Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

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Definitions & Abbreviations

FOWT	Floating offshore wind turbine
DOF	Degree-of-freedom
O&M	Operation and maintenance
ROV	Remotely operated vehicle
SPMT	Self-propelled modular transporter
FEED	Front-end engineering design
RFID	Radio-frequency identification
O&G	Oil and gas
TLP	Tension leg platform
WTG	Wind turbine generator

Executive Summary

The content of this deliverable relates to recommendations on floating substructure design. Findings are based on WP5 on industrialisation of floating wind turbine systems as well as other WPs related to this topic and the presented results address different phases of the lifecycle.

First, emphasis is drawn on large scale manufacturing. Different logistics and transport systems are available at production sites. In order to optimise logistical processes, the floater design, existing transport and crane systems and their load carrying capacity, among other things, must be taken into consideration. SPMTs are recommended for transportation of large blocks within the shipyard due to their modularity. Cranes need sufficient lifting capacity and height to carry the different floater components. In order to reduce offshore operations, wind turbine assembly at or near the manufacturing facility is recommended. For large-scale manufacturing of steel floaters, the usage of building shipyards instead of repair shipyards is beneficial. A detailed layout of the facility must be developed and available capacity in terms of the equipment, workspaces and manpower needs to be evaluated thoroughly. Prefabrication of (sub)blocks during fabrication, taking place at a separate site dedicated to handling the production of steel components, is highly recommended. The design must also be subdivided accordingly, and it is highly recommended to involve the manufacturer during the planning in order to consider best manufacturing practices and, eventually, incorporate design changes. Unlike the steel floater manufacturing, the methodology proposed for concrete floaters is more flexible in terms of site selection. Mobile concrete construction plants offer cost and time saving benefits. The use of pre-fabricated rebars instead of pre-cast concrete sub-blocks is also an option.

The installation procedure of a FOWT after manufacturing generally consists of load-out, transit to site and hook-up to mooring lines and dynamic cable. To facilitate the installation process and minimize costs, three main logistical aspects have to be considered: vessel requirements, distance from port to site and weather impact. The weather majorly impacts the installation procedure due to sensitivities of required marine operations to wave height and wind speed. This impact increases for larger distances. It may be, thus, beneficial to invest in closer ports and upgrade its infrastructure. High investments must be compared to the alternatives including higher risks regarding weather forecast and higher vessel costs. Furthermore, the floater towing speed, draft and other requirements, mooring and dynamic cable hook-up procedures and other technical aspects greatly influence installation, particularly for TLPs.

Workability considerations for O&M are mainly driven by the dynamic behavior of a floater design and environmental conditions. The combination of wave height and period is more relevant than the magnitude of the wave height only. Floating structures in general show large amplitude motions with low response frequencies. An evaluation of the frequency response of these structures is advised in order to check if the response spectrum lies within the frequency range that corresponds to the provocation of nausea and discomfort, which possibly increases the downtime.

For floating wind substructures, only limited information about the decommissioning process is available. Generally, floating devices will be detached from the mooring lines and towed to the shore for further decommissioning. Mooring lines may be recovered while pile anchors remain in the sea bed. This is a clear advantage over fixed-bottom structures. The decommissioning can be done, after the floaters are towed back to the port followed by recycling or disposal of the employed materials like steel, concrete, synthetics, etc.

Contents

1. Introduction

This deliverable provides recommendations and guidance on floating substructure design related to the life cycle of a floating wind farm: manufacturing methodologies for steel and concrete floating substructures including logistics at the production site; installation of floating wind farms; O&M considerations with a focus on workability and decommissioning of the structure. It is mainly based on findings and studies from WP5 focusing on industrialisation of floating wind turbine systems.

The baseline scenario for the analysis is based on the two selected LIFES50+ floaters from Dr. Techn. Olav Olsen (concrete semi-submersible) and NAUTILUS Floating Solutions (steel semi-submersible) and the reference wind farm with 50 units and a 10 MW wind turbine, where the production and installation of all floaters shall be completed within 2 years' time.

2. Manufacturing

Both steel and concrete floater manufacturing are considered, and recommendations are provided in the following.

2.1 Logistics at production site

Logistics and infrastructure at the production site are an important influencing factor for the large-scale manufacturing of floaters. The floater design must be taken into consideration to make these logistical processes more efficient. Floater design should enable easy transport operations. Existing transport systems must be analysed based on their dimensions, load carrying capacity and fastening systems and the design of the floater must be adjusted accordingly. E.g. floater design can be adapted for easy loading and offloading on SPMTs by integrating an additional transport pallet to the original design. Submersible Barges can be modified to speed up loading processes of floater sub modules by introducing ramps or sliding mechanisms.

Automatization of the workshop to maintain a constant production flow can drastically impact production times. Gantry cranes having magnetic grippers or similar features can be installed in workshops to minimize time for setup in turn easing the transport of steel sheets during prefabrication. Lifting and height capacities of the cranes must match the maximum weight and dimensions of the prefabricated modules. Sufficient space must be provided in workshops for rework and repair works to be carried out without stoppage of the production line.

SPMTs are recommended for transportation of large blocks within the shipyard. These modular transportation systems allow the transportation of very large structures with high mass, see Figure 1. More modules can be added to the system in order to increase its load carrying capacity.

Figure 1: Left: Transfers of vessel onto barge using SPMT [1]; Right: Shipyard transporters by KAMAG with payloads of up to 1300 tonnes [2].

