

Offshore Wind Energy Access Report 2024

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Summary

To satisfy the growing demand of renewable wind energy, new wind farms are being installed in new areas not developed thus far. This means that wind farms are being installed further and further offshore. These developments shape the evolution of the offshore wind energy access market supporting the operations & maintenance (O&M) activities.

Additional factors contribute to the evolution of the market with, on the one hand, pressure on the workforce to maintain an ever growing number of assets in an hostile environment. And, on the other hand, the emergence of the floating wind market and of new technologies enabling safer and more pleasant work condition for the human personnel, while the development of unmanned systems and smart maintenance through digitalisation alleviates the work load for manned maintenance operations requiring physical access to the offshore wind assets.

Better, safer and smarter access to offshore wind energy assets will have a positive impact on reducing the levelized cost of energy (LCoE) of offshore wind.

In this 7th edition of TNO Offshore Wind Access Report, up to date information on a variety of access vessels and systems to offshore wind assets is presented, with a highlight on their cargo capabilities and interoperability possibilities with novel digital and unmanned access technologies. The specific case of accessing floating offshore wind turbines is also reviewed by looking firstly at access systems tailored for floating missions, and later by presenting the benefits of O&M modelling for floating offshore wind. An introduction to human factors in the access market is made, highlighting motion sickness related studies for offshore wind maintenance personnel. Finally, the report presents an overview of emerging access related technologies which are changing the way offshore maintenance is being conducted.

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Introduction

Offshore wind energy continues to be a driving force in the global transition to renewable energy, promising substantial contributions to sustainable power generation. The expansion of offshore wind capacity is propelled by innovative technologies and strategies that address the challenges of accessing and maintaining wind turbines in increasingly remote and harsh marine environments. This report focuses on the current state of access vessels, systems and technologies, the emergence of digital solutions, and the evolving landscape of floating offshore wind farms.

A significant focus of this report is on the vessels and systems that facilitate access to offshore wind farms. The growing demand for offshore operations has spurred advancements in access vessels, including Crew Transfer Vessels (CTVs), Service Operation Vessels (SOVs), and emerging designs such as mini-SOVs and daughter craft. These innovations are complemented by specialized access systems, including gangways, cranes, and motion-compensated transfer systems that ensure safety and efficiency in challenging sea states.

The offshore wind sector is embracing digitalization and robotics to enhance operational efficiency and safety. This includes the deployment of autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and unmanned aerial vehicles (UAVs) for inspection, maintenance, and monitoring. Coupled with digital twins and data analytics, these technologies enable predictive maintenance and optimize logistical planning, reducing downtime and operational costs.

The rapid development of floating offshore wind turbines (FOWTs) introduces new opportunities and challenges. These structures, positioned in deeper waters, require specialized vessels and systems for installation, operation, and maintenance. The report examines the evolving market dynamics and innovations tailored to the floating wind sector, which is expected to play a critical role in the future of renewable energy.

Efficient planning and logistics are crucial for maximizing the potential of offshore wind farms. TNO's UWISE software that covers state-of-the-art simulation tools, offers advanced capabilities to model and optimize offshore wind farm logistics. The report features a case study on a floating wind farm, comparing two maintenance strategies—tow-to-port and self-hoisting cranes—highlighting their impacts on cost, downtime, and operational availability.

This report is designed for a diverse audience that includes policymakers, offshore wind energy developers, operations and maintenance (O&M) managers, vessel designers, and technology innovators in the renewable energy sector. It serves as a comprehensive resource for understanding the latest advancements, challenges, and opportunities in offshore wind energy access. By addressing key topics such as emerging access technologies, digitalization, and logistical optimization, the report equips stakeholders with the tools and knowledge to enhance efficiency, reduce costs, and ensure safety in offshore wind operations.

1 O&M access vessels and vehicles

1.1 Access vessels

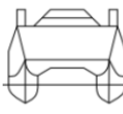
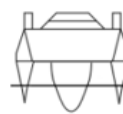
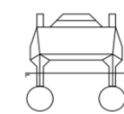
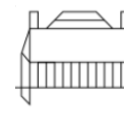
Accessing offshore wind turbines to perform maintenance tasks is an ever growing challenge due to the rapid increase of the number of installed offshore wind assets, and the increasing distance to shore for the new wind parks. These developments along with the arrival of floating offshore wind farms drives the constant need for developments and innovations in this sector.

In addition to the increase in the number of suitable access vessels and the adaptations required to operate further and for longer, the sector is witnessing considerable advancements aimed at enabling less impactful maintenance operations. Many of these vessels are now using, or are ready to be converted to [1]] alternative energy systems for propulsion and onboard usage, as discussed in the previous edition of the [report](#) [2]]. These developments are accompanied by design features to facilitate the work with emerging technologies such as unmanned vehicles or augmented reality, which are specifically discussed in section 5.

1.1.1 Crew Transfer Vessels (CTVs)

There are several different specialized CTVs that offer access to offshore wind farms with varied levels of seakeeping capability, manoeuvrability, cargo and personnel carrying capacity, and speeds according to their size and hull design (details in Table). CTVs are usually used as far as 40 nautical miles (74 km) from the base port [3]. CTVs operate on short missions and head back to the port at the end of the day (for longer missions SATVs and mini SOVs are used, see section 1.1.3 and 1.1.4).

Table 1.1: Characteristics of CTV types

	Monohull	Catamaran	Trimaran	SWATH	SES
Length [m]	12-25	15-27	20-32	20-32	26-28
Transit speed [knots]	15-25	18-27	18-22	18-23	35-39
Passenger capacity [-]	12	12	12	12/24	12/24
Cargo [tons]	5-10	10-20	10-20	2-10	3-5
H _s limit [m]	1-1.2	1.2-1.5	1.5-1.7	1.7-2	1.8-2.2
Sketch					
Image source	[4]	[4]	[5]	[4]	[4]

CTVs press against the turbine transition piece access ladder to transfer personnel to the wind turbine in sea states with $H_s \leq 1.5\text{m}$.

CTVs have varied carrying capacity for cargo depending on their hull shape and their sizes. In general they can carry a relatively limited amount of palletized equipment (cf. Table Table) in batches that can be lifted by the onboard folding boom cranes (typically 300kg to 1,5 ton depending on the lifting distance to reach [6]).

Supplies are primarily secured on the fore deck of CTVs in front of the superstructure. The cargo is strapped to the deck during transit.

Cargo is loaded from the quay side to the deck using a loading crane generally mounted on the fore deck of the CTV (or sometimes using quay mounted cranes where available). The cargo is then hoisted to the turbine from the deck of the CTV using a crane located on the transition piece platform.

CTVs are suitable for the deployment and recovery of relatively small and light underwater vessels, using the deck mounted crane and allocating suitable deck space to transport the vessels to the wind farm.

Similarly, these vessels are suited for the transport, deployment and recovery of small aerial vessels typically used for wind energy assets inspection missions. Sufficient deck space needs to be allocated for the safe interaction between personnel and the drone during the take-off and landing phases. In most cases, these drones also need to be sheltered from the elements while on deck as they may not be fully marinized.

Cargo transported on the deck of a CTV may, in some cases, be suitable to be air-lifted by aerial cargo drone (this is also the case with conventional helicopters). In this case, crew onboard the vessel needs to receive proper training to ensure proper cargo handling and suitable payload attachment.

The CTVs may interact with unmanned surface vessels (USVs). This is in nature quite similar to interacting with any other vessel. The major differences are that there is no crew on the autonomous vessel to talk to in order to adjust the approach, and the CTV crew has to autonomously transfer and fasten the mooring lines between the ships. The autonomous vessel can be used to deliver/collect equipment to/from the CTV using the deck mounted crane, or support the operations in various ways.

Finally, CTVs can be used as a base for unmanned vehicle pilots, or personnel supervising unmanned operations, or specialists guiding augmented reality enabled tasks.

1.1.2 Service Operation Vessels (SOVs)

Service Operation Vessels (SOVs) are larger vessels for offshore accommodation and storage. They can accommodate between 40 and 120 offshore wind personnel (excluding ship's crew) and typically do a bi-weekly rotation to shore to re-supply and switch technicians. SOVs provide enhanced comfort and safety to wind energy maintenance crews, with can optionally gain direct access to the turbines from the vessel using access gangways (Walk-to-Work vessels, W2W). Additionally, by ensuring shorter transit times and access with sea states where conventional access by the transition piece ladder is not be possible anymore, they enable increased effective working time.

Due to their high running costs, SOVs are more suited for further offshore operations where CTV transits to and fro can be avoided. SOVs are often paired with a fleet of fast daughter craft installed on davits that can be used when weather conditions allow to increase the number of maintenance team deployed in parallel, and enable to cover more distance within the wind park. Daughter craft are discussed further in section 1.1.110.



Figure 1.1: Service Operation Vessel [Vroon VOS Start](#) [7]

The layout of SOVs differ from one vessel to the other but some trends can be found in the design, where the wheelhouse and accommodation is located in the front of the vessel. The aft section of the boat generally accommodates deck storage and stores underneath. Amidship the transfer systems are located with eventual daughter craft on davits. A helideck may additionally be located to the front or the aft of the vessel.

Cargo capacity varies greatly from one vessel to the next and generally ranges between 30 tons for a smaller SOV, up to 2500 tons for a larger vessel. This cargo is then divided between deck storage, generally in standard shipping containers, and hold storage in palletised format. All storage spaces are generally connected to a lift to bring the cargo towards the access system for transfer to the turbine (gangway or crane), or to load in a daughter craft, or for loading from the dock.

