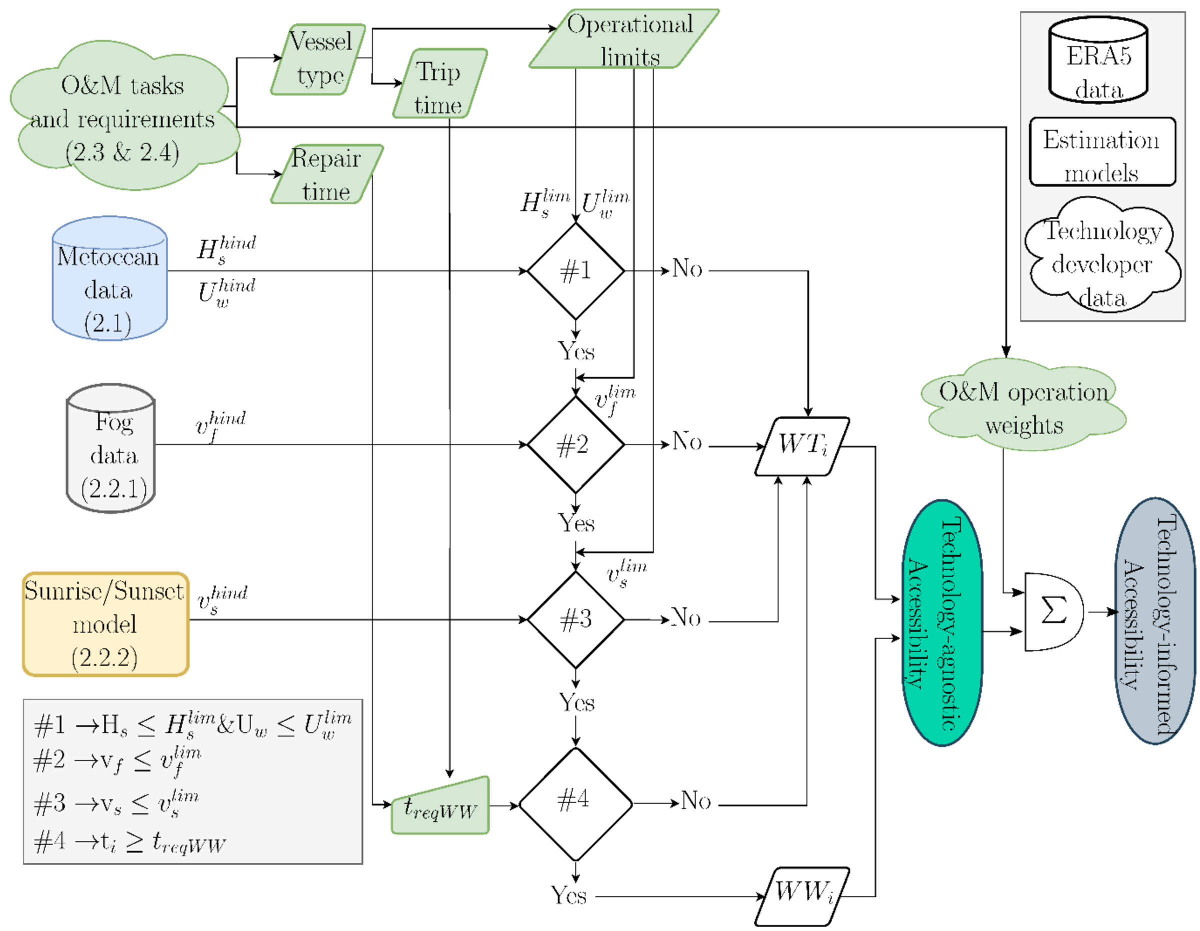


Figure 3. Proposed Accessibility Metric Framework: An Illustrative Overview with Section References

To calculate a comprehensive metric for a specific technology, it is necessary to synthesize the complete range of possible O&M interventions required. This includes various combinations of operational limits and repair/trip times that must be integrated into a single value. To accomplish this, the current study proposes a technology-informed accessibility metric that is based on the weighted average of these potential combinations as follows,

$$A_{ti} = \sum_{j=1}^{M_j} \omega_j \times A_{ta_j}\,, \tag{3}$$

where M_j is the total number of considered O&M tasks and ω_j stands for the weight of each of such interventions. The definitions of these weights are given in Section 2.4 and evaluated in Section 4.3.2. The visual representation of the algorithm is presented in Figure 3. It is divided into two distinct metrics, technology-agnostic and technology-informed. The upcoming sections will provide a broad overview of each model, including an explanation of the three conditions (#1, #2, and #3) that must be fulfilled to confirm a valid WW. These conditions are specific to metocean conditions, sea fog, and daylight restrictions, respectively.

2.1 Weather Window modeling with metocean data

The typical method of identifying suitable WWs for O&M tasks involves only H_s data, as presented in Figure 2. The process involves examining the hindcast dataset to locate consecutive data points below the H_{lim} threshold, removing any windows that do not meet the required window length (t_{WW_i} > t_{reqWW}), and calculating the length of each valid WW_i [7]. This process is visualized in Figure 4. However, accessibility is not solely limited by H_s, and an assessment that relies exclusively on H_s may result in an overestimation of actual accessibility. Some studies have incorporated both H_s and U_w constraints, requiring a valid WW to meet both H_s^{lim} and U_w^{lim} criteria, which can considerably reduce accessibility assessments. Figure 5 depicts the impact of including H_s & $U_w$in the evaluation process. Assuming a required window length of t_{reqWW} = 3 h, three window types are observed: the red window is too short to be usable, even when considering only H_s; the orange window becomes impractical when incorporating H_s & U_w constraints; and the green window is the only valid WW.

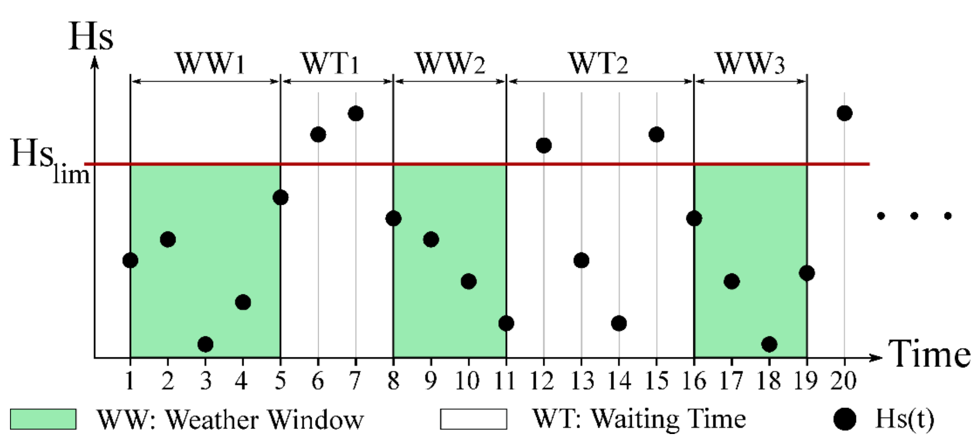


Figure 4. Weather Window identification based on only H_s^{lim} [33]

