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Safe procedures for personnel-transfer from a vessel to an offshore floating wind turbine

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Summary

This report is prepared to identify safe procedures for transfer of personnel from vessels to floating offshore wind turbines. The use of a gangway system mounted on the deck of a vessel is known to represent state of art for access to fixed offshore wind turbines. For floating offshore wind turbines, the transfer is involving two floating moving objects and the relative motion between these will limit the availability to use the system. Safe procedures at the vessel are critical and the vessel master will be in charge of the transfer. This report should, however, point to measures to be carried out to ensure safe transfer and be a support to all involved in the transfer of personnel.

The operator of the wind turbine will have to select vessel and equipment in accordance with an evaluation of the required availability to access the wind turbine. The capabilities of vessels are quite different and the vessel should be selected to have minimum of motions in normal wave situations. The motion of vessel and wind turbine foundation in long swells could also be a limiting factor for safe access.

It may also be necessary to evacuate personnel from offshore floating wind turbines, possibly caused by increasing weather situations where the limiting conditions are approaching. Other causes for evacuation or other emergency situations should also be identified.

KEYWORDS: floating wind turbine, maintenance and repair, personnel transfer, evacuation, bridge transfer system, vessel carrying bridge, availability, wave conditions.

Objective

With an increased number of offshore floating wind installations in harsh environmental areas, the safety of personnel entering the wind turbines for maintenance and repair is of concern. All necessary activities to ensure the safety of the personnel should be taken into account. The transfer from vessels to the installations is of particular concern. This report points to procedures to ensure the safety of all involved in offshore related wind activities.

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1. Introduction

1.1 Background

Wind turbines installed in shallow waters (up to a depth of approximately 30m) are normally supported by bottom fixed monopods driven into the seafloor. Alternatively, they are (in depths up approximately 70m) installed on top of steel frames or concrete tower support structures. Wind turbines in deeper waters are an integral part of an offshore floating structure. The support structure could be in the form of a semisubmersible (like the Wind Float concept) or a spar type platform (like the Hywind structures developed by Equinor), see Appendix A. The mooring can be through an arrangement of vertical tendons or by catenary anchor lines.

There will be a need for personnel to access the floating wind-turbines for maintenance and repair purposes. This access is a critical operation as the personnel have to walk to work (W2W) from one floating unit to another floating unit using a bridge access system. Although the “W2W technology” has been developed for bottom fixed wind turbines, the personnel transfer represents a higher degree of complexity when personnel have to access a floating unit from a vessel.

A wind turbine has an operational window determined by the wind condition at the site. When the wind velocity is very low, the turbine is at a standstill, and during high wind speeds, the wind turbine has to be stopped to avoid damages to the rotor. Offshore, wind generates waves and wind blowing over a long fetch will generate large waves limiting the possibility to enter the wind turbines. In case of swells, vessels and the wind turbine may move much, so wtw is not possible. However, a wind turbine stopped for maintenance or repair represents no income, and the operator will want to carry out the work needed as soon as possible. It is, therefore, of interest to develop safe procedures for personnel transfer from vessels to floating wind turbines. It should also be noted that restrictions to enter the wind turbines apply when bringing personnel safely onboard the vessels from the turbines after tasks have been finalized. In case of emergency, personnel may have to leave the wind turbine in a hurry.

The Meteorologic and Oceanographic conditions at the site and the motions of the wind turbine and the vessel are the critical factors for safe transfer. Therefore, the procedures will have to account for the weather and the vessel and wind turbine support structure’s (the facility’s) response to waves and wind. It should be noted that the vessel and the wind turbine foundation also could collide in the event of operations outside safe weather criteria, possibly causing damages to the vessel or the facility.

For the purpose of planning operations during the lifecycle of these installations, it will be useful to understand the average seasonal availability. The main limiting factors for the W2W solution are:

- Wave conditions (significant wave height, maximum wave-heights, wave period and direction)
- Wind and gust velocities
- Vessel response
- Motion limits for establishing and maintaining the connection of the walk to work system to the actual installation
- For floating wind installations, the installation response to the wave conditions must also be taken into account.