The SOVs are equipped with one or more “bump-and-jump” (see section 2.1) access ladder with in some cases an access ramp or a level access deck to transfer cargo and equipment to daughter craft and other small access vessels afloat.

SOVs are particularly suited to support the development of emerging technologies with their large carrying capacity, large deck spaces, onboard workshops, high capacity cranes, good network connectivity, ship roll stabilisers, and, sometimes, helideck.

The SOV offer multiple launch and recovery area for smaller drones such as inspection drones, and they can also accommodate larger cargo drones operations from the aft deck or eventually from the heliport. The first commercial use of cargo drones in offshore wind farm maintenance took place in 2023 with the involvement of the SOV Edda Mistral from Ørsted [8]. The suitable sea state window for launch and recovery is also wider compared to CTV thanks to vessel size, larger inertia, and ship stabilizers. Indoor or covered storage spaces and workshops offer many benefits for aerial drone durability and easy maintenance.

The large deck space, cranes and davits enable the easy deployment, recovery, and storage of unmanned underwater vehicles in the wind farm. It is also beneficial to interactions with unmanned surface vessels that SOVs are designed for and used to working with daughter craft. Some automated basket systems for the recovery of daughter craft could be well suited for safely working with autonomous floating vehicles [9].

Lastly, SOVs can be used as a base for offshore unmanned vehicles operations by accommodating vehicle pilots, unmanned operation supervisors, or specialists guiding augmented reality enabled maintenance.

1.1.3 Service Accommodation Transfer Vessels (SATVs)

SATVs are designed to bridge the gap between CTVs and SOVs, to operate swiftly on wind farms located further offshore with reduced costs. They are in effect a larger version of a CTV, with similar turbine access methods and improved sea going capabilities. Additionally, they offer accommodation facilities for a limited number of crew members and maintenance personnels. They are able to cater for 4 to 10 maintenance personnel over a period of one to two weeks. SATVs have an extended payload capacity for maintenance equipment and spare parts.



Figure 1.21.: Service Accommodation Transfer Vessel designed by [BMT](#) [10]

SATVs have storage space on the front deck, ahead of the superstructure, with the possibility of fastening 10ft and 20ft containers, with multiple fastening points on deck. They are also equipped with folding boom cranes with limited loading capacity (typically 300kg to 1,5 ton depending on the lifting distance to reach [6]).

The first vessels of this type, the [Ventus Formosa](#) and [Damen Fast crew supplier 3410](#), have an available deck space of 50 and 90m², with a cargo load capacity of 20 tons for the latter [11].

SATVs can offer the same advantages as CTV's when it comes to interacting with, deploying, and recovering unmanned vehicles with the additional benefits of the larger deck space that allows to accommodate larger unmanned vehicles, and can, possibly, offer better shelter for storage of these vehicles.

SATVs can also be used as a base for unmanned vehicle pilots, or personnel supervising unmanned operations, or specialists guiding augmented reality enabled tasks.

1.1.4 Mini Service Operation Vessels (Mini SOVs)

Another option to bridge the gap between CTVs and SOVs is the mini SOV. It can operate swiftly within the confines of further offshore wind farms for missions spanning over one to two weeks, and can accommodate a limited number of crew and technicians, for example 24 technicians on the OSD-IMT9604 "mini-SOV" [12] and on the DEME DP2 [13].

Mini SOVs are compact SOVs equipped with daughter craft, access cranes and/or gangways, and optionally a helipad.



Figure 1.3: [Mini SOV 6017](#) [14] with Z-Bridge B2W system [15]

Mini-SOVs have lesser equipment carrying capacity than their full size counterparts, but they still offer deck storage and covered storage, with easy transfer of cargo from the deck and storage location to the daughter craft or wind assets.

This type of vessel offers the same capabilities as a traditional SOV when it comes to interacting with emerging technologies.

1.1.1 Daughter craft

Daughter craft are high speed craft operating in tandem with SOVs (the mother craft) in far offshore windfarms. They are often equipped with a bow fender alike the ones found on CTVs. Daughter craft are stowed on the SOV by means of davits and can load personnel and equipment either before launch, or by using an access ladder system on the aft or on the side of the SOV, which is often complemented by a ramp or a level access deck to facilitate the transfer from mother to daughter craft.

These vessels are ideal to provide rapid response on wind assets located away from the SOV in far offshore windfarm and allow to extend the range of actions of the maintenance teams within the windfarm. This flexibility allows for improved O&M logistics and planning.

The main drawbacks from these vessels are:

1. Their limited sea keeping capabilities, due to their smaller size (which allow storage on the SOV), and in particular to their narrow hulls [16]. This means that daughter craft are currently mainly used during summer months;
2. Their limited personnel and cargo capacity, which means that, on the one hand, they may have a number of round trips to perform during a work day, and, on the other hand, some maintenance tasks may not be possible with a daughter craft;
3. Personnel transitioning offshore from a large vessel equipped with roll compensation mechanism to a smaller craft can be susceptible to motion sickness which would hinder their ability to work at their full potential.



Figure 1.4: North star's [Grace Darling](#) daughter craft [17]

Daughter craft have generally very limited storage capabilities and no onboard cranes. Cargo onboard is made up of small tools and equipment carried by maintenance technicians, in the vessel superstructure.

Daughter craft can be used to deploy small aerial drones and host the drone pilot onboard.

1.2 Helicopters

The fastest access solution to bring maintenance technician and equipment to an offshore wind energy asset is the helicopter. It can operate with winds up to 20 m/s provided that the sea state allows for water landing in case of an emergency. The helicopter can either hoist personnel and equipment or land on a helideck (substation or maintenance vessel).

However, this speed and agility comes at a cost, in monetary terms but also in operational terms, with limited payload capabilities and limited flying time (often needs to do one round trip for drop off and one round trip for pick up).

For operations without nearby access vessels, no emergency backup evacuation is possible until the helicopter returns.



Figure 1.5: Offshore wind helicopter access

As previously mentioned, the cargo carrying capacity of helicopters is rather limited.

In transfer operations, a typical carrying capacity is three to six technicians carrying each about 100kg of equipment and parts in the cabin of the aircraft. Technicians and equipment can be hoisted to the wind turbine or access vessel with a limit of 272 kg per hoist [18].

In short to medium range airlift operations, cargo can also be transported under the aircraft at the end of a sling. For this type of operation, the maximum load is typically 1000 kg using conventional helicopters [18].

Helicopters can be used to deliver, recover and re-supply unmanned systems in a wind farm. They can airlift the autonomous vessels either directly to a wind asset or to a support vessel. The presence of aerial drones constitutes a major risk for the operation of helicopters in wind farms. The regulatory framework is not currently formalised for unmanned aerial drone operation in wind farms. It is critical that helicopters and aerial drones co-habitation is clearly regulated in the near future, and that international standards are set to avoid the complexity of having different set of rules in every country and for operators to work in.

1.3 Effects of access vessels motion on maintenance personnel fitness for work

Beside technical access challenges, human driven factors are also a key parameter to enable safe access to wind energy assets for maintenance while ensuring that maintenance technicians are in optimal state to perform the tasks at hand.

Different access vessels offer different challenges and opportunities with regards to motion sickness:

- Smaller vessels operate in calmer sea states and get back to base at the end of each day, while larger far offshore operation vessels are at sea for longer period of time, also when the weather is rough, but offer more comfort services to their crew (food, rest areas, ...);
- Larger, slower vessels are equipped with stabilisers to reduce the entire vessel motion and are additionally equipped with motion compensated transfer systems while smaller and faster vessels can experience sudden, violent jolting motions;
- On faster vessels, dampened seats, meant to absorb the impact, desynchronise the people seated in them from the wave and boat motions, while on larger vessels the horizon is not visible at all times (from inside or at night);
- Transferring from a large vessel to a smaller one, such as from a SOV to a daughter craft, can cause discomfort due to the difference in motion between the two vessels;
- In the case of floating wind operations, not only the vessel is moving but the turbine and floater as well, with different motions and frequencies.

Research on the topic of personnel fitness by correlating Metocean data with human response to various sea states and vessels motions [19] [20] led to the development of O&M planning tools such as TNO's Despatch part of UWISE [21]. This research concluded that not only vertical acceleration led to sea sickness, but also side to side and fore/aft motions have a major impact on the technicians metabolism with lasting effect on their work throughout the day. Recent research [22] coupling UWISE with SafeTrans, a voyage simulation software, allowed to optimise O&M planning for floating offshore wind by accounting for vessels motion impact on maintenance personnel.

2 Access systems

Various access systems exist to transfer personnel or equipment to a wind turbine at sea. Different solutions are suited for different types of vessels and sea conditions, bring different capabilities and levels of safety, and affect the maintenance personnel in various way (fatigue, motion sickness, ...). Smaller vessels are suited for access solutions at sea level while larger vessels use gangways and cranes to directly access to the transition piece platform at an elevation of 15 to 20 or even 30 meters.

2.1 Bow fender

Smaller vessels such as CTVs, SATVs and daughter craft access turbines at sea level and are often equipped with a specifically designed bow fender that allows the vessel to press its bow against the foundation access ladder. The technicians are then transferred using the “bump and jump” method whereby, while the fender is firmly pressed against the ladder, technicians “jump” from the bow of the vessel to the ladder when the vessel reaches the crest of a wave, they then climb the ladder to the transition piece platform.