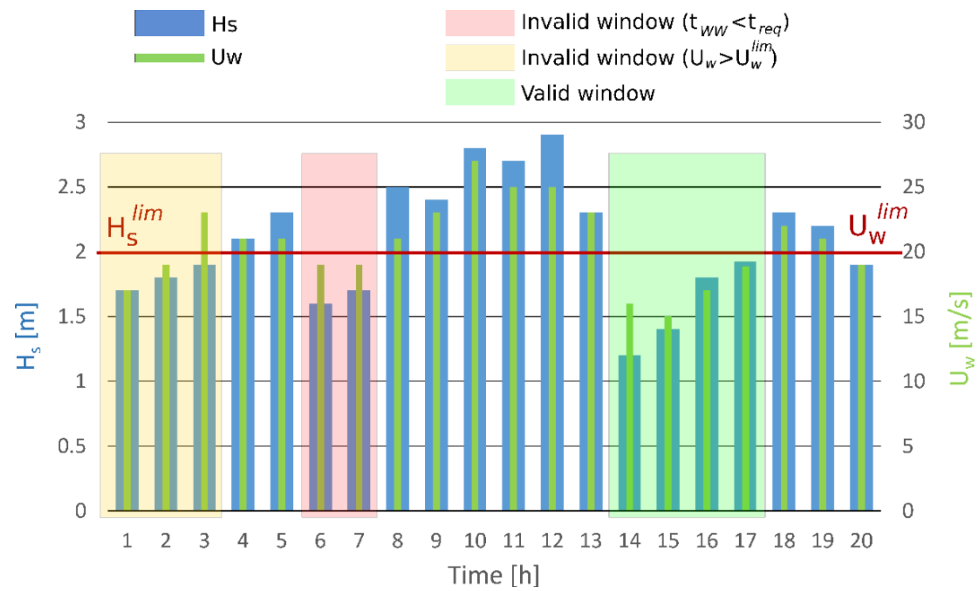


Figure 5. Illustrative Depiction of the Weather Window Identification Process

2.2 Visibility model

Visibility is a crucial factor that impacts the accessibility of offshore operations. O&M tasks become infeasible with low visibility, regardless of the metocean conditions. Unfortunately, studies presented in the literature tend to neglect the significance of visibility, as demonstrated in Table 1. Natural factors such as fog, heavy rain, lightning, and the absence of sunlight all contribute to limited visibility and can slow down the work or limit security. In this study, sunlight and fog factors are considered in accessibility calculations, given their significant impact at various stages of O&M operations. Sunlight is directly related to visibility, and in exceptional cases, artificial lighting may be used. Additionally, fog can be explained as the subproduct of the liquid water content in clouds, further aggravating visibility challenges.

2.2.1 Sea fog estimation

In this study, sea fog was identified as a major obstacle in performing offshore maintenance tasks due to its impact on visibility [18]. However, accurately modeling sea fog is challenging, as it depends on several factors, including cloud liquid water content. To address this, a threshold of 0.004 g/kg at 1000 hPa was determined based on previous studies in the maritime industry [18],

[36], and incorporated into the fog calculation using ERA5 reanalysis data. Non-foggy hours were identified using MATLAB code when the cloud liquid water content was below this threshold. As shown in Figure 3, this operational limit is included in the metocean data by adding an extra condition for identifying a valid weather window, ensuring that the impact of sea fog is considered during offshore maintenance operations.

2.2.2 Sunlight Estimation

In this study, the historical hours of daylight for a selected location were found using the solar calculator provided by the National Oceanic and Atmospheric Administration (NOAA) [37], which, itself, is based on equations from Astronomical Algorithms developed by Jean Meeus [38]. The model provides daily sunrise and sunset times, as well as both sun declination and elevation, to estimate sunlight duration over an arbitrary time period at a generic geographical location defined by longitude and latitude. This model is theoretically accurate, with an error of less than a minute for latitudes between $\pm 72^\circ$ and up to 10 minutes beyond the $\pm 72^\circ$ limit [37]. However, it should be noted that the estimation model is sensitive to the variation in atmospheric composition, which may cause the observed values to vary from the estimations. In any case, for the sake of simplicity, only sunlight hours were considered adequate for O&M operations in this study, neglecting the potential assistance of artificial illumination. Additionally, factors such as cloud density, rain, and direction of sunlight were not included in the evaluation, assuming that it was completely bright after sunrise. Figure 6 (a) and (b) illustrate the estimation of sunrise/sunset time and sunlight duration for a generic yearly period in the North of Spain, respectively.

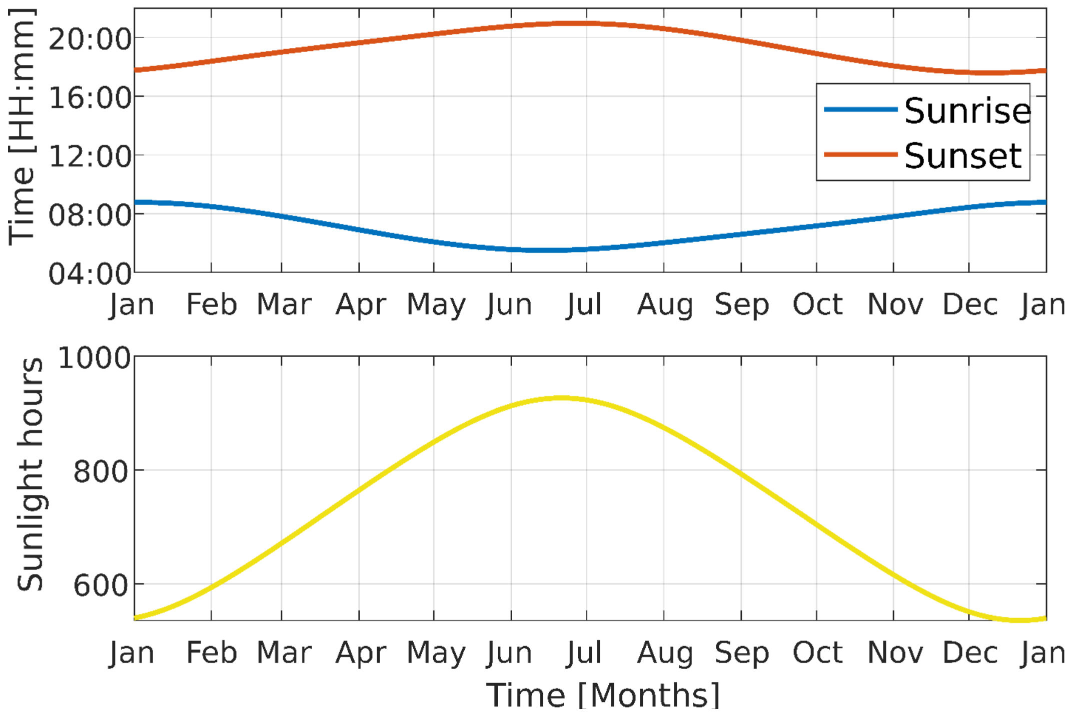


Figure 6. Sunlight Estimation Model Results: a) Annual Sunrise and Sunset Times and b) Duration of Sunlight Throughout the Year

2.3 O&M vessel classification

In O&M operations, the selection of assets is crucial for the success of the interventions, and among all the assets, vessels have the most significant impact on accessibility. The vessels used in O&M are classified into three groups depending on the type of intervention they perform. The Crew Transfer Vessel (CTV) is used for the transportation of operators, spare parts, and tools and for minor O&M tasks. The Field Support Vessel (FSV) is designed for medium O&M interventions, while the Heavy Lift Vessel (HLV) is proposed for major O&M operations that require large cranes mounted on the vessel to perform operations at higher altitudes [8], [34]. The operational limits of these vessels define the thresholds for the metocean data, as shown in Figure 3. The types of vessels used for maintenance and inspections in offshore wind turbine farms vary depending on the component to be repaired or replaced.

Table 2. Characteristics of O&M Vessels: operational limits [34]

Type of Vessel	H_s^{lim} $[m]$	U_w^{lim} $[m/s]$
CTV - like	2.5	30
FSV - like	1.8	30
HLV - like	1.5	25

Figure 7. O&M Fleet Vessel Categories: Visual Examples of a) Crew Transfer Vessel (CTV) [39]*, b) Field Support Vessel (FSV)* [40]*, and c) Heavy Lift Vessel (HLV)* [41]

2.4 Failure classification

Another crucial aspect of assessing the accessibility of offshore wind turbines is understanding the failures and repairs that may occur. However, the complexity of these turbines can make this analysis challenging. To address this, a classification system has been proposed in [8] which components are grouped based on similarities in failure rates, repair times and O&M requirements. This allows for a manageable amount of data to be used in assessing the technology-informed metric, which combines three types of O&M interventions weighted by failure rates or downtime caused by failures.

In addition, studies have analyzed the frequency and type of failures in offshore wind turbines and categorized them based on the equipment, labor, and other expenses necessary for repairs. This information is then used to determine the time and equipment needed for repairs. Table 3 provides statistical data on these failures, which can be used to calculate the required maintenance operations for a hypothetical wind farm at any location. By incorporating this information into accessibility assessments, O&M strategies can be optimized for each turbine. For further details on the definition of the parameters shown in Table 3, the reader is referred to [8].