An upgrade of crane capacities on dry docks is likely required. Not only is it important to ensure that the cranes possess sufficient lifting capacity to carry the different floater components while lifting it to the dry docks, it also needs to be ensured that there are sufficient number of cranes to satisfy the required large-scale production output. Additional cranes may be needed to be setup at the dry blocks to minimize waiting times and quicken the transfer of blocks within the final assembly line, see Figure 2.

Figure 2: Left: Inner lock gate at Harland & Wolff [3]; Right: Navantia Puerto Real Shipyard view of the gantry and construction cranes [4].

It is highly recommended to carry out the wind turbine assembly operations at or near the same facility where the floater manufacturing takes place (Figure 3). This way, the need for offshore operations for wind turbine installation will be eliminated considerably reducing the development time. Investing in a crawler crane of sufficient height, lifting capacity and span specifications must be setup for this onshore operation. The area must be prepared for the storage of wind turbine parts and the unrestricted movement of the crane to increase efficiency.

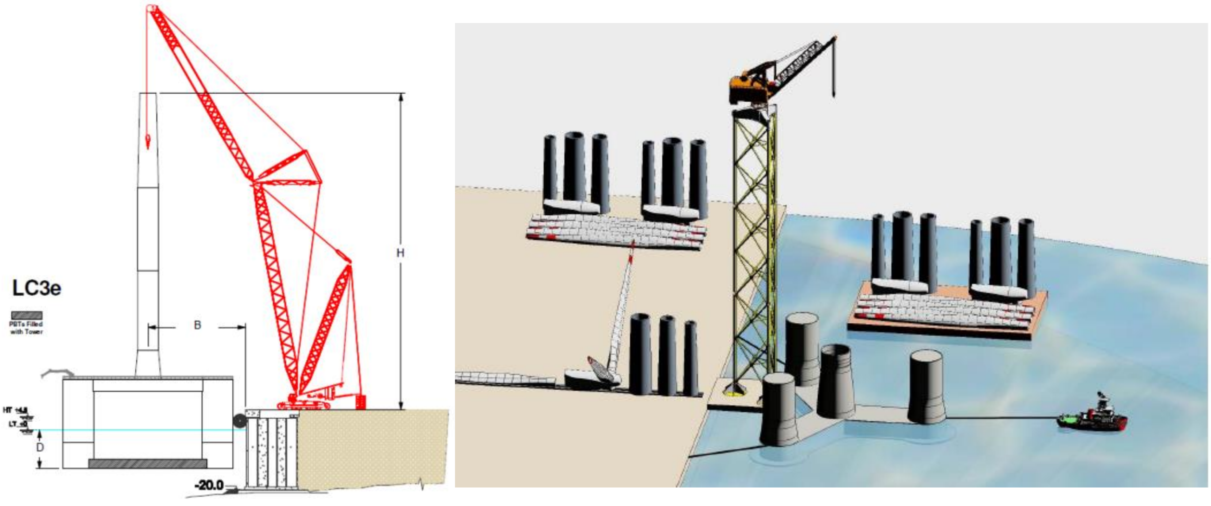

Figure 3: Left: Schematic assembly of wind turbine tower [NAUTILUS Floating Solutions]; Right: Illustration of exemplary wind turbine assembly at quay side [Dr. Techn. Olav Olsen].

In general, it must be ensured that only the optimum logistical pathways and areas are selected so that the travel time is kept at a minimum level. A thorough investigation of these transport lanes must always precede the FEED stage so that the floater logistics can be mapped in an efficient manner. State-of-the-art 3D mapping services are available to accurately map these pathways which can be later used for simulating logistical runs with enhanced precision.

Adequate number of sea transport vessels such as tug boats, sea cranes (if relevant) and barges must be made available based on the required production output. The logistical pathways must also be planned accordingly by taking into account the influencing weather conditions. The distance to the port and the weather in particular have a major influence on planning installation and O&M operations.

Since the manufacturing strategy will be draw on existing infrastructure and shipyards, the influence of other traffic and reserved capacity for other projects must also be assessed. Ideally, shipyards which are relatively less busy must be chosen in order to minimize interferences during the floater manufacturing.

2.2 Recommendations for steel floater manufacturing

For large-scale manufacturing of steel floaters, the usage of building shipyards instead of repair shipyards is recommended as these kinds of shipyards usually have a full-fledged steel fabrication facility close by. In general, shipyards are located at shore or close to the open sea at large rivers which makes them a well-suited production facility in comparison to inland facilities, which increase the overall distance to the farm installation site. These characteristics make these yards well suited for the large-scale manufacturing of steel floaters. The employees of the yard are also well trained in operations related to steel structures due to their experience in dealing with ship building and other offshore O&G structures, maybe even related to wind energy projects such as jackets or monopiles.

Particularly, a manufacturing methodology is proposed that makes usage of existing shipyard facilities. It must be ensured that the chosen facility complies with the dimensions of the floater. A detailed layout of the facility must be drawn considering additional space requirements which may be needed if an upgrade is necessary. Existing fabrication facilities generally have necessary equipment already available according to their ship building and steel fabrication needs. But if a large-scale production scenario needs to be initiated, the available capacity of these facilities in terms of the equipment, workspaces and manpower needs to be thoroughly evaluated and the capacity constraints must be identified. Trade-offs between outsourcing a part of the operations or capacity to other shipyards would then have to be considered and the most economically viable option must be chosen.