This method is risky as technicians need to jump (step over) at a suitable time to avoid accidents which can only be done when the sea state is fairly calm.

Equipment can be lifted from the vessel’s deck using a crane installed on the turbine TP platform.

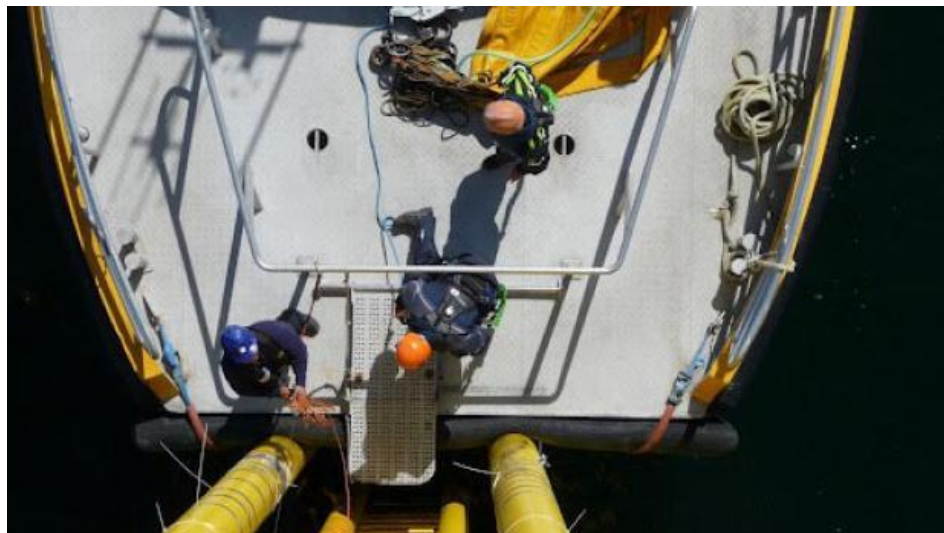


Figure 1.6: CTV in position for a bump and jump transfer [23]

2.2 Bow grippers systems

Some smaller boat can be fitted with a more sophisticated bow systems to allow for safer transfer of maintenance technicians to the TP ladder by using a bow gripper. Systems, such as the [MOBIMAR](#) gripper [24] or [Tube Docking Device](#) [25], require the vessel to be designed for the selected gripper technology. The gripper secures the bow of the boat to the access ladder, holding the bow of the boat above most waves crests.



Figure 1.7: [MOBIMAR](#) bow gripper [26]

2.3 Compact gangway systems

Compact gangway systems, such as [Houlder TAS](#) [27] or [MaXccess](#) [28], are short bridges designed to be fitted to the foredeck deck of an access vessel. They connect the end of the bridge to the TP ladder while technicians are transferring over. There are both active and passive motion compensation systems which can be fitted to vessels based on their characteristics, such as vessel length, deck layout, and active or passive ship positioning system, to name the main ones.



Figure 1.8: Crew transfer with the Houlder TAS bow bridge [29]

2.4 Get Up Safe system

The get up safe, [Ørsted](#) has recently been introduced to the wind energy industry to safely transfer technicians from a CTV onto the turbine transition piece platform.

The system, activated and operated from the CTV, uses a motion compensated hoist installed on the transition piece to lift the technician from the deck, away from the ladder, onto the turbine. It automatically adjusts the hoisting line position to account for the motion of the vessel [30].

This system both reduces risks and physical exertion for the technicians.

This new system has been extensively tested by Ørsted on 165 turbines of the Hornsea 2 wind farm, with over 10 000 transfers completed as of November 2024 [31].

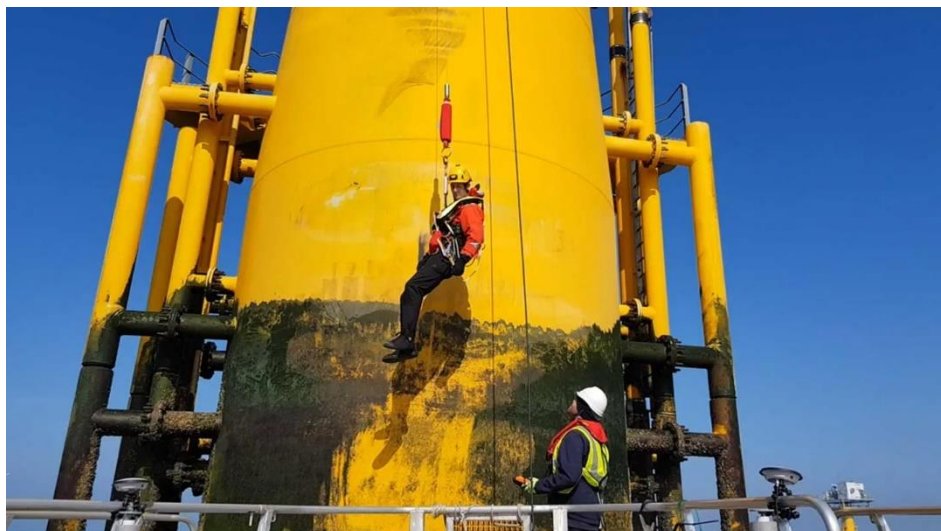


Figure 1.9: Get Up Safe personnel transfer system [32]

2.5 Gangway and walk-to-work systems

Walk-to-work and gangway systems are designed for larger vessels and provide safe access for maintenance personnel with smaller equipment directly to the turbine transition piece. They are generally installed amidship on the upper deck of access vessels and have motion compensation systems to cancel out relative motions between the vessel and wind turbine.

Motion compensation can be achieved in two ways, either passively whereby motion control is achieved by means of a mechanical link that passively adjusts the gangway orientation, or actively through sensors, actuators and control mechanisms. The major part of walk-to-work gangway systems rely on active motion compensation and an increasing number of these systems can also act as a crane to lift objects up to 1000 kg.

The market for this type of access systems is fairly large and details about the various commercially available systems can be found in the previous edition of the [report](#) [2].



Figure 1.10: [SMST](#) L series gangway with height adjustment (courtesy of SMST)

2.6 Cranes

Transferring parts and tools on offshore wind energy assets is key to performing maintenance operations. When the weight of equipment to transfer between the turbine and vessel, or when the drop zone is hard to reach, it is necessary to use dedicated cranes. Typically, these cranes, placed on the deck of the access vessel, are fitted with motion compensation systems. Some cranes are also suitable to transport personnel using personnel transfer pods.

With the growth of wind turbine size and the need to maintain bigger and heavier components, the use of cranes is becoming more and more popular in wind energy O&M operations. More information about the various commercially available systems can be found in the previous edition of the [report](#) [2].



Figure 1.11: [Eagle Access system](#) (courtesy of Eagle Access)

3 Accessibility for Floating Offshore Wind Turbines

In recent years, the development of floating offshore wind turbines (FOWTs) has seen considerable advancement, as highlighted by numerous studies [33]. The technology has progressed from conceptual designs to real-world applications, evidenced by the successful launch of several pilot and demonstration-scale projects worldwide. Notable examples include the WindFloat Atlantic project in Portugal, with a capacity of 25 MW, and the Hywind Scotland project, with a capacity of 30 MW. Looking forward, the sector anticipates a significant expansion, with projections indicating the potential for 250 GW of installed floating wind capacity by the year 2050 [34].

Achieving this ambitious goal and fully realizing the potential of FOWTs necessitates extensive marine operations during both the transportation and installation (T&I) and operations and maintenance (O&M) phases. A critical component of these operations is accessibility, particularly regarding the vessels and systems used to install, service, and maintain the turbines. Due to their offshore locations, often in deeper waters and more challenging sea conditions than bottom-fixed turbines, accessing FOWTs requires specialized vessels and advanced access systems capable of operating safely and efficiently under such conditions.

Since the FOWT industry is still in its early development stages, best practices based on real-world experience are yet to be fully established, especially concerning accessibility solutions. This situation offers a unique opportunity for in-depth investigation into the evolving market dynamics and the specific operational challenges of floating wind technology, particularly in the context of vessel and system accessibility for installation and O&M activities. Developing effective strategies for vessel deployment and access systems is crucial to minimize downtime and enhance the reliability and safety of FOWT operations.

The FOWT sector stands to benefit from a second-mover advantage by adopting and adapting strategies and insights gained from the more established bottom-fixed offshore wind industry. This includes leveraging existing vessel designs and access technologies while innovating to meet the unique requirements of floating structures. Collaborative efforts between industry stakeholders can accelerate the development of specialized vessels and access systems, optimizing them for the specific demands of FOWTs and contributing to the sector's overall growth and sustainability.

3.1 Access Vessels

The installation, operation and maintenance (O&M), and decommissioning of Floating Offshore Wind Turbines (FOWTs) require specialized vessels capable of handling deep-water locations and challenging metocean conditions. Key access vessels include:

- Floating Installation Vessels



Figure 3.1: Installation vessels from [Damen](#)

Installation vessels are specialized ships designed to transport, handle, and install large components of floating wind turbines. They are equipped with advanced dynamic positioning systems, cranes, and deck space to manage the assembly of massive structures, such as turbine towers, nacelles, blades, and floating foundations. Unlike bottom-fixed wind farms, where components are installed directly onto pre-constructed foundations, floating turbines require more flexibility and manoeuvrability, as the components must be precisely aligned and connected on floating platforms that are often subject to the movement of wind and waves. These vessels can be semi-submersible vessels with advanced stability mechanisms to ensure smooth installation in challenging offshore conditions.