Table 3. Categorization of Operational Types: Incorporating Failure and Repair Data, and Vessel Requirements [8]

Type of Operation	Minor Repair	Medium Repair	Major Repair
Failure-rate (λ) [/turbine/year]	6.81	1.17	0.29
Repair-time (μ) [hours]	6.67	17.64	116.19
Vessel type	CTV	FSV	HLV

3 Case Study

The case study aims to evaluate and analyze the accessibility of offshore wind energy resources across various European waters. To achieve this objective, five distinct locations have been strategically selected to represent a wide range of metocean conditions, wave heights, wind speeds and other relevant environmental factors. This careful selection of geographic areas is crucial for obtaining representative findings that reflect the vast range of offshore wind environments throughout Europe.

The methodology employed in this thesis involves the use of two distinct types of metrics: technology-agnostic metrics and technology-informed metrics. Technology-agnostic metrics allow for a broader understanding of the general accessibility of offshore wind resources, independent of specific technological constraints or limitations. This high-level perspective is important in gaining insight into the potential for offshore wind development across the chosen locations.

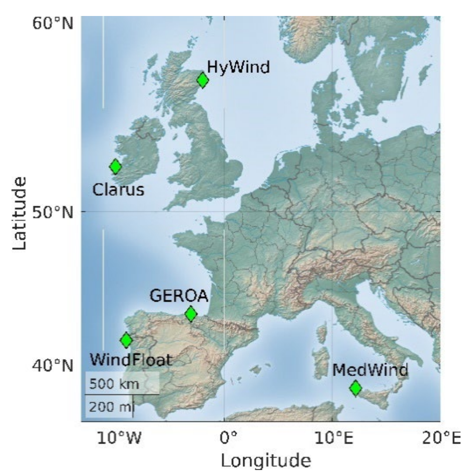
Conversely, the technology-informed metrics in this thesis take a more focused approach by analyzing data collected from approximately 350 offshore wind turbines, all manufactured by a leading industry player. The turbines included in this study have been in operation for a period of 3 to 10 years and are distributed across 5 to 10 wind farms throughout Europe. This comprehensive dataset comprises more than 1,768 turbine-years of operational data, encompassing various aspects of offshore wind technologies such as performance, efficiency, and reliability, as well as other crucial factors like maintenance requirements, costs, and environmental impacts [8].

By incorporating these real-world insights from a significant sample of offshore wind turbines, the technology-informed approach effectively represents a generic offshore wind case. A more accurate evaluation of the possibilities for offshore wind projects in the area is made possible by this extensive and detailed take on the accessibility of European waters for offshore wind energy development.

3.1 Geographical Locations

Five strategic locations have been meticulously chosen based on their relevance to the offshore wind energy sector in European waters. Both offshore wind farms that are already operational and those that are in the development or early deployment stages are included in these locations. The five locations include the lower Atlantic Ocean, along the Portuguese coast; the upper Atlantic Ocean, off the western coast of Ireland; the North Sea, near the northeastern coast of Scotland; the Mediterranean Sea, specifically the Tyrrhenian Sea in Italy; and the Gulf of Biscay, adjacent to the Basque coast. Comprehensive information on the wind farms deployed or planned in these areas is compiled and presented in Table 4.

Table 4. Geographical Positions and Development Stages of Selected Wind Farms

Wind Farm Name	Country	Project Phase	Latitude	Longitude	**Map**
Kincardine Hywind	Scotland	Fully Commissioned	57.2° N	2° W	
MedWind	Italy	Concept/ Early Planning	38.3° N	12.2° E	
GEROA	Basque Country	Fully Commissioned	43.5° N	3.1° W	
WindFloat	Portugal	Fully Commissioned	41.7° N	9.1° W	
Clarus	Ireland	Concept/ Early Planning	52.6° N	10.1° W	

3.2 Metocean Data

For each of the five selected locations, metocean data has been obtained from the ERA5 reanalysis dataset, the fifth generation of ECMWF reanalysis for global climate and weather. This dataset encompasses a comprehensive range of atmospheric, oceanic and land-surface parameters, offering a high level of granularity for both spatial and temporal analysis [42]. The data covers a 60-year period between 1959 and 2019 and includes significant wave height (H_s), wind speed (U_w)

at 100-meter height, cloud liquid water content at 1000 hPa pressure level, mean wave direction and other variables. Additionally, sunlight hours have been estimated for each location to provide a more complete understanding of the environmental conditions at each site. The ERA5 data used in this study has a spatial resolution of 0.25° in both latitude and longitude and a time resolution of 1 hour, spanning from 1959 to 2019.

In order to assess the logistics of operations and maintenance (O&M) activities, the closest harbors from which O&M vessels are expected to depart have been identified for each location. This information enables the calculation of the distance from the wind farm to the port and the estimation of trip time as a function of the cruise speed of each vessel. It is important to note, however, that the specific capabilities of each harbor are not considered in this analysis, assuming that all harbors can accommodate all types of O&M vessels and interventions.

3.3 ORE Technology

In this thesis, data obtained from the study performed by [8] is employed to analyze the failure rates of wind turbines, placing special emphasis on around 350 offshore wind turbines spread across numerous European regions. The analysis not only determines the failure rates but also reveals the particular components that cause these failures. Furthermore, the duration required for repairs, the average expenses involved in repairing, the number of technicians needed, and the essential equipment for completing these repairs are carefully examined.

3.3.1 Power generation characteristics

The study referenced for this analysis [8] focuses on offshore wind turbines that have been in operation for a duration of 3 to 10 years and are distributed among 5 to 10 separate wind farms situated across various European countries. The comprehensive dataset collected for this investigation comprises more than 1768 turbine years of operational data, providing a significant sample size for assessment.

Due to the need for maintaining confidentiality, certain specifics, such as the exact number of wind farms and turbines involved, the nominal power of the turbines, the blade size, and the drivetrain configuration of the turbine types utilized in the analysis are not disclosed. However, it has been mentioned that the turbines being examined are modern, multi-megawatt units, all sharing identical blade sizes and nominal power capacities.

To offer a general idea of the turbine dimensions, it is stated that the rotor diameters fall within a range of 80 meters to 120 meters. Additionally, the rated power of these turbines varies between 2 and 4 megawatts.

3.3.2 Failure data and classification

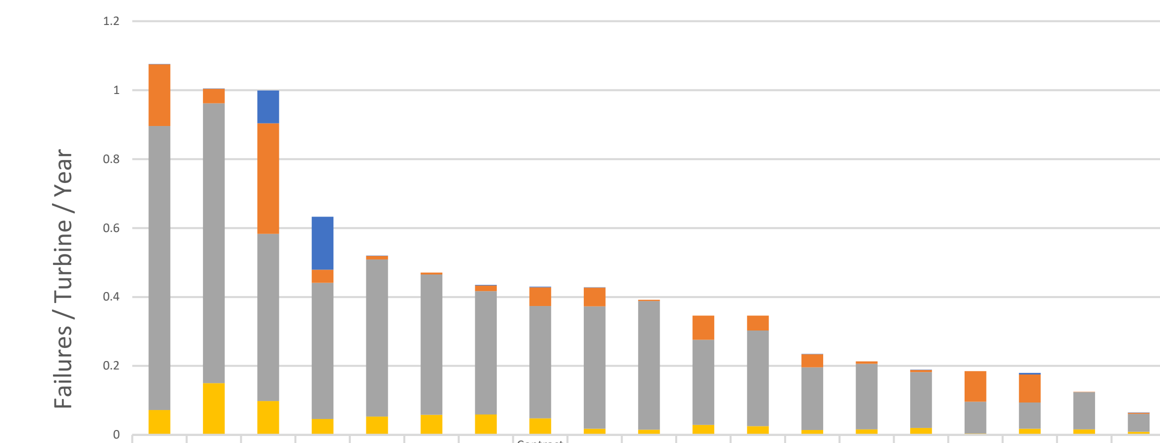
In the wind energy industry, there is no universally agreed-upon definition for a fault. Nevertheless, according to the source cited as reference [8], a fault can be described as any task requiring access to the turbine and the use of materials beyond the scope of planned operation. This definition excludes failures that can be resolved through remote, automatic, or manual restarts. Furthermore, the definition does not impose any restrictions on the type or size of materials employed, encompassing everything from small consumable items like carbon brushes to large pieces of equipment such as generators.