Pre-fabrication of (sub)blocks during fabrication is highly recommended, for example refer to Figure 4. This means that the pre-fabrication would take place at separate sites dedicated to handling the production of steel modules for the floater. These modules would be then transferred to the coating area and, finally, to the assembly area where the entire floater gradually takes shape. It must be investigated whether the available workshops are designed to meet pre-fabrication. The design must also be subdivided accordingly into pre-fabrication modules while considering the facility, transportation and manpower constraints. It is highly recommended to involve the manufacturer/fabricator during the planning of block subdivision to ensure the design breakdown takes every aspect of the manufacturing process into account. Manufacturers also are well informed about the best practices and may recommend designers about design changes which may have critical cost saving benefits.

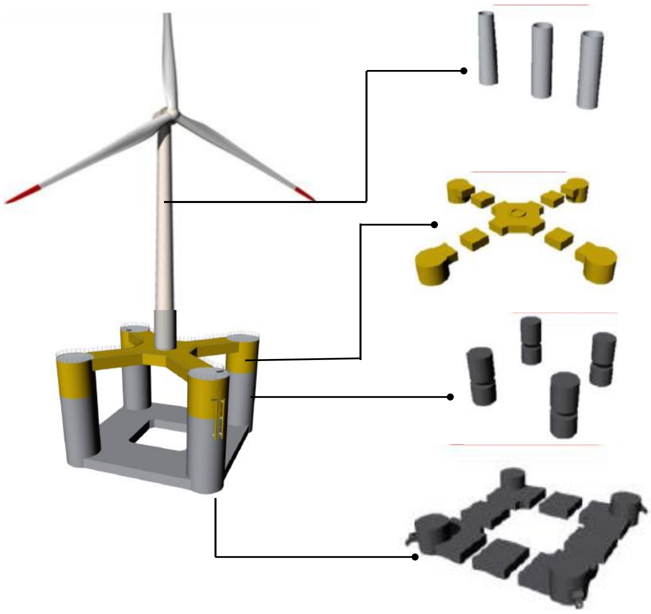

Figure 4. Basic design breakdown of the NAUTILUS floater using sub-blocks [modified from NAUTILUS Floating Solutions].

The list of recommended upgrades needed in case of existing shipyards is as follows:

- Dry docks (if applied) need to be upgraded for final assembly of multiple floaters.
- Inclusion of an additional sea lock within the dry-dock to make more room for final assembly before float-up (depending on the production methodology), see Figure 2.
- Workshop automation by equipping high-tech rolling, bending and cutting machines
- Gantry cranes with magnetic grippers for easy material handling.
- Automatized submerged arc welding machines for better quality and efficient welding.
- Storage areas with high tech RFID tracking system to track material flow is recommended
- Load bearing capacity must be checked for the accommodation of floater parts
- Workshops, coating sites and dry docks must be ideally located close to each other to minimize time spent in logistical operations
- An assembly sequence following a serial continuous production flow is found to perform faster than a parallel batch production flow.

2.3 Recommendations for concrete floater manufacturing

For the large-scale manufacturing of concrete floaters, a manufacturing study performed in the scope of this project proposes the setup of a dedicated manufacturing facility that concentrates solely on producing multiple floater units. Building such a manufacturing facility dedicated to the manufacturing of floating units will be an expensive undertaking involving large capital investments. But the nature of concrete construction allows its construction to take place anywhere given sufficient area is available. So, unlike the steel floater manufacturing which is restricted to shipyards, the manufacturing methodology proposed for concrete floaters is more flexible when it comes to site selection. Inexpensive land can be selected rather than expensive locations.

The nature of concrete construction enables the production to be conducted anywhere. The concrete industry has lately adapted its industrial practices to benefit from the flexibility offered by site selection. Mobile construction sites have recently gained popularity due to their numerous cost and time saving benefits (Figure 5). These sites are characterized by their quick installation times and ability to be adjusted or upgraded economically. Mobile construction sites use modular units for setting up the plant.

The equipment needed for the operations can all be easily transported by normal transport vehicles. The modules also offer ample variations in setting up the facility thereby easing the site constraints when designing the floater. Nevertheless, there is a requirement of setting up a separate facility for pre-fabrication of rebars close to the final assembly site. If this is not possible due to limited space, then the option of outsourcing pre-fabricated rebars must be considered.

Figure 5: Left: Mobile batch plant during transportation [5]; Right: Examples of 'quick assembly' plant modules [5].

The large size and weight of the concrete floater makes it dependent on suitable cranes and lifts. Therefore, the proposed methodology recommends the manufacturing to take place in two distinct phases. The first phase involves onshore construction involving the partial production of the floater. A potential cost-effective alternative for minimizing the investments in heavy cranes to lift the concrete blocks that make up the floater is to use pre-fabricated rebars (Figure 6) instead of pre-cast concrete subblocks. This would enable easy transport of these pre-fabricated rebar modules and also will not require large cranes. These rebars can be transported to the site and assembled to the final shape, following which formwork and casting operations can take place. Considerable planning might be needed during the subdivision of rebar design in order to enable optimal assembly conditions without affecting structural integrity of the structure during its launching and transport operations. State of the art designing software are available to provide optimal rebar and formwork design solutions.