- Heavy-Lift Vessels



Figure 3.2: Heavy lift vessel from [Wartsila](#)

Heavy lift vessels play a crucial role in handling and transporting the large and heavy floating platforms, mooring systems, and turbine components. They are equipped with extremely powerful cranes capable of lifting and placing the floating substructures onto the sea, mating the turbine structure with the floating substructure, or installing them at the port before

towing them to the offshore site. Heavy lift vessels are essential for installing key components, such as the floating foundations, anchor systems, and substations, which are considerably heavier and more complex than those used in bottom-fixed wind farms. Their capacity to lift and transport massive loads over long distances is critical for the successful deployment of floating wind turbines, ensuring safe and efficient installation operations.

- Tug vessels



Figure 3.3: Towing operation at the Kincardine wind farm by [Boskalis](#)

Tug vessels are indispensable for floating wind farms, as they are responsible for towing the floating platforms to their designated offshore locations. Unlike bottom-fixed turbines, which are constructed and installed at the site, floating turbines are typically assembled in port and then towed to their offshore installation points. Tug vessels manoeuvre the floating structures to the wet storage point, transport them to the designated offshore site, and ensure they are accurately positioned and securely anchored to the seabed using mooring lines. Their versatility and strength make them essential in anchoring operations, where they support the installation of mooring systems that keep the floating turbines stable against ocean currents and strong winds.

In addition to their role during installation, tug vessels are also crucial during operations and maintenance (O&M) activities. When floating turbines require major maintenance or repair, sometimes they are towed back to port for servicing, avoiding the need for complex offshore repairs. After maintenance is completed, tug vessels tow the turbines back to their designated locations offshore and ensure reconnection to the cable and the mooring system. This process significantly enhances the flexibility of O&M operations in floating wind farms, as the turbines can be efficiently transported to and from the port as needed.

Other supporting vessels, such as crew transfer vessels (CTVs) and service operation vessels (SOVs), are similar to those used in bottom-fixed wind farms. These vessels are used for transporting personnel, equipment, and smaller components to and from the offshore platforms. However, due to the deeper water locations and dynamic nature of floating wind farms, higher operational limits are required for the safety and operability of access vessels. Stronger wave forces, higher wind speeds, and more challenging sea conditions necessitate more robust vessel designs and advanced dynamic positioning systems to ensure safe access for technicians and equipment during installation, operation, and maintenance. As a result, floating wind farms often demand vessels that can withstand these harsher offshore environments while maintaining operational efficiency.

- **Unmanned Vessels for Floating Wind**

Unmanned vessels are emerging as an integral part of the floating wind industry, providing enhanced efficiency, safety, and cost-effectiveness in operations such as inspections and surveys. Floating wind farms, typically located in deeper waters and harsher marine environments, require innovative approaches to monitoring and maintaining components that are difficult to access by traditional methods. Unmanned vessels offer a solution to these challenges, particularly in the areas of inspection and survey operations.

Inspection activities: In floating wind farms, conducting regular visual inspections of key components such as turbine blades, towers, and other structural elements is essential for ensuring operational integrity. However, harsh weather conditions, including high winds and rough seas, can make it challenging—and at times unsafe—for technicians to physically access these components for traditional inspections. Unmanned vessels equipped with advanced robotics and camera systems offer a safer, more efficient alternative. These vessels can autonomously navigate to the wind turbines and perform detailed visual inspections of hard-to-reach areas. The use of robotics minimizes the need for human presence in dangerous offshore environments, reducing the risk to personnel and allowing inspections to take place even in adverse weather conditions. Furthermore, real-time data transmission enables technicians to analyze the condition of components from shore-based facilities, ensuring timely maintenance and reducing downtime for repairs.

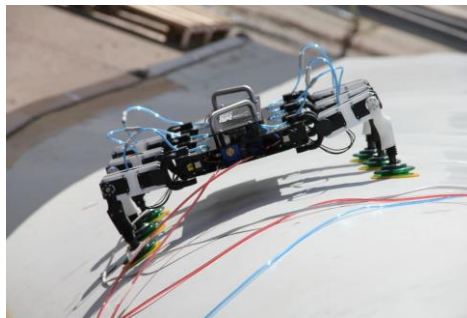


Figure 3.4: Blade inspection by [Bladebug](#)

Survey vessels: Unmanned survey vessels play a critical role in monitoring underwater components, such as cables and mooring lines, which are vital for the stability and energy transmission of floating wind turbines. Due to the deep-water locations of floating wind farms, traditional survey methods can be both time-consuming and costly. Unmanned survey vessels, equipped with sonar, sensors, and underwater drones, provide a more efficient solution. These vessels can autonomously perform detailed surveys of subsea components, identifying any potential issues such as wear, corrosion, or displacement of mooring lines, which would otherwise be difficult to detect. By utilizing unmanned vessels for these surveys, operators can reduce the need for divers or manned missions in deep waters, leading to safer, more cost-effective operations. The ability to continuously monitor these critical components ensures that any potential issues are addressed promptly, helping to extend the operational life of the wind farm and avoid costly repairs or downtime.

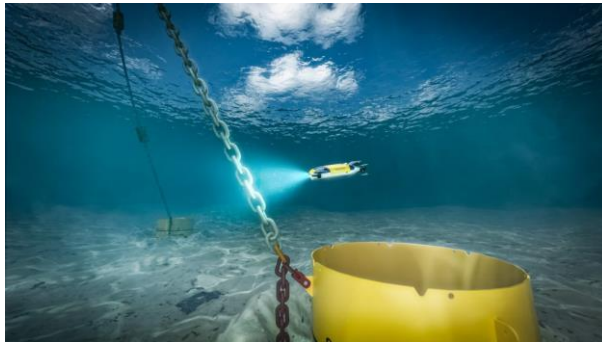


Figure 3.5: Underwater inspection of mooring lines using the concept from [Ocean Engineering](#)

Unmanned vessels, through their role in both inspection and survey operations, are poised to become key assets in the floating wind industry, offering enhanced safety, efficiency, and sustainability for offshore operations, also bringing in the extensive learnings from decades of ROV operations for oil/ gas offshore installations.

3.2 Access Systems

Advancements in access systems are pivotal for enhancing the safety, efficiency, and cost-effectiveness of floating offshore wind turbine (FOWT) installation and operation and maintenance (O&M) activities. With FOWT being more complex due to their dynamic nature and location in deeper waters, several key innovations in access technologies are transforming the way these turbines are maintained and operated.

- Self-Erecting/Hoisting Crane Technologies



Figure 3.6: Blade installation/repair using the [WindSpider](#) crane technology

These cranes provide a versatile and cost-effective solution for replacing major turbine components offshore, eliminating the need to tow turbines back to port. They can be adapted to various turbine models and sizes, simplifying logistics and reducing costs associated with wind turbine maintenance. The challenge lies in mounting the self-erecting crane onto the FOWT and in the maximum loads the crane can lift.

- Motion Compensation Systems for Cranes



Figure 3.7: Active heave compensation by [Sequalize](#) for heavy lifting operations

Active Heave Compensation (AHC) systems are crucial for cranes used in the installation and maintenance of floating wind turbines, as they counteract the vertical motion caused by waves on floating platforms or vessels. AHC systems actively adjust the crane's movements to stabilize the load, ensuring precise lifting and positioning even in rough sea conditions. This technology is particularly relevant in the floating wind industry, where offshore operations are often conducted in deep waters with significant wave activity. Although AHC systems are relatively new and still under continuous development, they will play a critical role in floating-to-floating operations, where cranes on floating vessels are used to lift and install components on floating wind platforms. By minimizing the impact of wave-induced heaving, AHC systems enhance safety, reduce operational delays, and increase the workability window for installation and maintenance. This improves the efficiency of marine operations, lowers project costs, and helps ensure continuous operation in challenging sea conditions, making AHC systems essential for the growing floating wind sector.

4 Emerging Concepts and Technologies

Industry 4.0 is transforming the offshore wind industry, by the integration of intelligent information and communications technology to create a network of real and virtual devices [35]. Technological advancements are driving significant improvements in the efficiency, reliability, and safety of offshore wind operations. The use of robots allows maintenance tasks to be performed autonomously or remotely by technicians, which reduces the risk for technicians in harsh offshore conditions.

Additionally, the abundance of data generated by offshore wind farms allows for data-driven optimization of maintenance strategies, leading to fewer interventions and less downtime. Figure 4.1 shows the distribution of high potential incidents¹ per location for offshore work in 2022. It can be noted that almost 80% of all high potential incidents occurred offshore. This percentage can be drastically reduced by replacing human offshore work with robots and by using smart algorithms to optimize maintenance. This chapter describes first the robotization of offshore wind farms, and secondly the use of data analytics.