For the calculation of the failure rate, the total number of failures across all periods per turbine is divided by the sum of all time periods in hours and then divided again by the number of hours in a year. This calculation can be simplified using the following equation:

$$\lambda = \frac{\sum_{i=1}^{I} \sum_{k=1}^{K} \frac{n_{i,k}}{N_i}}{\sum_{i=1}^{I} \frac{T_i}{8760}}, \qquad (4)$$

λ: failure rate per turbine per year, I: frequency of data collection intervals, K: the number of subassemblies, $n_{i,k}$: the number of failures, N_i = the number of turbines, T_i = overall time period in hours

An essential aspect of analyzing offshore wind turbines' O&M interventions is the collection and classification of failure data, which includes failure rates and repair times. The failure data employed in this study are based on average values corresponding to ten offshore wind farms, as presented in [25]. Failures are classified according to the total cost of materials used, as illustrated in Table 3. Repairs below €1000 are considered minor, those between €1000 and €10,000 are classified as major, and repairs costing more than €10,000 are regarded as major replacements. It should be noted that these costs solely represent material expenses and do not encompass other expenses such as turbine access, technician fees, or equipment rental costs.

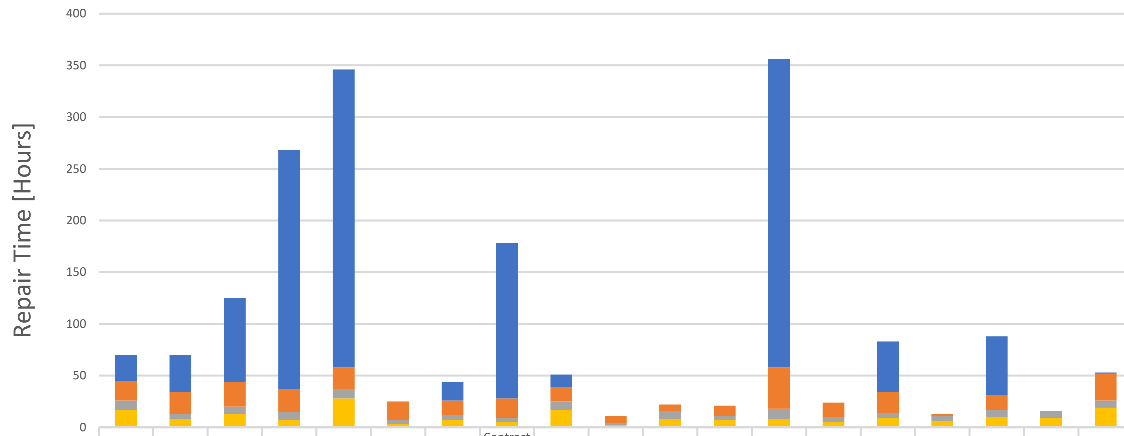


	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contractor /Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps /Motors	Hub	Heaters / Coolers	Yaw System	Tower /Foundation	Power Supply /Converter	Service Items	Transformer
Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
Major Repair	0.179	0.042	0.321	0.038	0.01	0.006	0.016	0.054	0.054	0.004	0.07	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.19	0.162	0.092	0.076	0.108	0.052
No Data	0.072	0.15	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.02	0.004	0.018	0.016	0.009

Figure 8. Pareto Chart of Subassembly Failure Rates and Associated Costs [8]

By employing failure rates and repair times, a simplified approach for modeling system failures via a stochastic process can be facilitated. Further information on the parameters illustrated in Table 3 can be found in [8]. It is essential to recognize that long O&M interventions cannot be executed continuously due to visibility acting as a limiting factor unless artificial light is utilized. As a result, it is assumed that major repairs are conducted by operators who stay overnight on accommodation vessels, performing subtasks of the major repair intervention during available windows.

Table 2 presents the characteristics of vessels needed for various O&M interventions, which includes their operational limits in relation to wave and wind conditions. These values are sourced from [34], though different studies might offer alternative values. The uncertainty of these data, however, is not examined in this study.



	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contractor /Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps /Motors	Hub	Heaters / Coolers	Yaw System	Tower /Foundation	Power Supply /Converter	Service Items	Transformer
Major Replacement	25	36	81	231	288	0	18	150	12	0	0	0	298	0	49	0	57	0	1
Major Repair	19	21	24	22	21	18	14	19	14	7	6	10	40	14	20	2	14		26
Minor Repair	9	5	7	8	9	4	5	4	8	2	8	4	10	5	5	5	7	7	7
No Data	17	8	13	7	28	3	7	5	17	2	8	7	8	5	9	6	10	9	19

No Data Minor Repair Major Repair Major Replacement

Figure 9. Pareto Chart Illustrating Average Repair Times for Each Subassembly/Component [8]

The creation of Table 3, which categorizes repairs based on the total cost of materials used, was accomplished through information obtained from two Pareto charts and previous research in this field [43]. This categorization lays the foundation for technology-informed accessibility calculations. By utilizing this table, it becomes possible to identify repair types that demand specific tools and equipment, as well as those that can be addressed through remote or automatic methods. This information is critical in estimating the cost and time required to perform the repairs, which is a significant factor in the decision-making process for offshore wind turbine O&M interventions.

4 Results

This section presents the main outcomes of the study and is divided into two main parts. On the one hand, the potential of the technology-agnostic accessibility metric is evaluated. On the other hand, the technology-informed accessibility metric suggested in the present study is evaluated and the sensitivity of the metric to the definition of weights is quantified. Additionally, the novel technology-informed metric is used to evaluate the impact of visibility, intra-annual and inter-annual variations and characteristics of different geographical locations. Through this analysis, insights are provided into the effectiveness of these metrics in accurately quantifying the accessibility of offshore wind turbines for O&M interventions.

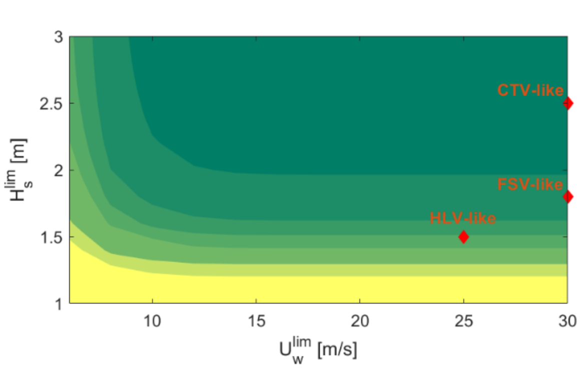
4.1 Technology - Agnostic Accessibility

The feasibility of safely accessing a wind farm for different O&M interventions is demonstrated by the technology-agnostic accessibility metric. However, a single metric is obtained for each specific technology and O&M intervention, making a general accessibility analysis challenging, and requiring a sensitivity analysis that varies the operational limit thresholds and the duration of the required operation. Figures 10 (a) and (b) illustrate such a sensitivity analysis for a broad range of operational limits ($1\leq H_s^{lim} \leq 3$ and $6\leq U_w^{lim} \leq 30$ with t_{reqWW} = 8 h) and WW requirements ($1\leq H_s^{lim} \leq 3$ and $4\leq t_{reqWW} \leq 12$ for U_w^{lim}= 30 m/s), respectively, in terms of the expected mean waiting time(WT) off the Basque coast.

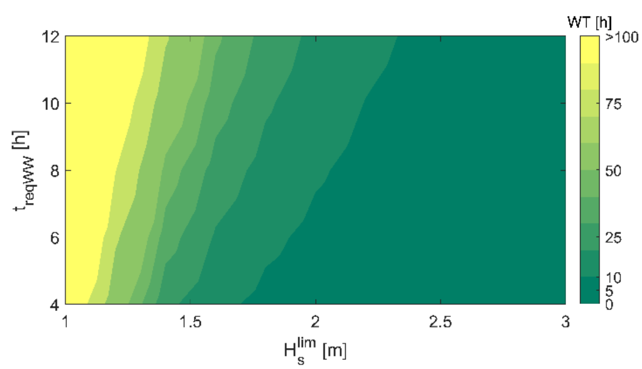
The results reveal that the mean WT is significant ($5 \leq WT \leq 30$ h) for the vast majority of the analyzed conditions, but increases significantly as operational limits become more restrictive or the required WW duration extends. However, Figures 10 (a) and (b) depict the average conditions, which can vary significantly over the year. Therefore, Figures 10 (c) and (d) illustrate the same WT sensitivity analysis for the Summer period, showing significantly lower WTs than the annual averages in Figures 10 (a) and (b). Conversely, Figure 10 (e) and (f) demonstrate the WT sensitivity analysis for the Winter period, revealing a dramatic reduction in accessibility, indicating that Winter conditions are incompatible with most O&M interventions.