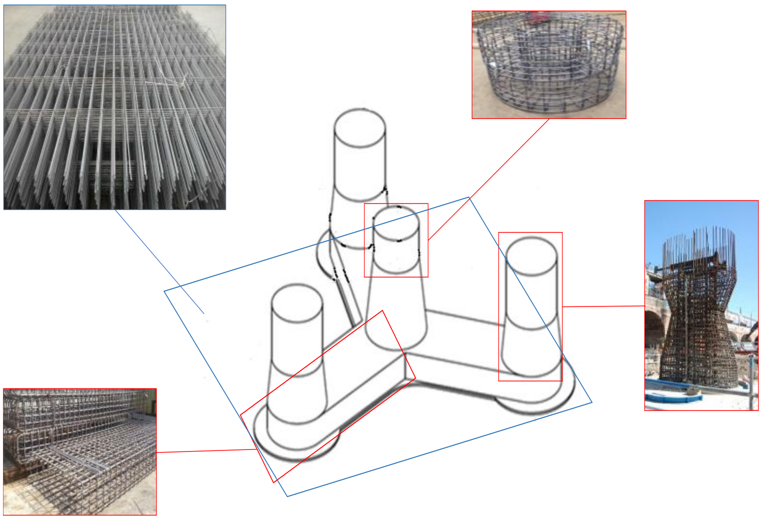

Figure 6. Exemplary subdivision of the floater design into prefabricated steel rebar elements [modified from Dr. Techn. Olav Olsen].

The onshore assembly ends with launching the structure onto a barge that would transport it to a nearby inshore facility where the remaining construction and assembly takes place. During launching the semi-finished structure is skid onto the barge using skid lanes which is a common practice in this industry. It must be ensured that the barge and the onshore cranes offer sufficient load carrying capacity. Moreover, the number of cranes and barges must be adjusted according to the required capacity to meet the demand of the required number of units. Further investigation might be necessary to check whether the structural integrity of the semi-finished structure is maintained during its launch and internal transportation.

The wind turbine assembly on the floater is proposed to be carried out at a separate location/facility with a sufficient draft. Once again, the site must be selected according to the available area for storage of the wind turbine parts and with sufficient number of cranes having sufficient load carrying capacity and additionally sufficient lifting height, particularly for large WTGs. The dimensions of the shipyard docks must be able to accommodate the floater of the desired size and weight. For the storage of the completed floating wind turbine systems, towing them to a separate, sheltered layup site where they are temporarily stored with adequate mooring is proposed. These sites are well regulated and are often used for the storage of container vessels offshore. These storage areas are located offshore, and they usually have very low layup charges in comparison to ports.

3. Floating wind farm installation

This chapter covers the influence of the process of the floating wind farm installation on economic and environmental issues. The installation procedure of a floater consists of different steps and is launched after all shoreside work is finished. Generally, shoreside work implies the fabrication of the floater and the assembly and mounting of the wind turbine onto the floating substructure. It is further assumed that both dynamic cable and mooring system are pre-laid and not part of the herein considered installation process focussing on the substructure.

The float out – as the first part of the installation procedure – of the floater is port specific. For example, in the case of a dry-dock, the dock is flooded, and the floater is towed out, while in the case of a construction barge, the barge is submerged in order to initiate the installation. After the floater is prepared for the transit to the offshore wind farm site, typically involving temporary changes of the ballast, it is moved by appropriate towing vessels. Simple tug boats might be sufficient for self-stabilizing floaters and appropriate proximity from port to site, while projects in regions with more severe weather conditions or larger distances from port to site might require more resistant and specialized vessels. This does not apply for TLPs or other floater types, which are not self-stable. For these floater types, individual transport strategies are developed, usually. After the arrival at the wind farm site, the actual installation is initiated. The mooring lines are picked up by suitable vessels, depending on both mooring and site characteristics. Conditional upon the chosen technology, the hook-up is made. After the floater is connected to the mooring system, its ballast is adjusted in order to reach stable and safe operating conditions. Afterwards it is connected to the grid by attaching the pre-laid dynamic cable. Finally, the installation is terminated by testing and confirming the floating wind turbine functionality and operation.

In the following sections main influences and mutual effects of this installation process on other project phases are described. These are summarised as economic considerations. Additionally, main stakeholder considerations are taken into account.

3.1 Economic considerations

The choices, which are made within the installation procedures, also affect other phases of the project or are influenced by them. In order to facilitate the installation process and minimize its costs, three main aspects have to be considered: Firstly, the required vessel types, secondly, the distance from port to site and, thirdly, the weather impact. While less specialized vessels are both better available and also less cost intensive due to lower charter rates, they can only be utilized, if the boundary conditions are suitable. This directly relates to the other two main aspects, mentioned above.

The weather majorly impacts the installation procedure primarily by governing the timeframes when installation vessels can operate and necessary marine operations are performed, such as the connection of the floater to the mooring lines. This impact increases if larger distances have to be covered and therefore require more time. This leads to increased risk regarding the accuracy of weather forecasts and higher contingency considerations. Smaller distances between port and site therefore reduce the weather impact and reduce risk and cost. The influence of the weather and the resulting increased stand-by times are illustrated exemplary in Figure 7 for the LIFES50+ site B (Gulf of Maine, medium weather conditions) and site C (West of Barra, severe weather conditions) (see definitions in [6]). Differences arise in terms of the installation times and costs.