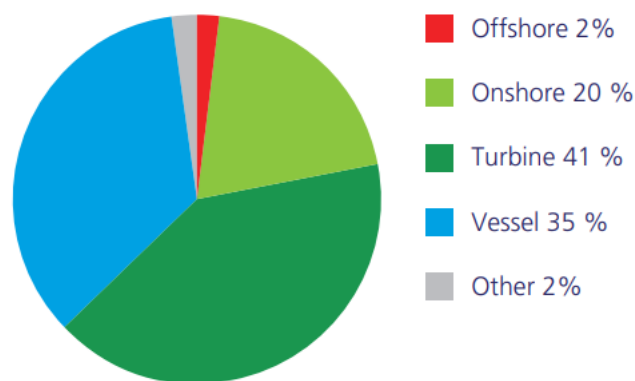


Figure 4.1: distribution of high potential incidents in 2022 [36]

4.1 Robotics in Offshore Wind

The use of robots is not only an improvement in the safety of offshore wind but it can also lead to increased efficiency. Robots can work in harsher weather conditions and in the case of (semi-) permanent robots which are 24/7 on location, there is no need for expensive vessels, and they can intervene immediately to minimize downtime.

¹ High potential incidents are incidents or near misses that have the potential to cause a fatality or life changing injury

4.1.1 Remotely Operated Vehicle

Remotely operated vehicles (ROVs) in offshore wind generally refer to underwater robots controlled by a technician on a vessel or on land. These multifunctional vehicles assist in the maintenance and visual inspection of foundations and cables. ROVs are typically equipped with cameras and, depending on their class, robotic arms.

ROVs are classified into four main categories:

- **Work Class ROV:** weighing several thousand kilograms, are substantial systems that require large support vessels and specialized launch and recovery systems. These vehicles, operated by multiple skilled technicians, are equipped with powerful manipulator arms capable of handling heavy tools and performing complex tasks. As such, they are indispensable for the installation, repair, operation, maintenance, and recovery of offshore infrastructure.
- **Light Work Class ROV:** weighing several hundred kilograms, are typically deployed from smaller vessels than larger work-class ROVs. While these systems offer a balance between size and capability, they are limited in their power output and manipulator strength. They are well-suited for tasks requiring moderate interventions, such as object retrieval and the operation of medium-sized tools.
- **Observation ROV:** weighing up to 100 kg, these ROVs can be deployed from smaller vessels compared to work-class ROVs. Given their size and technological constraints, they are typically used for visual inspections and basic manipulation tasks, such as object retrieval, using less sophisticated robotic arms.
- **Mini ROV:** these ROVs, weighing less than 50 kg, are primarily deployed as observation tools for visual inspections. In some cases, they may be equipped with simple gripper arms for basic manipulation tasks, such as retrieving objects from the seabed [37].

Currently, most ROVs are hydraulic and tethered to a support vessel, which provides power and control signals. However, the cable limits the range and has the risk of becoming entangled with, for example, the ship's propeller.

To address traditional ROV limitations, untethered electric versions are emerging as a promising alternative. They are more environmentally friendly, lighter, and have fewer components, leading to increased reliability. Additionally, electric ROVs can be deployed as resident systems “living” within a wind farm and can be charged in underwater E-garages. This approach offers greater flexibility and efficiency in offshore operations [38].



Figure 4.2: a light workclass ROV from Boskalis, Seabeam Panther-X Plus [39]

4.1.2 Unmanned Surface Vessel

An Unmanned or Uncrewed Surface Vessel (USV) is, as the name suggests, a vessel that can operate without a crew. The USV is controlled from a remote operation centre onshore, which reduces safety risks. USVs can be deployed for several tasks: 1) inspection of offshore assets such as foundations, scour protection and cables, 2) unmanned logistics from shore to SOV or from SOV to wind turbine and 3) hydrographic and geophysical surveys. Additionally, some USVs can be used for multimodal operations and can transport an (e)ROV, UAV or AUV to exploit synergies between tasks, improve workability and reduce costs.

Despite their potential, USVs currently face regulatory constraints. International regulations, primarily established for manned vessels, have not yet fully caught up with developments in unmanned technology. A key challenge is the requirement for a human captain on board under the Safety of Life at Sea (SOLAS) framework for safety and legal purposes. Currently, USV testing is conducted under the supervision of accompanying manned vessels and in designated areas. To unlock the full potential of USVs, international cooperation through the International Maritime Organization is crucial. Updating the SOLAS framework to address unmanned operations is an important step. One of the key issues to be resolved is establishing a clear line of responsibility in the event of USV incidents.



Figure 4.3: Fugro Orca USV [40]

4.1.3 Unmanned Aerial Vehicle

The use of Unmanned Aerial Vehicles (UAVs), also known as drones, is common practice in the offshore wind sector [41]. These vehicles are used for inspection, especially for rotor blades, and transport. For inspection, drones are equipped with high-resolution digital cameras, infrared thermographic cameras, X-ray equipment, LiDARs or a combination of these enabling detailed inspections of wind turbines. Digital cameras capture visual data of the tower, nacelle, and rotor blades, while thermal cameras detect potential structural defects by identifying temperature anomalies. LiDAR, on the other hand, provides accurate 3D point cloud data, allowing for detailed measurements of the turbine structure and its surroundings. Traditionally, these inspections were conducted by teams of rope access technicians, a labor-intensive, weather-sensitive and time-consuming process. However, with the advent of drone technology, inspection times have been halved for an average wind farm [41].

The current transport drones can carry up to 100kg of cargo. The results of the tests performed with these are promising. For example, transporting a normal load, of evacuation equipment, from a vessel to a nacelle with a drone takes only 4 minutes. Without drones, cranes are required, and the total duration can be up to 6 hours [42]. With increasing flight ranges and the ability to carry heavier loads, drone technology is developing rapidly. This year in June, the German Aerospace Center opened an area where drones can be tested with a take-off mass of up to 800 kilograms and can also operate beyond visual line of sight (BVLOS) [43]. It is likely that in the long-term future drones will also transport technicians to the wind turbines.

However, the deployment of BVLOS drones in offshore wind activities is currently hampered by regulatory challenges. International cooperation is needed to develop a uniform framework for operating drones in offshore environments. While national aviation authorities are beginning to explore the potential of BVLOS activities, challenges remain, particularly with regard to airspace management and safety concerns. For example, the presence of recreational aviation activities, such as recreational aircraft and paragliding, may pose additional risks to drone operations. The Netherlands, for example, is experimenting with designated flight corridors over coastal areas. Ensuring safe coexistence with these activities requires careful planning and coordination. Furthermore, the transition to international airspace beyond 12 nautical miles introduces further complexity, as national aviation authorities have limited control over these areas.



Figure 4.4: Heavy-lift drone transporting cargo from a vessel to the nacelle of a wind turbine [44]

4.1.4 Autonomous Underwater Vehicle

Autonomous Underwater Vehicles (AUVs) are robots that operate underwater without direct human input. The tasks for AUVs are similar to ROVs or USVs but instead of being operated by a pilot AUVs are autonomous.

To this day, AUVs are primarily used for bathymetry surveys, since the technology for fully autonomous inspection of underwater infrastructure and foundations or the marine environment is not yet mature and still under development. However, technological advancements are enabling them to undertake more complex tasks, such as the inspection of underwater infrastructure and the marine environment.

For instance, Lobster Robotics has developed the Lobster Scout, an AUV capable of capturing high-resolution, georeferenced images of the seabed with a resolution of up to 1.6 mm per pixel. This level of detail allows for precise inspection of underwater infrastructure and marine ecosystems. Furthermore, Lobster Robotics leverages artificial intelligence to analyze the collected data, identifying various species and generating valuable insights about the seabed [45].



Figure 4.5: AUV from ECA Group [46]

4.1.5 Residential Vehicles

Residential vehicles are robots that “live” at the offshore wind farm. Residential vehicles, or robots stationed permanently or semi-permanently at offshore wind farms, offer significant advantages in terms of cost, safety, and operational efficiency. ROV's can be housed in underwater garages, while USVs and AUVs can be docked at charging stations and UAVs can be returned to a drone platform. At these locations, they can share their sensor data to the outside world, be recharged, refueled, and updated with the latest software and weather data pertinent to the wind farm. This ensures their readiness for immediate deployment [47]. This approach reduces the reliance on support vessels, leading to lower operational costs and a smaller environmental footprint. While the use of residential vehicles is still in its infancy, there are companies conducting pilots.

For example, Saipem's Hydrone-R has completed this year a six month period of continuous autonomous and remotely controlled work. The underwater drone, which is a combination of an ROV and AUV depending on whether it is remotely controlled or not, perform inspections and interventions on subsea assets of a Norwegian oil and gas field [48].

Further, Eelume has designed a residential system in the shape of an eel with a diameter of only 20cm. This innovative robotic arm can travel long distances, conduct inspections, and perform light interventions on subsea infrastructure, such as pipelines. Eelume's unique modular design allows for various configurations and payloads, enabling it to adapt to different operational tasks [49] [50].

Another example of a more semi-residential design, Oceaneering has developed the Liberty Resident system with a mobile docking station. The docking system can be deployed with ROV or AUV at a desired location and the mothership can then move to another location for simultaneous operations.