The overall, Summer, and Winter WTs are identified for the three O&M vessels described in Table 2, as illustrated in Figure 10 (a), (c), and (e), in order to focus the analysis on more specific conditions. The results for the three vessels are specified in Table 5, which includes not only overall results but also those corresponding to the Summer and Winter periods, demonstrating significant differences between distinct O&M vessels, geographical locations, and seasons.

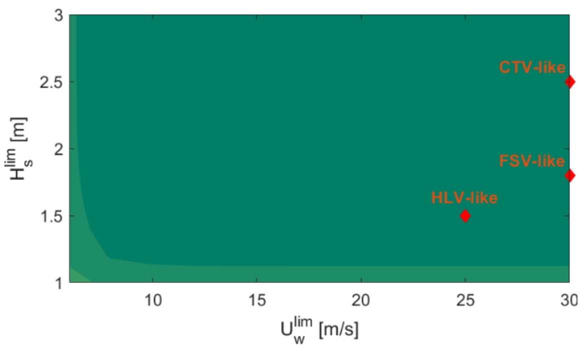
The wind farms Hywind and MedWind show relatively high accessibility, even in Winter, with a maximum waiting time period of 50 hours for the HLV. The GEROA wind farm also exhibits decent accessibility in terms of overall metrics. However, the difference between Summer and Winter conditions is considerably larger with very accessible Summer periods and relatively restricted Winters. In contrast, WindFloat and Clarus, particularly the latter, display very limited accessibility. For instance, Winter accessibility conditions for MedWind are less restrictive than the Summer accessibility conditions for Clarus and similar to those for WindFloat, indicating that O&M interventions may be unfeasible during the Winter period.

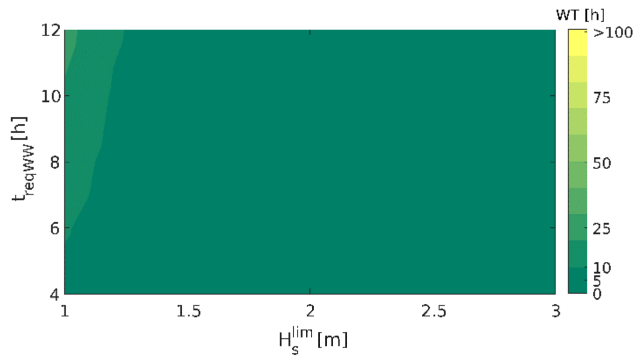


a) Overall WT sensitivity: H_s^{lim} vs. U_w^{lim}



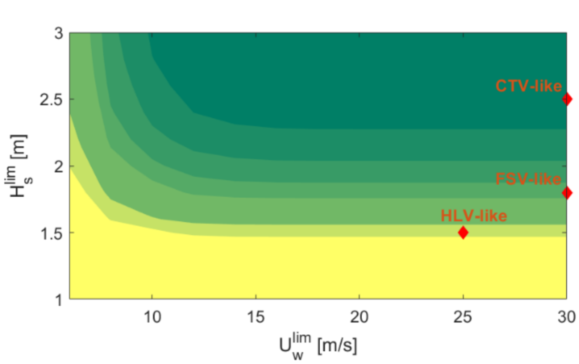
b) Overall WT sensitivity: H_s^{lim} vs. t_{reqWW}

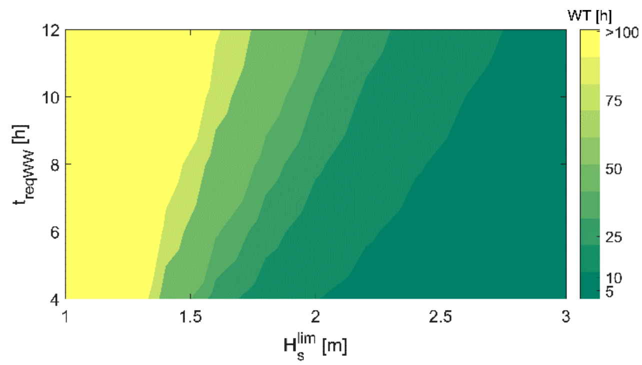




c) Summer WT sensitivity: H_s^{lim} vs. U_w^{lim}

d) Summer WT sensitivity: H_s^{lim} vs. t_{reqWW}





e) Winter WT sensitivity: H_s^{lim} vs. U_w^{lim}

f) Winter WT sensitivity: H_s^{lim} vs. t_{reqWW}

Figure 10. Sensitivity Analysis of Technology-Agnostic Accessibility Assessment Off the Coast of Basque Country

Table 5. Evaluation of Waiting Times for Three Types of O&M Vessels at Five Examined Locations in this Thesis

Wind Farm Name	Overall WT [h]			Summer WT [h]			Winter WT [h]		
	CTV	FSV	HLV	CTV	FSV	HLV	CTV	FSV	HLV
Hywind	3.9	12.6	24.0	0.3	1.6	3.5	8.5	26.3	50.0
MedWind	2.6	7.2	11.9	0.2	1.1	2.2	5.8	14.9	24.7
GEROA	4.6	16.4	34.3	0.3	1.4	3.1	10.9	39.9	86.1
WindFloat	19.8	107.5	248.5	1.2	10.3	25.0	48.7	283.1	577.4
Clarus	66.9	272.4	477.1	4.7	18.8	40.8	194.0	699.6	1125.8

4.2 Technology - Informed Accessibility

However, the data summarized in Table 5 are gathered for three O&M vessels and is not linked to any specific details about failures or repairs. Thus, the discussion of the technology-related information and the unconventional visibility information included in the technology-informed metric is assessed in Sections 4.2.1 and 4.2.2, respectively. After evaluating and defining the O&M operation weights and visibility factors, a variability analysis is carried out across the last few decades in Section 4.3.1 and across different European sites in Section 4.3.2.

4.2.1 Assessing Metric Weights: Comparing Failure-based and Downtime-based Approaches

A metric is provided that measures the accessibility of a specific offshore renewable energy (ORE) technology. A weighted average is used, taking into account three groups of different types of maintenance interventions found in Table 3. The importance of each group is represented by the weights.

By using two approaches based on failure rates and/or repair times from Table 3, the weights are calculated. In the failure-based approach, only the occurrence of failure for each maintenance intervention group is considered. However, in the downtime-based approach, both the failure rate and the required repair time of each maintenance operation group are taken into account, focusing on not only the failure but also the repair characteristics.

Weights for both failure-based and downtime-based approaches are displayed in Table 6. These weights depend on the occurrence of each type of failure when considering only faults or combining faults with repair times. It is observed that minor repairs dominate in the failure-based metric, while their dominance is significantly reduced in the downtime-based approach. A noteworthy difference is found in the major repairs group, where the impact increases tenfold in the downtime-based approach, rising from 3.5% to 33.8%.

Due to the increased importance of medium and major repairs, lower accessibility is observed: up to 15% for the GEROA wind farm, as illustrated in Figure 11. Similar values are also seen for other geographic locations listed in Table 4. The downtime-based approach is regarded as more comprehensive, leading to the recommendation of the technology-informed metric based on downtime-based weights as the reference metric for future implementations.