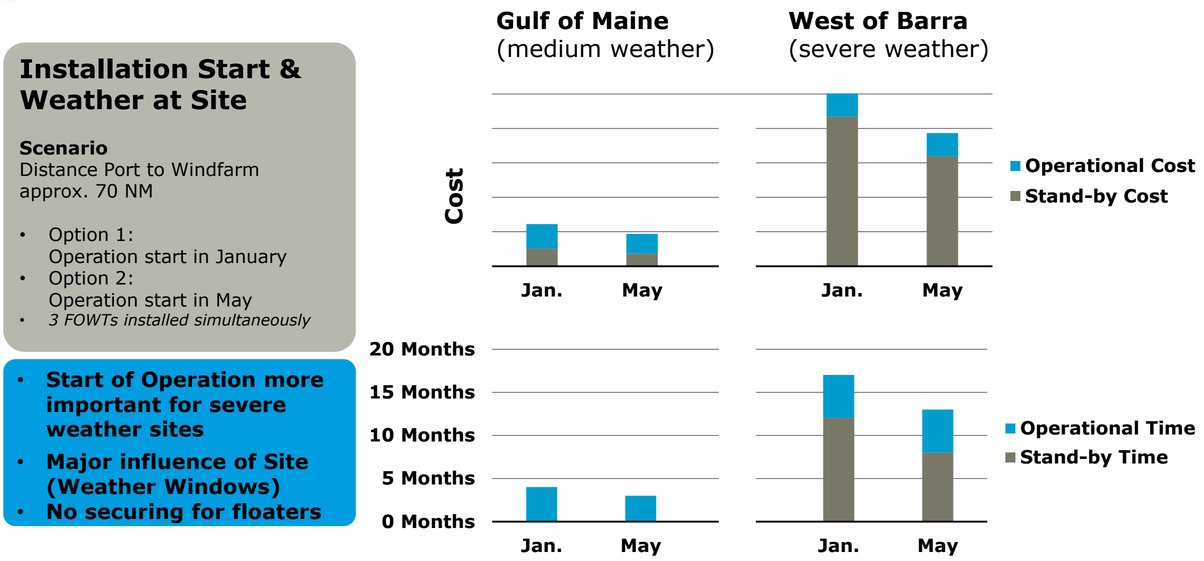

Figure 7: Influence of environmental conditions and installation start.

Regarding the port choice, economic factors become crucial. The optimal port meets the high infrastructure requirements of floating wind and is located in the direct proximity of the intended wind farm site. If this is available, the effect of the other mentioned factors is minimized. As for LIFES50+ site C (West of Barra) [6], deep-water sites, which can be exploited by floating wind, are often distant from suitable ports. It can then be considered to invest in a closer port and upgrade its infrastructure for the requirements of the project. The likely high investments must be compared to the alternatives including higher risks regarding weather forecast and higher vessel costs. A comparison of those two options of either a close port which requires certain upgrades and a more distant port are compared for LIFES50+ site C in Figure 8. As a result, additional costs and time for the different distances are found.

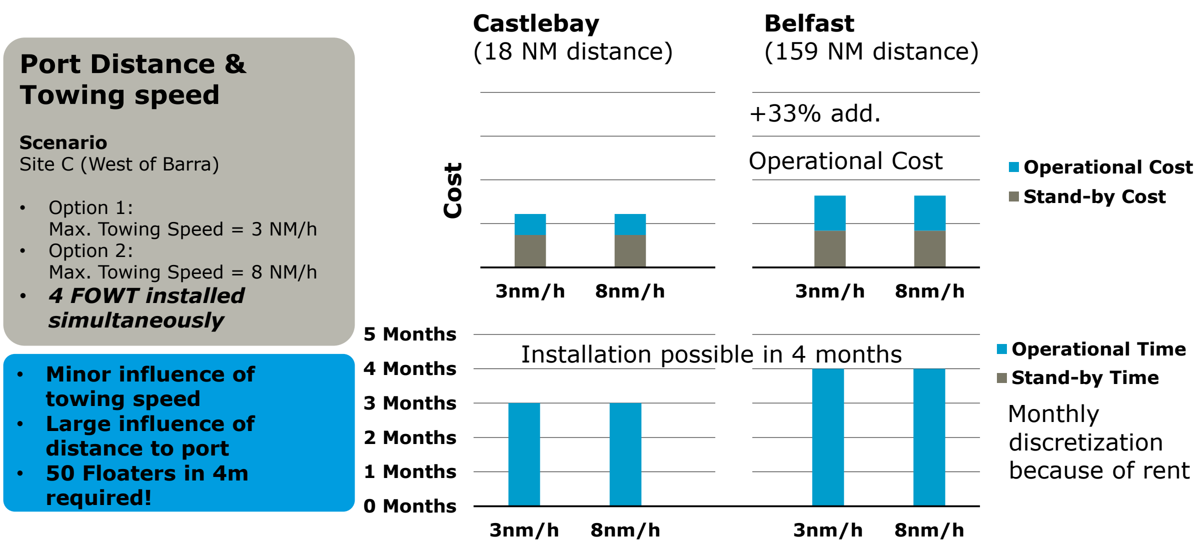

Figure 8: Influence of port distance and towing speed, 4 FOWTs installed in parallel.

These three main aspects, vessel types, port-site distance and weather impact, are also the factors which influence further operational processes in the life cycle of the wind farm. For all manufacturing processes, O&M, logistics and decommissioning, these factors are important. The infrastructure and accessibility of the port is especially important for logistics and manufacturing considerations. Regarding these two, existing ports with possible ship yard infrastructure would be favourable. For O&M and decommissioning phase, the proximity and the independency of weather are higher rated, which would favour closer ports instead. It can be summed up, that if no ideal port exists, often trade-off considerations are governing: Often, an advantage for one phase or aspect can result into disadvantages for another phase or aspect. The ideal solution is therefore very much dependent on the project characteristics, e.g. the chosen substructure concept.

The above discussion furthermore does not include floater design aspects such as the complexity of the required marine operations, which varies significantly amongst different concepts. TLP and spar designs are more challenging due to the tendon system installation being more complex and challenging, respectively the deep draft of the spar limiting port selection and possibly requiring large heavy lift vessels for near-shore WTG assembly.