It should be noticed that W2W between two floating installations in Northern North Sea may be considerably more challenging than W2W to a fixed installation from a vessel in Southern North Sea sea-state conditions.

1.2 Purpose

The purpose of the report is to suggest procedures for safe use of a bridge access system for floating offshore wind turbines. The report should help the operator to evaluate the conditions for access and the expected downtime due to problematic weather conditions. The procedures will also cover other Major Accident hazards as, for example, ship impacts and DP failures.

1.3 Scope of work

The safe transfer from a vessel onto a floating offshore wind turbine will be covered. The bridge system shall be investigated for two possible uses:

- a planned and controlled access to the wind turbine, as required by operations or a not time critical return from the wind turbine to the vessel.
- an emergency evacuation from the wind turbine under critical events

The report will establish functional requirements for the vessel and bridge system and the likely availability. The report will only briefly include the specification of winterization requirements to ensure the functionality and reliability of the bridge evacuation system, in case of freezing weather and spray icing. The report will also include a discussion of the space required for the landing areas on the wind turbine facility.

The report is based on the use of a passive system for the bridge system. An active system, similar to the Ampelmann motion compensated gangway [1], is not considered. The main reason for this is the complexity of the active system and the lack of operational experience for transfer of personnel between two moving objects.

1.4 Definitions and Abbreviations

Elevation	The vertical distance from sea level to the landing area for the bridge on the wind turbine support unit or from sea level to the bridge on the vessel.
Evacuation	Removal of personnel from the facility in the event of a dimensioning event that could seriously affect the people on board and the integrity of the facility.
Facility	The wind turbine floating support unit.
Transfer	Transfer of personnel to or from the facility in a normal safe situation.
Vessel	The vessel the bridge is installed on.
DSHA	Defined Situations of Hazards and Accidents.
Hs	Significant wave height, the average of the 1/3 highest wases in a measurement series. Hs is close to the average wave height estimated by an experienced captain.
POB	Persons on Board.
RAOs	Response Amplitude Operators for vessel and wind turbine.

1.5 Displacement RAOs

Vessel motions in waves can be defined by displacement RAOs (Response Amplitude Operators) that are specified on the Displacement RAOs page of the vessel type data form. Each displacement RAO consists of a pair of numbers that define the vessel response, for one particular degree of freedom, to one particular wave direction and period. The two numbers are amplitudes, which relate the amplitude of the vessel motion to the amplitude of the wave, and a phase, which defines the timing of the vessel motion relative to the wave.

Example: A surge RAO of 0.5 in a wave of height 4m (and hence a wave amplitude of 2m) means that the vessel surges -1m to +1m from its static position; a pitch RAO of 0.5° per meter in the same wave means that the vessel pitches from -1° to + 1°.

A vessel has 6 degrees of freedom: 3 translations (surge, sway, heave) and 3 rotations (roll, pitch, yaw), so the RAO data set consists of 6 amplitude and phase pairs for each wave period and direction, see figure 1.1. The RAO amplitude and phase vary for different types of vessels, and for a given vessel type they vary with draught, wave direction, forward speed and wave period / frequency. It is important to obtain accurate values for the RAO amplitude and phase if the dynamics of the system are to be correctly modelled.

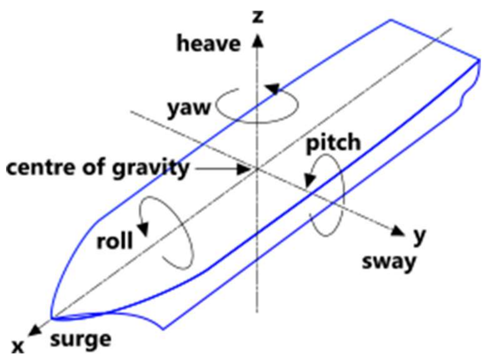

Figure 1.1 Vessel motions defined by displacement RAOs

The wave used as the input to the calculations is estimated as the maximum wave height, Hmax, of a storm with 3-hour persistence and a mean period equal to the spectral peak period. This results in Hmax = 1.86 x Hs. The value 1.86 x Hs is normally used to determine the maximum wave heights required for the design process. It is the amplitude of the wave (half of Hmax) that is used together with the RAO figures to find the relevant vessel and wind turbine movements.