Table 6. Weights Assigned to Failure and Downtime for the Technology-Informed Accessibility Metric

Type of Operation	Calculation	Minor repair	Medium repair	Major Repair
Failure-based occurrence	$\omega_{fb} = \frac{\lambda_j}{\sum_{j=1}^{M_j} \lambda_j}$ [%]	82.3	14.1	3.5
Downtime-based occurrence	$\omega_{db} = \frac{\lambda_j \times \mu_j}{\sum_{j=1}^{M_j} \lambda_j \times \mu_j}$ [%]	46.5	20.7	33.8

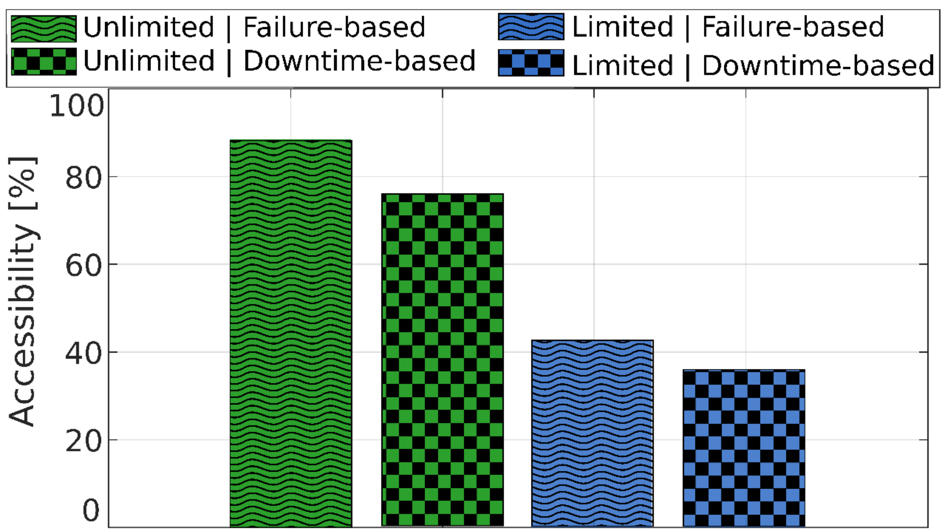
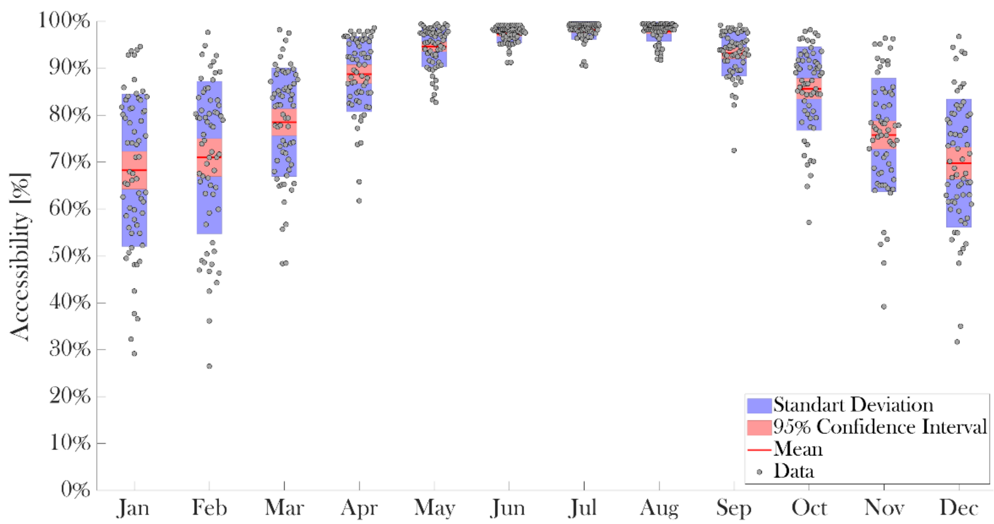


Figure 11. Comparison of Accessibility Metrics Based on Failure and Downtime for the GEROA Wind Farm

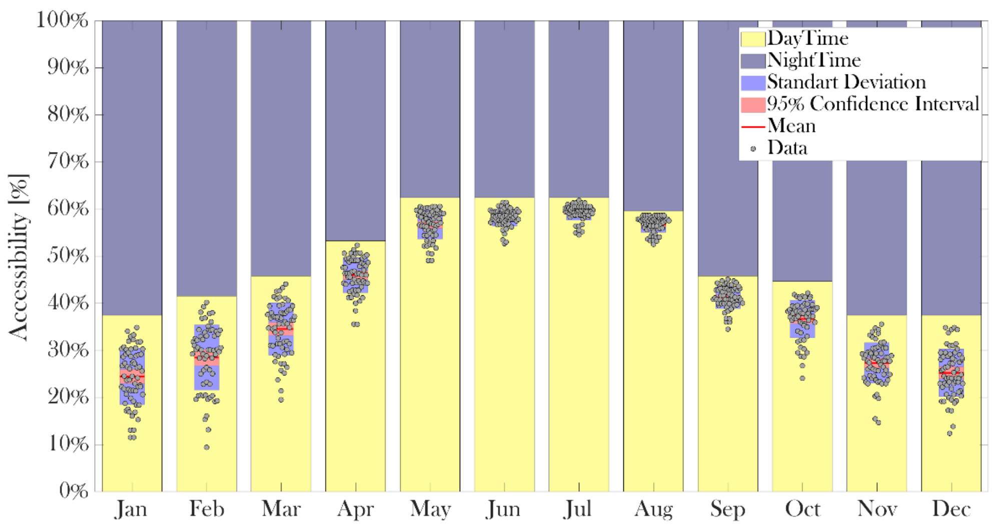
4.2.2 Impact of Visibility

Most studies assume unlimited visibility, as shown in Table 1. Figure 12 (a) displays the GEROA wind farm's accessibility with this assumption, evaluating each month over 60 years. Accessibility is high (almost 100%) from April to October but decreases in winter. The average accessibility remains between 70%-100% throughout the year with this assumption.

When considering a more realistic scenario with limited sunlight hours and sea fog, accessibility drops significantly, as seen in Figure 12 (b). This drop assumes artificial light isn't suitable for maintenance work. The highest average accessibility in the realistic scenario is around 60% during summer months, much lower than the lowest average value in the unlimited scenario (almost 70%). Figure 12 (b) shows the difference between the unlimited and limited assumptions for the GEROA wind farm's accessibility metric. Differences grow beyond 40% when using both failure- and downtime-based weights. Ignoring visibility when assessing accessibility can be risky, leading to misleading conclusions for decision-making. The 80% threshold mentioned in the literature for 90% availability is never reached with limited visibility, even in summer.



a) Assumption of Unlimited Visibility



b) Realistic, Limited Visibility

Figure 12. Monthly Accessibility Off the Basque Coast under a) Assumption of Unlimited Visibility and b) Realistic, Limited Visibility

Sunlight is the most important factor for visibility, reducing accessibility by 60% in winter and 40% in summer, as seen in Figure 13. The daylight factor also has a significant impact on the visibility assessment. If twilight is considered suitable for maintenance work, accessibility can increase considerably. Twilight duration varies by location, but if one hour of twilight before and after sunrise and sunset is considered, accessibility increases by almost 10%, as demonstrated in Figure 13. In contrast, the reduction in visibility due to sea fog accounts for only a 5% decrease in the worst-case scenario.

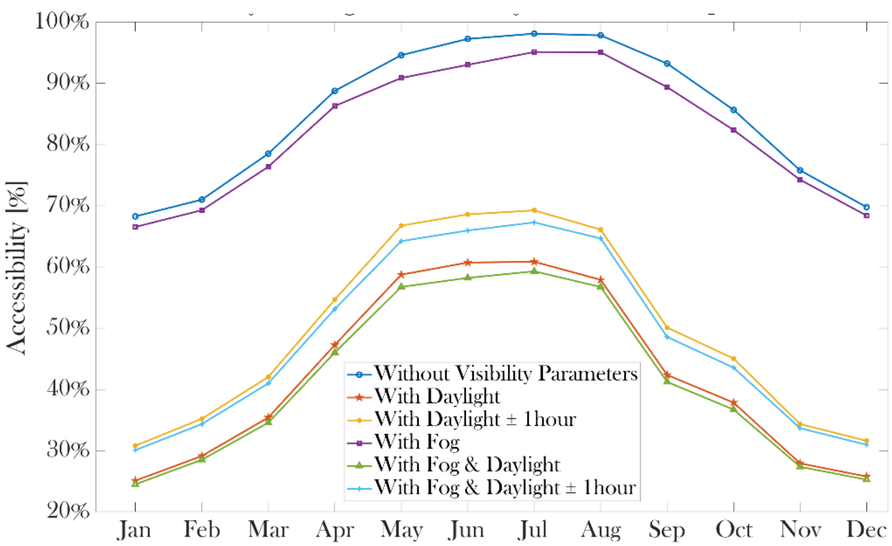


Figure 13. Impact of different visibility factors

4.3 Accessibility assessment

Upon analyzing the sensitivity of various factors and approaches used to calculate the technology-informed accessibility metric, this metric is employed to assess accessibility across Europe over the last six decades, spanning from 1959 to 2019.