3.2 Stakeholder considerations

Apart from the operational and technical aspects, external stakeholder interests may also be influenced by the installation process. Regarding environmental impact, floating wind has the potential, to decrease the ecological impact on the marine ecosystem in comparison to conventional offshore structures. For example, noisy hammering during the installation, as in the case of monopiles, is not required and the impact is eliminated for floating. The anchor systems are, in the case of drag embedded anchors, also fully recoverable. This further reduces the environmental impact.

The installation procedure itself does not influence other major stakeholders. For floating wind farms in general, military and cargo transport should be taken into account in order to ensure a safe and undisturbed operation of the wind farm.

The impact of the mooring line resting and moving on the seabed, particularly for large footprint catenary steel chain system may be a problem for marine life. Also reports suggest possible risks for whales and other larger species regarding entanglement and/or marine space blockage.

4. Operations and maintenance with a focus on workability

Floating offshore wind turbine (FOWT) structures in general have a higher motion response in all six DOF in comparison to fixed-bottom structures. This fact should be taken into account evaluating the accessibility of a floating substructure during the Operations & Maintenance (O&M) phase. In case of floating units, access is not only obstructed by wave height, but also by various other factors that influence the structure's dynamic motion assuming the turbine is not in operation. These factors range from wind speed and direction, turbulence, wave characteristics and currents to ice and marine growth [7]. They also substantially impact weather windows (see also section 3), in turn affecting accessibility times. However, accessibility must not only consider weather windows, but also consider the motion criteria for working conditions on the offshore floating structure. These are basically times at which the structure can be accessed but workability is compromised due to increased exposure to motion [8].

There have been several studies investigating the impact of motion on workability and the different types of health risks have also been addressed. But it was found that most of these studies were conducted for high frequency motions (global and local motions of the body). However, the global motions experienced on FOWTs are typically in the lower frequency ranges (below 1 Hz). This phenomenon is also known as the whole-body vibration and is a common cause for motion sickness and feelings of nausea. This puts floating offshore wind turbine substructures out of the scope related to assessable working conditions [9].

Since existing standards and design practices did not evaluate the impact of low frequency motion on humans adequately, separate workability studies were conducted. These studies indicated that humans are limited in ability to work in certain conditions, which further reduces the downtime. It was found that most of the non-workable conditions were caused by translational accelerations rather than rotational motions. Another counterintuitive finding was that workability did not necessarily get worse at higher sea states and found to be even more significant at lower wave height and low frequency sea states [8]. Indeed, the combination of wave height and wave period is more relevant than the magnitude of the wave height only. The results from the workability studies showed that there is a 5% reduction in weather windows for maintenance related activities when threshold values for motion exposure are considered, which in turn increases downtime and reduces availability. The reduction in availability may lead to financial losses or higher investor risk while investing in FOWT technology. For this reason, it is recommended to consider the motion criteria in the design phase of a new project [8].

A general methodology to determine a workability index (as the fraction of time in which maintenance tasks could be carried out) is presented in Figure 9. Extensive aero-servo-hydro-elastic simulation studies with three-hours of interval (step 3 were also conducted to assess the workability of FOWT concepts, at site conditions similar to the three LIFES50+ selected sites (see reference sites in [6]). In these studies, the workability of four FOWT systems with the 10 MW turbine as mentioned in [8], were compared to that of a baseline monopile foundation carrying an 8 MW turbine. The results showed that workability is potentially hindered for both the fixed-bottom and floating structures. Fixed-bottom structures do not necessarily perform better. However, floating structures in general show larger amplitude motions with three out of four floaters exhibiting less favourable conditions than the fixed-bottom structure. But surprisingly, one floater (semi-submersible type) showed to be less critical to workability than the fixed-bottom type.

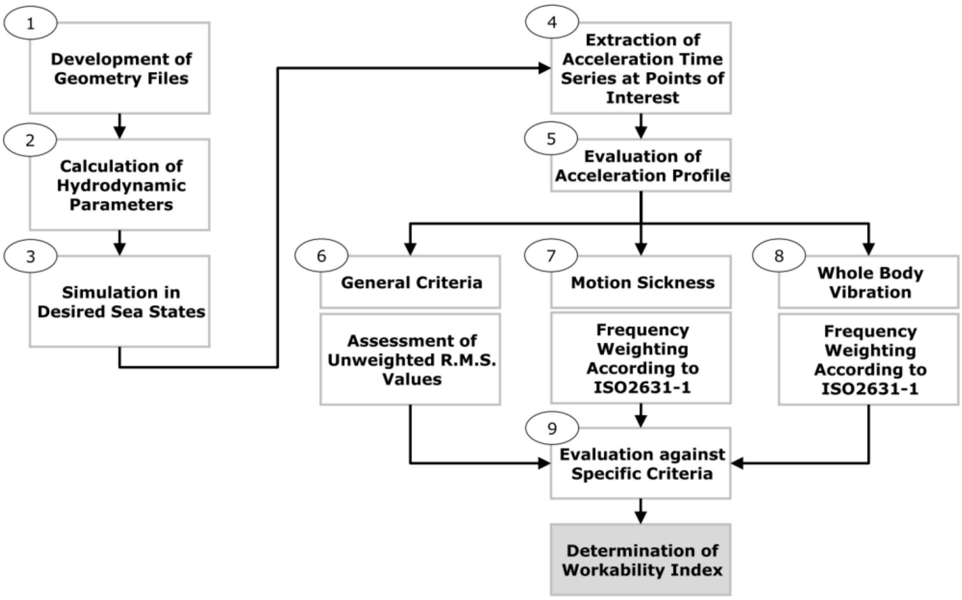

Figure 9. Methodology for determination of workability index for floating offshore wind turbines from [8].