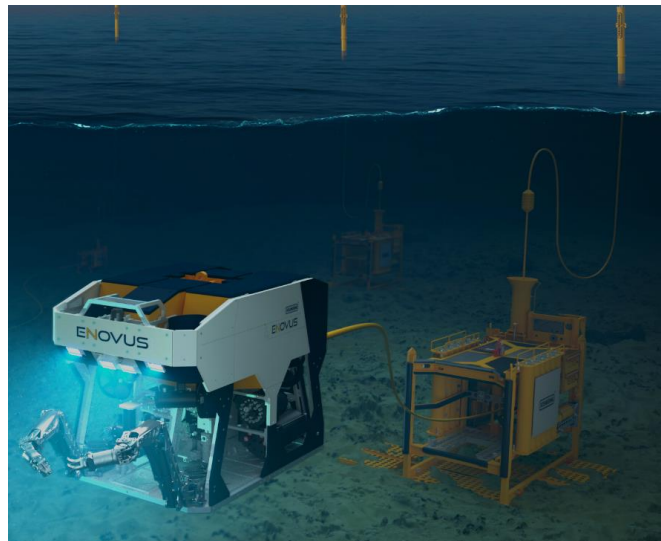


Figure 4.6: semi-resident ROV [51]

4.1.6 Overview

In general, the robots that are currently deployed in the offshore wind sector primarily serve inspection, survey, transport, and repair functions. The use of robots offers several shared advantages, including improved safety by reducing manual labor, faster completion of the tasks and increased sustainability through the use of smaller, less polluting vehicles.

However, fully autonomous robots are not yet widely adopted due to regulatory hurdles and technological limitations. Complex tasks, such as repairs, often still necessitate human intervention, although simpler repairs can be carried out by ROVs. This is also a concern for wind farm operators, as robots can currently only perform relatively simple tasks and often struggle with non-standard tasks or unexpected real-time situations. This means that technicians are often still required to execute the work and it is less cost-effective to purchase an expensive robot. Additionally, social acceptance of autonomous robots remains a significant consideration for the industry. Table 4.1 shows an overview of the advantages and disadvantages per robot.

Despite these challenges, ongoing technological advancements hold the promise of fully autonomous wind farms in the future. As these technologies mature, they have the potential to revolutionize offshore wind operations, increasing efficiency, reducing costs, and minimizing environmental impact. Figure 4.7 shows a floating wind turbine with all kinds of (autonomous) robots with their charging points.

Table 4.1: Advantages and disadvantages per robot

	Remote Operated Vehicle - ROV	Unmanned Surface Vessel - USV	Unmanned Aerial Vehicle - UAV	Autonomous Underwater Vehicle - AUV	Resident
Pros	– Safer: no risky diving operations are required	– Safer: no human intervention – Sustainable: due to the size of the vessel (less fuel 97% Fugro) – Costs: less expensive compared to crewed vessels – Flexibility: no crew is needed – Operating windows: higher weather limits – Multimodal: can carry an ROV, AUV or UAV	– Safer: no human intervention – Sustainable: less emissions due to size of the UAV compared to vessels and helicopters for transport – Costs: they can perform inspection (2 times faster) and transport cargo faster (10-15 times) than traditional methods – Accessibility: UAVs can inspect difficult to reach locations	– Autonomous – Sustainable: less emissions due to size of the AUV compared to vessels – Accessibility: AUV have larger operating windows and can operate in deeper waters – Costs: AUVs can perform a bathymetry survey significantly faster than traditional vessels	– Availability: 24/7 on location and immediately deployable. Resulting in quicker intervention and less downtime – Sustainable: no vessel transits needed anymore
Cons	– Dependence on a support vessel – Limited mobility due to tether	– Regulations – Social acceptance: aspects related to the acceptance of robotics, such as human trust in the robots	– Regulations – Limited carrying capacity – Limited weather limits – Limited flight time: due to battery	– Regulations – Data quality: does not meet the quality of the traditional vessel – Less suitable for complex tasks – Communication – Limited operation time: due to battery	– Regulations – Costs: high initial costs while the robot is idle for most of the time – Complex technology (immature) – Lower flexibility



Figure 4.7: floating wind turbine with multiple (autonomous) robots and their charging points [41]

4.2 Data Analytics

In the previous section, the robotization of wind farms has been discussed, but the ongoing digitalization also brings further automation and in-depth modeling of offshore wind farms. This section discusses the further applications of data in offshore wind access. This means, for example, that data is used to train technicians, optimize maintenance planning, reduce the number of interventions, and develop a digital twin for monitoring the wind turbine.

4.2.1 Reducing Number of Interventions

By using data analysis, the number of interventions can be significantly reduced. There are three key areas where data can play a role in reducing the number of interventions. The first is adaptive control: by knowing the weather conditions and the types of loads they impose on the wind turbine, the configuration can be adjusted to obtain an optimal yield-load ratio. Secondly, data can help to perform maintenance when it is most effective in terms of costs, stand-still and duration of repair. For this, it is important to know the real-time status of the wind turbine and the failure probabilities of the components. Finally, by optimizing logistics planning, maintenance tasks can be combined, reducing the number of turbine accesses.

4.2.2 Digital Twin

Nowadays, all kinds of sensors are placed on wind turbines to collect data about the performance and the conditions of components. These sensors measure, among other things, vibrations, temperature, oil pressure, voltage, strain, loads, and wind speed. This data can be used to develop a virtual model of the real wind turbine, a so-called digital twin, to monitor the real-time status of the wind turbine. A digital twin is a powerful tool for monitoring and maintaining the wind turbine. For example, using advanced models in combination with continuous input of measurement data allows the digital twin to calculate what happens in places in the turbine that are not equipped with sensors. Thereby, it can also simulate what

happens if a specific component is repaired or replaced. This can support the windfarm owners to do effective maintenance at the right time.

4.2.3 Predictive maintenance

Monitoring the current status of the turbine and acting on this is called condition-based maintenance. On the other hand, predictive maintenance takes it one step further by predicting when the turbine will need maintenance. Advanced data analytics and machine learning models use historical data to identify patterns that indicate wear and potential failures. Maintenance is then attempted before a failure occurs. In practice, this means that intervention is made when a certain threshold value is exceeded. The optimal timing of maintenance is a delicate balance: delaying maintenance risks potential failures, while premature intervention can lead to unnecessary costs. By strategically scheduling maintenance, the goal is to maximize turbine uptime and lifespan.

4.2.4 Opportunistic maintenance

Opportunistic maintenance (OM) is a strategy aimed at maximizing the efficiency of maintenance activities. It involves flexibly using advantageous moments or opportunities to perform maintenance. Instead of strictly adhering to predefined schedules, OM uses situations that present themselves as opportunities to perform maintenance, with minimal additional travel costs or downtime. This results in cost savings and increased turbine availability. A distinction can be made between three different types of opportunities:

- **Despatch-based opportunities:** bundling maintenance tasks when vessels are already scheduled for planned or corrective maintenance, these vessels can also be used for other tasks because they are already on location.
- **Access-based opportunities:** planning maintenance in favorable weather conditions which minimizes the delays.
- **Market-based opportunities:** planning maintenance during periods of low energy production or low energy prices to minimize the production loss during the maintenance task. High availability and low prices of vessels and technicians belong also to this opportunity.

To properly implement this complex logistics strategy, a lot of information is required. The complete maintenance planning must be known, preferably also from nearby wind farms. Whereby maintenance planning consists of planned, corrective and preventive maintenance for which also data-driven decisions must be made to determine whether it is beneficial to perform the maintenance task now instead of at a later time. If opportunistic maintenance is performed well, it can lead to fewer vessel trips. This in turn increases the availability of vessels and technicians. Furthermore, it will be safer when there are fewer trips because the total time spent offshore is reduced. It will also reduce the direct costs of the operation meaning the production loss and maintenance costs.

4.2.5 Virtual Reality Training

Today, several companies are offering virtual reality (VR) training for offshore wind energy. This relatively new technology has many advantages with safety first. With VR training technicians can practice dangerous procedures in a safe, controlled environment. Since only a VR headset is needed for training it is also cheaper and less time consuming compared to physical training as no training rooms or costly training setups, such as full scale nacelles, are needed and fewer instructors. The training itself can also be repeated as often as necessary.

Often the trainings are also fully monitored, meaning that data-driven evaluations can be used afterwards to determine where the trainee needs additional support or the training method needs to be improved [52].

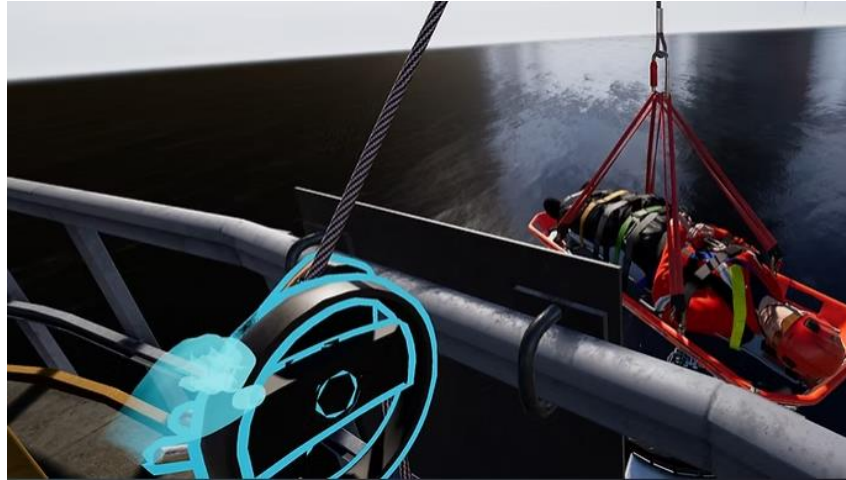


Figure 4.8: VR training [52]

4.2.6 Augmented Reality

While not yet adopted in the offshore wind industry, augmented reality (AR) holds significant potential to enhance maintenance operations. By overlaying digital information onto the real-world view, AR can provide technicians with real-time guidance and support. For instance, remote experts can observe the technician's work through an AR device and offer step-by-step instructions for complex tasks. Manuals, data logs or instruction movies can be projected through the AR device to offer the on-site technician with all the relevant information needed to come to effective solutions.