4.3.1 Intra-Annual and Inter-Annual Variability

In Section 4.2.2, monthly accessibility metrics are presented, illustrating a clear difference between Summer and Winter months. However, the intra-annual variability is more complex, and the mean accessibility metric conceals this complexity behind a single value. It has been concluded that accessibility is more consistent during the Summer months, but variability is demonstrated by monthly histograms and the corresponding probability density functions (PDFs) in Figure 14. The inter-annual variability of sunlight is found to be negligible, with the main source of these variations being the inter-annual fluctuation of metocean conditions. As a result, the variability analysis in Figure 14 is based on accessibility estimations using the unlimited visibility assumption. During Summer months, accessibility varies within a 10% range between 90-100%, and over 90% of the time, the variability is reduced to the 95-100% range. Variability increases substantially to around 20% during Spring and Autumn and up to 60% during Winter.

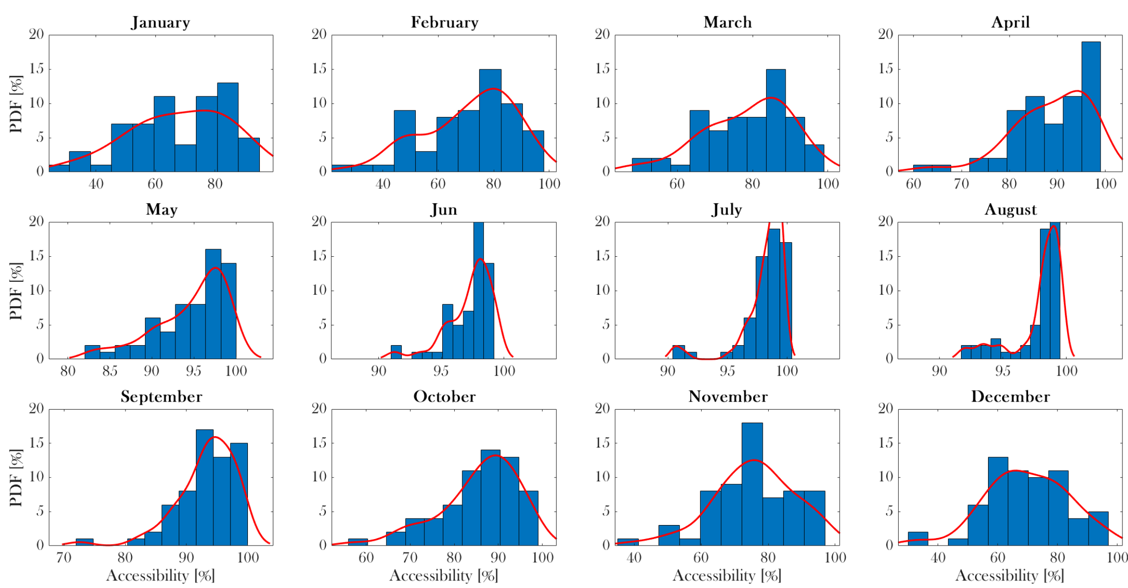
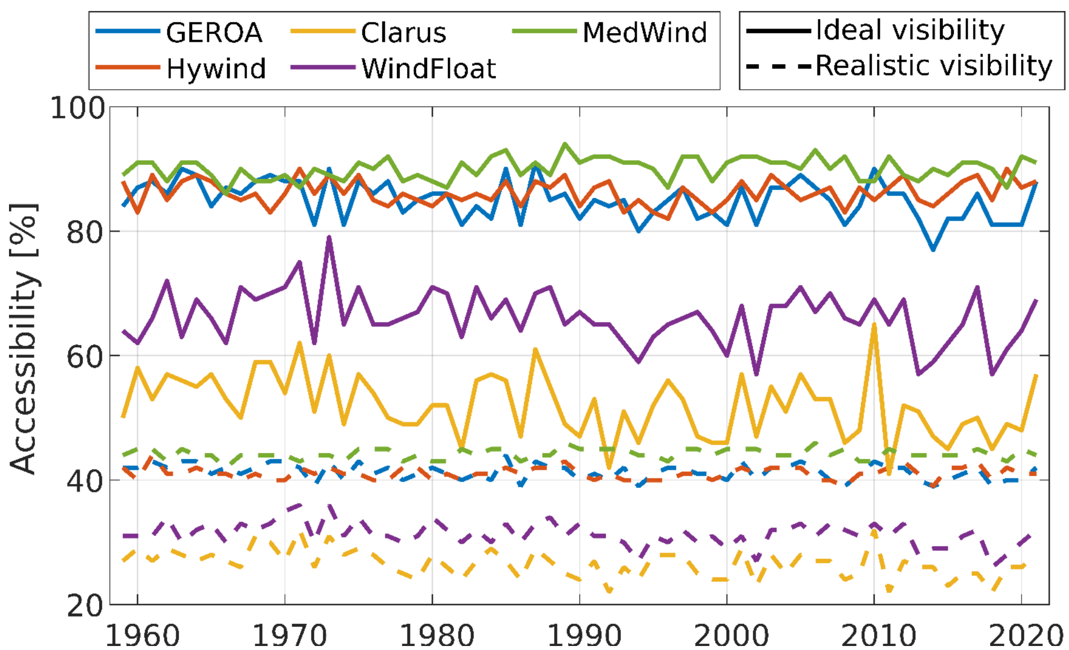


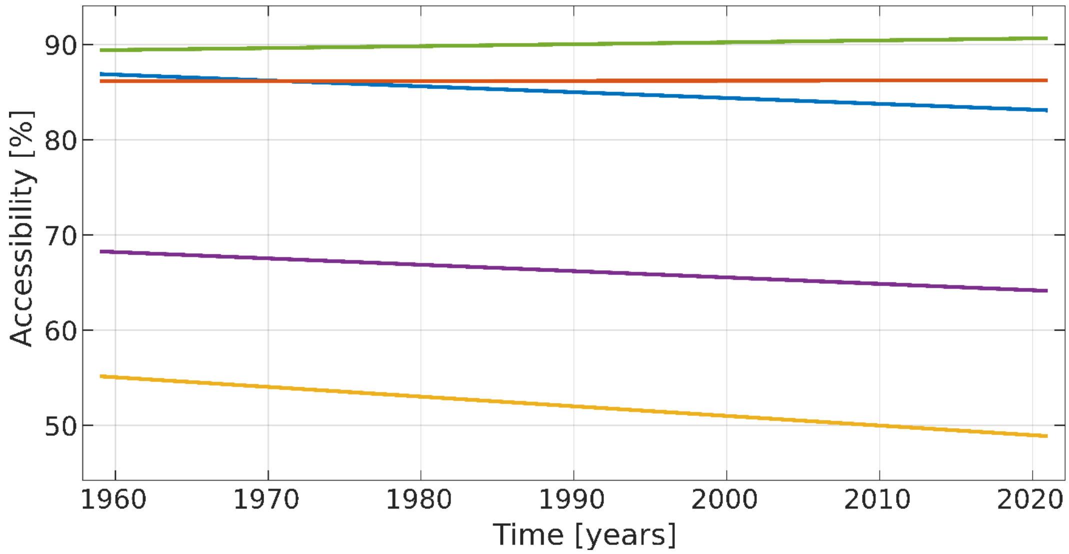
Figure 14. Intra-annual accessibility variability

In addition to the well-known inter-annual variations of the resource, recent studies have identified longer-term trends for metocean data, demonstrating the non-stationarity of the resource [44], [45], caused by rising ocean temperatures and global warming. Consequently, it is expected that global warming may also impact O&M for ORE technologies. In this regard, a pioneering study in [46] concludes that the impact of climate change on O&M is almost negligible and may result in a small increase in vessel operability. However, the results obtained in the present study, as shown in Figure 15, indicate that accessibility trends over the last six decades across Europe are either negligible (Hywind and MedWind) or slightly negative (about a 5% reduction in GEROA, Clarus, and WindFloat), suggesting that vessel operability is either maintained or reduced. It should be noted that the trends in Figure 15(b) are derived from linear regression.