The simulations showed large amplitude motions with low response frequencies for FOWT structures. Evaluating the frequency response of these structures during the design phase is, thus, highly recommended in order to check if the response spectrum lies within the frequency range that corresponds to the provocation of nausea and discomfort, see Figure 10.

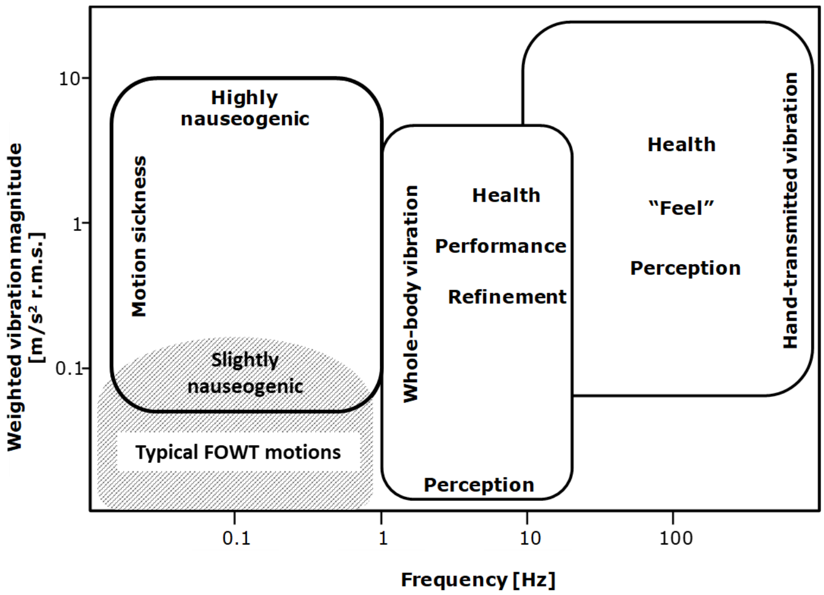

Figure 10. Classification of motion characteristics modified from [10].

In addition to that, the amplitudes must be compared with acceleration limits. Besides, the severity of the effect of whole-body vibration on human comfort is assessed based on the acceleration and frequency parameters of an oscillating signal. However, it is still hard to assess the health risks to the well-being from a working environment in which humans are exposed to significant motion, as clear acceleration limits for certain working conditions on (floating) offshore structures have not been defined yet. Furthermore, the sensitivity to motion varies from person to person making the definition of fixed motion criteria challenging. Moreover, the impact of decreased workability on downtime under certain sea states was found to be highly site specific. Hence, a comparison between the motion response of an asset, irrespective of floating or fixed bottom types, and the site conditions should always be made before drawing conclusions. The dynamic behavior based on the floater design and environmental conditions are key drivers for workability. In case unfavourable workability conditions are detected at highly occurring sea states, design adjustments must be made accordingly [11]. Additional, publicly available and field experience on workability on floating wind turbines is needed to perform further investigations and contribute to new standards and design practices.

In this study, workability was a focus as this topic has been neglected and not addressed very often in previous studies. Apart from workability, accessibility from service vessels to the floater is another topic with differences to bottom fixed substructures. A number of studies on accessibility exist, suggesting that the relative motion of vessel and floater is the key aspect. Here, a floater may actually show improved accessibility compared to fixed structures in case its motion is in phase with the vessel; in contrast for out-of-phase conditions, accessibility is much decreased. This emphasizes the relevance of site conditions (wave periods) and natural periods of the floater and vessels.

Furthermore, maintenance, particularly for major repairs, is a topic widely discussed in floating wind. Here tow-to-port solutions are discussed, but their technical and particularly economic feasibility is not clearly demonstrated yet and most likely dependent on multiple parameters, such as site conditions, maintenance port distance and infrastructure, and floater design.

5. Decommissioning

O&G industry shows, that the neglection of the decommissioning strategy may lead to increase of efforts and costs [12]. In order to get an overview over the existing offshore decommissioning strategies, common methods of both floating O&G and conventional fixed-bottom offshore are reviewed. Afterwards challenges and opportunities for floating wind are stated.

5.1 Review of existing decommissioning strategies

Existing decommissions strategies both for O&G and fixed-bottom wind are briefly discussed in the following with respect to their applicability to FOWT.

5.1.1 Oil and gas

Proserv Offshore shows in its "state-of-the-art" review of O&G decommissioning how different O&G devices would be decommissioned [13]. The application to floating wind is, however, difficult. The reason is that for O&G, the main attention is paid to the decommissioning of the pipelines in order to prevent oil leakages. For floating constructions, only limited information about the decommissioning process is available. Generally, it is simply stated, that floating devices are detached from the mooring lines and towed to the shore for further decommissioning. While floating wind often considers drag embedded anchors, which can be recovered, the Proserv Offshore study considers O&G pile anchors to remain in the sea bed and not being removed. The mooring lines are however recovered. Sea disposal of parts is generally often considered for certain parts of the structure. The application to floating wind is difficult also due to increasing awareness and considerations of environmental impact. The cost assumptions cannot be transferred easily, due to high risks and safety factors of O&G devices on the one site and high revenue per device on the other side. Furthermore, the size of O&G platforms and also the total amount of installed devices are much different to floating wind. While O&G floating substructures are large but singular installations, floating wind substructures are considerably smaller in size, however must be decommissioned in larger numbers for a larger scale wind farm. For the detailed decommissioning procedures, like the usage of ROVs to detach the mooring lines in larger water depths, the experience from the O&G industry might be useful. Regarding decommissioning strategies, floating wind can most probably not exclusively rely on the O&G experience.