5 Modelling offshore accessibility

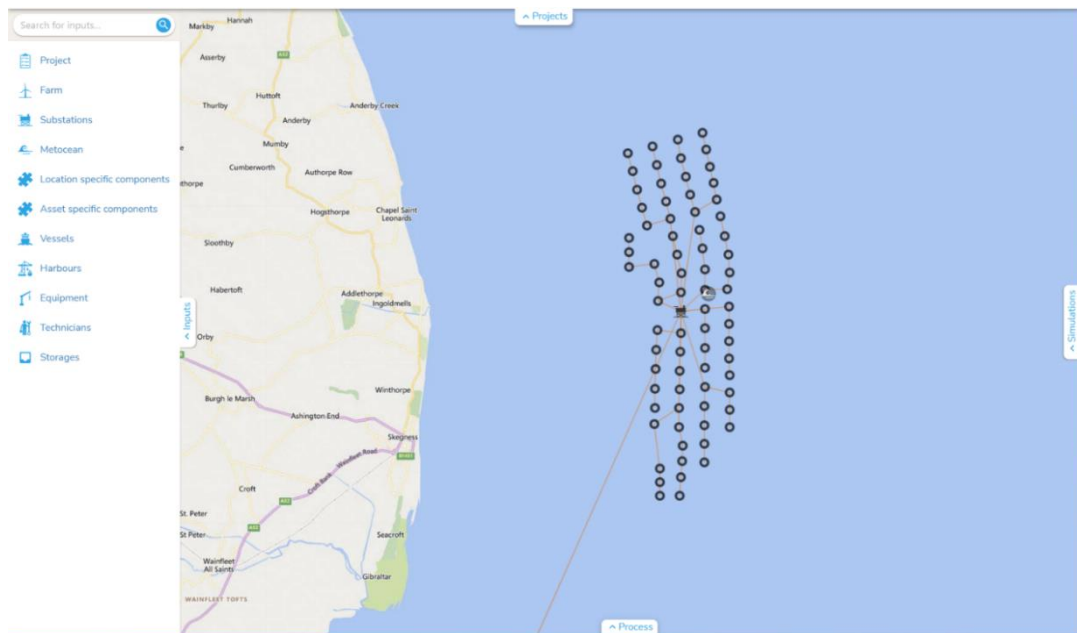


Figure 5.1: User interface for UWise tool showing the list of user defined inputs and offshore wind farm location

In the development, operation, and maintenance of offshore wind and solar PV farms, effective logistics and planning are critical to ensuring cost-efficiency and maximizing energy production. Modelling offshore accessibility plays a pivotal role in this process, as it directly impacts the operational strategies of installation, maintenance, and decommissioning phases. This chapter explores the significance of accessibility modelling and highlights the capabilities of advanced simulation tools like TNO's Unified Windfarm Simulation Environment (UWiSE) in addressing these challenges.

[UWiSE](#), developed by the TNO wind group, is an advanced software platform designed to simulate and optimize logistics for offshore wind farms. Building on TNO's legacy in the wind energy industry, UWiSE integrates advanced discrete event simulation with a map-based graphical interface, providing a powerful tool for industry professionals. It evolved from the widely used "ECN O&M Tool," introduced in 2005, and later refined into the "ECN O&M Calculator" in 2011. As the complexity of offshore wind farm logistics has grown, UWiSE has introduced dedicated modules—Install, O&M Planner, Decommission, and Dispatch—that allow for comprehensive, multi-year simulations of logistics and operations.

This chapter will also include a case study focused on a floating wind farm site, where two distinct maintenance strategies for accessing the offshore location will be evaluated using the O&M Planner module of the UWiSE tool.

5.1 UWise O&M Planner

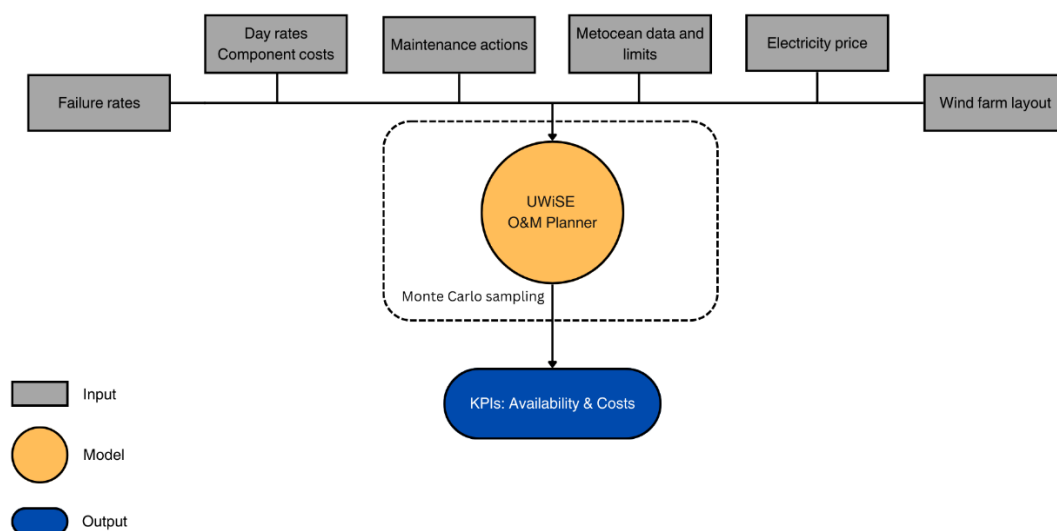


Figure 5.2: Schematic showing the input and output space of UWise O&M Planner tool.

The UWise O&M Planner, employs a time-sequential discrete-event simulation technique to model maintenance operations over a chosen operational lifespan (can be full life time, or a shorter period of e.g. 5 years) of an offshore wind farm. This sophisticated model enables the detailed analysis of expected OPEX (operational expenditure) by integrating both controllable and uncontrollable variables.

Controllable variables encompass factors such as electricity prices, wind farm layout, anticipated component failure rates, day rates, replacement costs, and required maintenance actions. These variables allow operators to manage aspects of the wind farm's operations that can be directly influenced. On the other hand, uncontrollable variables, such as weather conditions, are based on historical met-ocean data, reflecting the inherent uncertainty and variability of offshore operations.

To incorporate variability into both inputs and outputs, UWise O&M Planner utilizes the Monte Carlo technique. Through this approach, pseudo-random samples are generated to simulate failure events based on probability distribution of component failure rates. When a failure occurs, the simulation consults a weather database to assess whether maintenance activities can be performed within predefined operational weather limits.

If the random sample shows that wind or wave conditions exceed the specified weather thresholds, the O&M action is delayed until conditions improve, creating realistic operational scenarios. The total duration of these delays is factored into the overall time required to complete the maintenance, which in turn influences the total O&M costs. This process allows the UWise O&M Planner to provide a detailed and probabilistic evaluation of offshore wind farm maintenance operations, accounting for the unpredictable nature of marine environments.

5.2 Case study

Table 5.1: Wind farm characteristics

Farm layout	100 x 15 MW
Turbine	15 MW NREL reference turbine
Floater	UMaine VoltturnUS-S semi-submersible type
Location	North Sea: MarramWind
Water depth	87 - 117.5 m
Port	Fraserburgh
Distance to port	96.83 km
Operational lifetime	25 years

In this floating wind farm case study, the MarramWind offshore wind farm, located in the North Sea, is selected for simulation to evaluate the performance and logistics of maintenance strategies using the UWise O&M Planner module. The MarramWind site features a water depth ranging from 87 to 117.5 meters, making it only suitable for floating wind turbines. The operational port for the simulation is Fraserburgh, located 97 kms from the wind farm site.

The simulations are set over a 25-year operational lifetime, modelling a fictive yet realistic scenario of 100 floating wind turbines, each with a capacity of 15 MW. The wind farm utilizes the NREL 15 MW reference turbine mounted on UMaine VoltturnUS-S semi-submersible floaters, which are well-suited to the site's water depths. The UWise O&M Planner will be used to analyse a blade replacement replacement activity using two strategies:

- Tow to port for blade replacement

The Tow-to-Port (T2P) strategy involves transporting the FOWT to an O&M port facility where the blade replacement is carried out. This method follows several key steps:

1. **Disconnection and Towing:** The FOWT is disconnected from its mooring lines (MLs) and inter-array cables (IACs), which are securely stored at a designated buoy on the relevant offshore location. Proper sealing of the IACs is crucial to prevent water ingress and subsequent damage to the electrical systems. After disconnection, the FOWT is towed to port using a lead tug and an assisting tug vessel.
2. **Port-Side Blade Replacement:** Upon arrival at the port, the FOWT is positioned, and an onshore crane is used to replace the blade. This step involves precise handling to ensure that the new blade is securely installed on the turbine tower.
3. **Re-Towing and Reconnection:** After the blade replacement, the FOWT is towed back to the offshore site, where it is reconnected to the pre-stored MLs and IACs, ready to resume operations.

The operational limits during this process are dictated by both weather and motion constraints. The key weather parameters include significant wave height (H_s) and wind speed (U_{10}).