The analysis of accessibility metrics over time reveals a complex pattern of variability, with significant differences between Summer and Winter months. Additionally, the potential impact of global warming on O&M for ORE technologies has been explored, with findings suggesting that the effect is either negligible or slightly negative.



a) Long-term trends

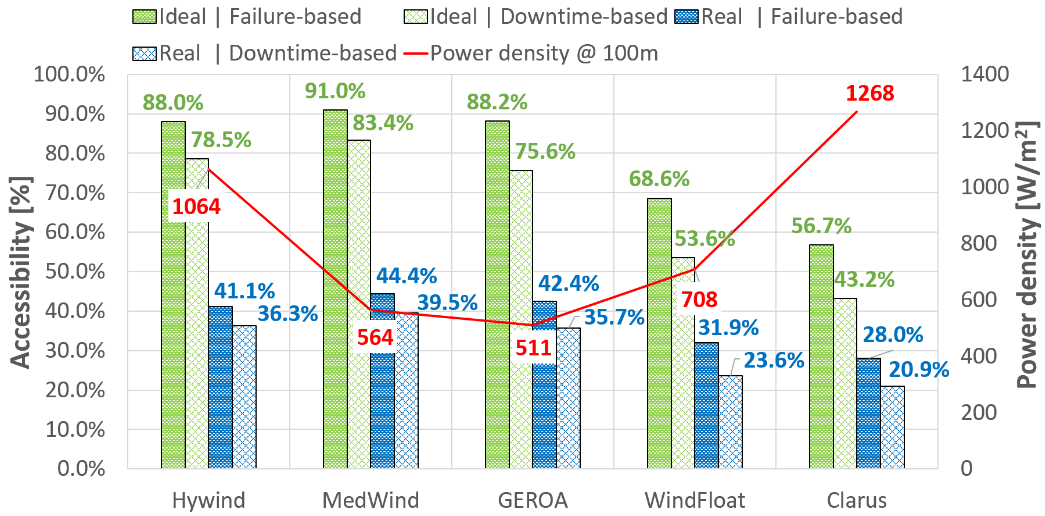


b) Linear regression of the trends

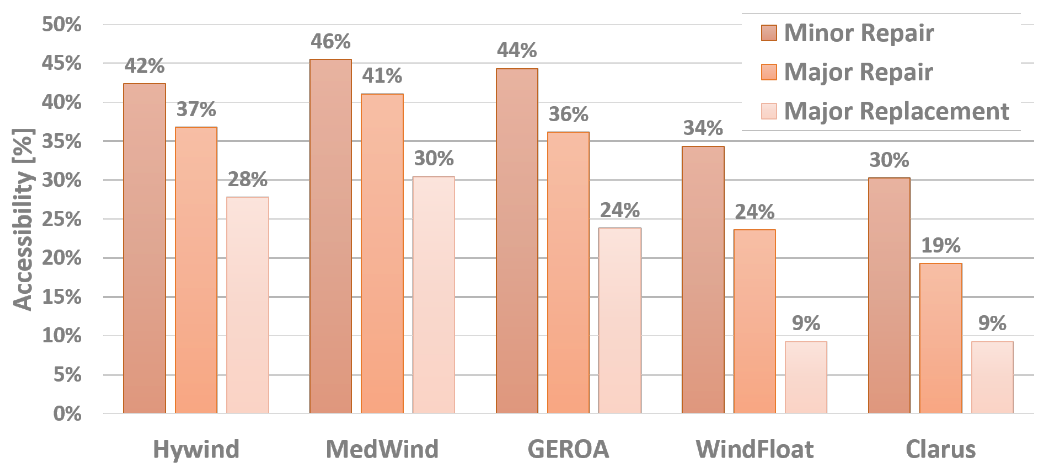
Figure 15. Accessibility Variability Across Decades: Inter-Annual Analysis

4.3.2 Sensitivity to Geographical Location

Ultimately, the relationship between resource potential and accessibility was assessed to evaluate its relevance for site-selection decision-makers, as the ideal location should possess both high energy density and accessibility. However, such a combination is rare, leading to a trade-off typically being pursued. Among the five sites analyzed in the study, MedWind and GEROA wind farms exhibited the highest accessibility (just over 40%), but were also the two locations with the lowest energy density, as demonstrated in Figure 16 (a). In contrast, WindFloat and Clarus had significantly lower accessibility (about 30%), partially due to their considerably larger energy density. The Hywind farm was an exception to this trend, with an accessibility of over 40% and one of the highest energy densities among the five locations.



a) Accessibility and power density of whole wind turbine



b) Accessibility by subassembly/component class

Figure 16. Assessing the Impact of Geographic Location on Overall Accessibility: a) Overall Wind Turbine, and b) Categorized by Subassembly/Component Groups

It was observed that the difference between unlimited and limited (realistic) visibility assumptions was slightly larger for Northern locations, although the difference between Southern and Northern locations was less significant than expected. The overall accessibility metrics in Figure 16 (a) were derived from the weighted sum of the accessibility metrics for the different O&M intervention classes defined in Table 3, using both failure- and downtime-based weights. The impact of these approaches was found to be similar across all geographical locations. However, accessibility for each type of O&M intervention varied significantly depending on the location. Figure 16 (b) displays the accessibility of each intervention class at every location, providing valuable information for O&M service providers.

Accessibility for minor repair interventions was relatively high, slightly higher than the overall accessibility, while accessibility for medium repair interventions was somewhat lower. However, major repair interventions were found to be very difficult to perform, especially in locations facing the open ocean, such as the West coasts of Portugal and Ireland, where accessibility dropped below 10%. In fact, the windows for major repair interventions only appeared during the Summer months.

It could be argued that unexpected major failures are more likely to occur in the Winter period due to higher loads and stress on mechanical and electrical components. In this worst-case scenario, the entire system would be non-operational for several months, resulting in significant losses. Within this context, predictive and scheduled maintenance became even more important, but required a more conservative estimation of the remaining useful life for each component, leading to increased maintenance costs.

5 Conclusion

In this thesis, the importance of selecting the right locations for the deployment of offshore renewable energy farms is emphasized, with the goal of ensuring efficient energy generation and the commercial success of the technologies used.

Traditional site selection methods have mainly focused on energy generation capacity, which often leads to an oversimplification of operation and maintenance (O&M) aspects. It is crucial to understand that accessibility is a key factor that greatly affects both O&M costs and energy generation. The present thesis proposes a technology-informed accessibility metric that includes important factors such as metocean conditions, visibility, O&M logistics, and the characteristics of various O&M interventions.

The impact of each type of O&M intervention on the final accessibility rate is shown to be significant. The technology-informed accessibility metric is calculated using a weighted average approach, in which the weights of the various types of O&M interventions are estimated through a failure-based and a downtime-based method. The former, which only considers information related to failures, is shown to overestimate accessibility by about 10%. On the other hand, the latter approach also includes information about repairs, resulting in a more complete accessibility metric.

Furthermore, the results show that visibility is a critical factor that must be considered when assessing accessibility. If not considered, accessibility can be overestimated by up to 60% in the winter and around 40% in the summer. Sunlight is found to be particularly important for visibility considerations, much more than other factors such as sea fog, which contributes to less than 5% of the total reduction in accessibility. In fact, the sensitivity of accessibility to twilight duration is greater, increasing by up to 10% if twilight is considered suitable for O&M interventions.

However, if the absence of sunlight poses a problem for O&M tasks, the longest available weather windows are reduced to about 18 hours. As a result, any major intervention requiring longer windows becomes unfeasible. Alternative strategies must be explored, such as using artificial light, breaking lengthy interventions into shorter, consecutive tasks, or towing the system to port to allow the safe execution of O&M tasks regardless of metocean conditions. The consideration of these alternative strategies is expected to affect the accessibility rates presented in this study.

Regarding the long-term trends of the resource due to global warming, the impact appears to be relatively low, but in the opposite direction compared to suggestions in other literature. Accessibility remains relatively constant over the past six decades in the North Sea and the Mediterranean Sea, while it appears to decrease by about 5% in sites located in the Atlantic Ocean. However, these conclusions require further investigation before they can be considered final.

In conclusion, this thesis highlights the importance of considering accessibility in the site selection process. Although locations with both high power density and accessibility are ideal, such a combination is found to be very rare. Only the site in North-East Scotland meets both requirements, while, in the remaining sites, high power density leads to lower accessibility. This is highly relevant for decision-makers involved in site selection, as the main factor for decision-making is the final cost of energy.

Future work will concentrate on improving and automating the process of measuring accessibility. This will allow for the analysis of more areas in greater detail, while taking into account additional factors that were not included in this study, such as thunderstorms, lightning, ocean currents, and commercial trade routes. Moreover, the effect of accessibility on energy generation and operation and maintenance (O&M) costs can be estimated using a complete techno-economic model that effectively includes O&M aspects. Determining the influence of accessibility on energy generation and O&M costs will be an important focus in future studies.

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