5.1.2 Fixed-bottom offshore

Fixed-bottom offshore wind is less applicable to the requirements of decommissioning of floating wind. For conventional fixed-bottom offshore, the wind turbine has to be removed from the substructure on site. Afterwards, the substructure is often left on site or piles are cut (Figure 11). Both these steps differ from floating wind. The only comparable part of the decommissioning procedure is the decommissioning of the cables, both inter-array and export cables. Since the removal of these cables would "involve extreme costs" and also "cause substantial damage and disruption to the seabed given the extensive length of the cables" [14], the cables are often left buried and in situ and are not removed. It can be assumed, that similar choices will be made for floating wind farm applications.

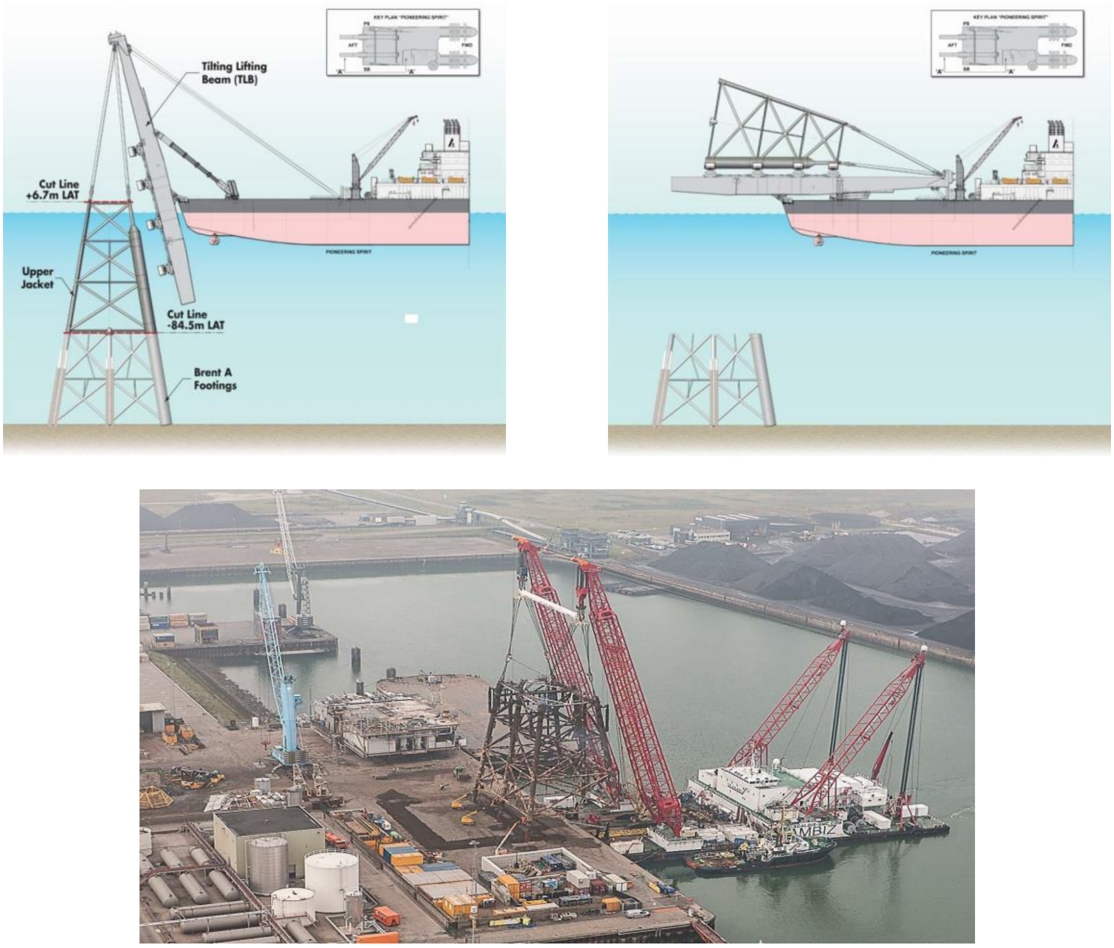

Figure 11: Top: Schematic illustration of the procedure for lifting of the upper part of a jacket using a specialised vessel [15]; Bottom: Jacket is unloaded at a disposal yard [16].

5.2 Challenges and opportunities

Due to the young age of floating wind industry, not many details have yet been published to definitely designate, how the decommissioning should be conducted. The main advantage of smaller floating devices in terms of decommissioning is their mobility. The decommissioning can be done, after the floaters are towed back to the port, which favours also the disposal. No obvious use of specialized vessels is required for this type of decommissioning. For the detachment of the mooring lines, experience from the O&G industry could be utilized. A challenge is the size of the floating substructures. Even though, they are much smaller than their O&G counterparts, feasible recycling or disposal options for the high number of substructures in large scale offshore wind farms have to be found. For mooring lines, the disposal seems more sustainable for steel, since they are more likely to be recycled. According to the American Iron and Steel Institute, “Steel is the most recycled material on the planet, more than all other materials combined.” And: “Steel retains an extremely high overall recycling rate, which in 2014, stood at 86 percent.” [17]. Theoretical, this can be also achieved for synthetic lines provided that recycling procedures are optimised. Concrete recycling is becoming more attractive because of increased environmental awareness, new legislative regulations and potential cost reductions. For example, after crushing and removing of rebar by means of magnets or sorting devices, recycled concrete can be used as aggregate for mixing new concrete.

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