Table 5.2: Operation steps for the tow to port operations.



Vessels	Action	Duration (h)	Weather limits [H_s , U_{10}]
Lead tug + Assist tug + Onshore crane	Mobilize vessels	24	-
	Transfer technicians	1	-
	Transit to site	distance/ vessel speed	[3, 12]
	Turn off WT	-	-
	Couple with WT	8	[1.75, 15]
	Disconnect MLs & IACs + joint IACs	60	[1.75, 15]
	Tow WT to port	distance/ towing speed	[3, 12]
	Quayside operation	6	-
	Replace component	MCR (hrs.) component	-
	Test & check WT	3	-
	Couple with WT	8	[1.75, 15]
	Quayside operation	6	-
	Tow WT to site	distance/ towing speed	[3, 12]
	Dejoint IACs	12	[1.75, 15]
	Reconnect MLs & IACs	60	[1.75, 15]
	WT pre run	4	-
	Turn on WT	-	-
	Transit to port	distance/ vessel speed	[3, 12]
	Transfer technicians	1	-
	Demobilize vessels	24	-

- Self-hoisting crane for blade replacement

The Self-Hoisting Crane (SHC) strategy offers an alternative approach, allowing MCR operations to be carried out directly offshore without the need to tow the FOWT to port. This method is advantageous as it mitigates the motion-related challenges of towing and allows for faster completion of blade replacement.

1. Transporting the SHC System: In the SHC strategy, the self-hoisting crane and the replacement blade are transported to the offshore wind farm site on a dedicated platform, towed by a small tug vessel. Upon reaching the site, the platform is ballasted to its operational draft and coupled with the FOWT.
2. Hoisting the SHC to the Nacelle: Once the platform is secured, the SHC is hoisted from the (heave-compensated) platform to the elevation of the nacelle on the wind turbine

- tower. The crane is mounted on the FOWT structure, eliminating relative motions between the crane and the turbine during lifting operations. This stabilization is critical for ensuring the safe and precise handling of the blade during replacement.
3. Blade Replacement Offshore: With the SHC in position at nacelle height, the blade replacement is performed. The SHC system is equipped with stabilization winches to minimize movement during the lifting and installation of the blade, ensuring the component is securely installed on the turbine.

Table 5.3: Operations steps for self-hoisting crane operations.



Vessels	Action	Duration (h)	Weather limits [H_s , U_{10}]
CTV + Small tug + Self hoisting crane	Mobilize vessel	24	-
	Transfer technicians and component	4	-
	Tow SHC platform to site	distance/speed	[3,15]
	Turn off WT	-	-
	Couple SHC platform to WT	1	[2, 15]
	Install crane from platform to tower top	3	[3.5, 15]
	Replace component	MCR (hrs.) $\times$ 1.2	[3.5, 15]
	Lower crane and preparation	3	[3.5, 15]
	Decouple SHC platform from WT	1	[2, 15]
	Turn on WT	-	-
	Tow SHC platform to port	distance/speed	[3,15]
	Transfer technicians and component	4	-
	Demobilize vessels	24	-

In the following analysis, two Operation and Maintenance (O&M) strategies will be evaluated based on two key performance indicators (KPIs): Maintenance and Downtime Cost (MDC) and Time-based Availability (A_T). These KPIs offer a comprehensive framework for assessing the financial and operational efficiency of wind farm maintenance activities in assessing different O&M strategies.

KPI I: Maintenance and Downtime Cost (MDC), expressed in k€/MW/year, encompasses the combined costs of vessel usage, technician labor, spare parts, and revenue losses due to downtime, normalized per megawatt capacity on an annual basis. This KPI provides a holistic view of the financial impact of maintenance on the overall operations and is calculated as follows:

$$MDC = \sum \frac{(C_{v,i} + C_{t,i} + C_{s,i} + L_{r,i})}{MW \cdot year}$$

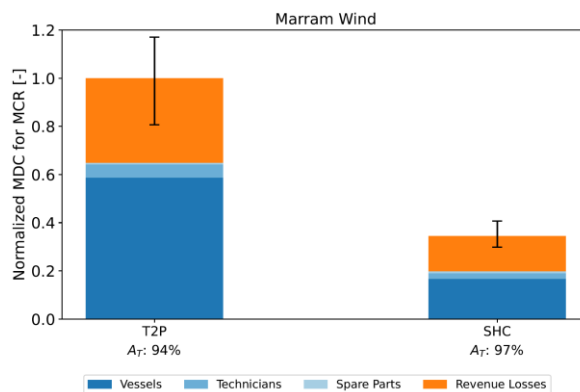
where $C_{v,i}$ is the cost of vessels, $C_{t,i}$ is the cost of technicians, $C_{s,i}$ is the cost of spare parts, and $L_{r,i}$ represents revenue loss due to downtime, with i indicating each O&M action. Here, n is the total number of O&M actions, MW represents the wind farm's total capacity in megawatts, and year denotes the operational period of the wind farm in years.

KPI II: Time-based Availability (A_T), on the other hand, reflects the operational effectiveness of the wind farm by measuring the percentage of time the turbines remain active compared to the total possible operational hours. A higher A_T score signifies reduced downtime and increased energy production. It is calculated as follows:

$$A_T = \left(\frac{T_o}{T_t} \right) \times 100$$

where T_o is the actual operational time, and T_t is the total possible operational time.

It is important to recognize that these KPIs are specific to this analysis and do not account for additional expenses, such as insurance or harbor fees, which may be considered in other studies.



The results for the Marram Wind case study reveal distinct differences between the T2P (Transport to Port) and SHC (Self Hoisting Crane) strategies when evaluated based on the Maintenance and Downtime Cost (MDC) and Time-based Availability (A_T).

The T2P strategy shows a relatively high normalized MDC, reaching approximately 1.0 on the normalized scale. This indicates significant costs due to the combined expenses from vessels, technicians, spare parts, and revenue losses associated with downtime. Notably, vessel costs make up the largest portion of the total MDC, followed by revenue losses, highlighting the substantial costs incurred when turbines are transported back to port for maintenance. This transportation requirement increases both the operational downtime and the financial impact, reducing overall maintenance efficiency. In terms of availability, the T2P strategy achieves an A_T value of 94%, reflecting the effect of extended downtime needed for transporting equipment back to port. The lower availability score for T2P suggests that it may not be the most efficient strategy for maintaining turbine uptime and optimizing energy production.

On the other hand, the SHC strategy exhibits a markedly lower MDC, with values around 0.6 on the normalized scale, which is a significant improvement over T2P. This reduction is primarily due to decreased reliance on vessels, which in turn leads to lower associated revenue losses from downtime. By utilizing self-hoisting cranes for on-site maintenance, SHC eliminates the need for transporting turbines to port, effectively reducing both direct maintenance costs and the overall downtime costs. Additionally, SHC achieves a higher availability score of 97%, indicating greater operational efficiency. This higher A_T value demonstrates that SHC is more effective in minimizing downtime, thereby maximizing the wind farm's energy production potential.

Modelling offshore operations is a complex and multifaceted task that requires careful data acquisition, critical input evaluation, rigorous statistical analysis, and thoughtful interpretation to serve the needs of a diverse range of stakeholders. TNO's expertise in this area is built on years of experience, which includes the development of specialized tools dedicated to the analysis of offshore activities in collaboration with the industry. These tools enable comprehensive evaluations, helping stakeholders to make informed decisions based on robust data insights. For those interested in learning more about this analysis or discussing specific needs, TNO welcomes inquiries and is available for further information.

Conclusions and future outlook

In this report, an updated overview of offshore wind access solutions is presented, covering a wide variety of related topics.

The various access vessels being used for offshore wind O&M have been presented, with an outlook on cargo capabilities, storage and handling. A thorough review of available and new access systems is given, and the importance of considering human factors in O&M operations while selecting vessel and transfer systems is covered briefly.

The emerging topic of accessing floating offshore wind structures has been presented, with an in depth review of the specific challenges and access solutions specific to the floating wind market.

Subsequently, the emerging solutions and technologies in the offshore wind energy access market are highlighted, showcasing various innovative unmanned vessels and digital monitoring solutions that are expected to play a pivotal role in the future of offshore access and O&M operations.

The report concludes with a showcase of TNO's O&M operation modelling tools, such as TNO UWISE, demonstrated through a floating offshore wind access study. This highlights the crucial role of logistical tools in efficient planning and ensuring access to offshore wind energy assets for O&M purposes.

The information presented in this year's report can be used as a baseline to understand the various access solutions currently available to wind farm operators, and fuel initiatives to address the increasing vessel scarcity in the wind energy access market that sometimes causes extended downtime during critical O&M operations.

In addition to the increase in the number of suitable access vessels and the adaptations required to operate further and for longer periods, the sector is witnessing considerable advancements aimed at enabling less impactful maintenance operations. Many of these vessels are now using, or are ready to be converted to, alternative energy systems for propulsion and onboard usage, as discussed in the previous edition of the report. The key focus of innovations on the market should be on minimizing greenhouse gases emissions, enhancing human safety offshore, developing of tailored solutions for new markets such as floating offshore wind, and promoting the use of optimised and smart maintenance.

TNO will follow the developments of offshore wind access vessels and systems and intends to update this report every year, making sure to report on the rapid advances in floating wind access and digitalization while keeping an eye on the latest developments in the field.

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