Hs is the significant wave height. Hs the average of the 1/3 highest wases in a measurement series. Hs is close to the average wave height estimated by an experienced captain.

RAOs can be obtained from the designer of a vessel type or the ship owner. It should, however, be noted that the RAO for a commercial service vessel is considered proprietary and commercially sensitive information. The RAOs effectively determine what operations can be undertaken by the vessel in a given sea state and is thus sensitive in commercial bidding as a key operational limit for the vessel

1.6 Maintenance and need for access to turbines

As for all technical installations, there is a need for regular visits by maintenance crews to carry out preventative maintenance or to repair faults.

Operations and maintenance are critical elements and a significant amount of the costs associated with a wind farm. As with all maintenance planning, there is a trade-off between intensity and amount of maintenance (which add significant cost) and the risk of significant failures. Typical maintenance frequency for preventative maintenance is reported to be 2-4 maintenance visits per year. In addition, repair visits (corrective maintenance may become necessary should a critical fault occur. As long as the critical fault persists, there is a loss of revenue and a need for access outside the normal maintenance intervals may be required.

Typical maintenance tasks may include:

- Inspect electrical cabinet, gearbox, generators, yaw system, and brake
- Assess blades and blade pitching
- Survey tower foundation
- Measure oil and lubrication levels, sample, and if necessary, replacement
- Drive train alignment
- Examine and tighten bolts
- Check ventilation, air filters, and shock absorbers
- Inspect bearing and connections
- Evaluate nacelle
- Repair cracks and corrosion

This report will not explore further maintenance needs, typical faults and their frequency and so on. It will simply be reasonably assumed that there is a need for regular access to the turbines for maintenance and repair.

2. Method

Access to offshore wind turbines is predominantly carried out by maintenance crews operating from vessels equipped with a gangway which can be manoeuvred, attached to the installation and used as a walkway for the crews. Depending on the conditions, duration and operational needs, the walkway can remain attached while the crews carry out their visit or be withdrawn and reattached when the crew needs to leave the installation. The combined gangway and support vessel are most commonly known as Walk-to-work solutions, or by the abbreviation W2W.

The limitations for use of W2W solutions will be discussed more extensively in a separate section. However, as all commercial wind farms in operation are developed with bottom fixed foundations, the use of W2W is limited only by the physical limitations of the specific W2W system and the movement of the vessel, driven by the actual wave and weather condition.

For floating wind installations, this problem is complicated by the movement of the floating wind installation, i.e., the physical limitations of the gangway are challenged not only by vessel's movements, but the joint movement of the vessel and the wind installation in response to the environmental conditions.

For the purposes of this report, the bridge system is assumed installed on the vessel. The bridge system will be extended to the facility in order to allow transfer of personnel.

The following list of assumptions are made:

- The system shall be able to handle the safe transfer of up to 15 persons over a short period of, say 15 minutes.
- The vessel should be selected with respect to acceptable downtime in case of urgent maintenance needs. In the North Sea, vessels of the type of regular offshore support vessels, for example Esvagt Aurora or Stril Barents will have a low downtime compared to smaller vessels. The vessel should be able to travel at a speed of minimum 20 knots in an emergency.
- Considerations of the working environment conditions for people using the bridge evacuation system are of secondary importance. The exposure time during a transfer is considered low.
- The DP class for the vessel is assumed as DP2. This ensures there is redundancy in both the power generation and the DP positioning system.
- The bridge will be fabricated in aluminum for the benefit of the stability of the vessel.

The availability of the transfer system will be influenced by a number of environmental factors and the combination of these environmental factors. The assessment of the availability of the transfer system is based on the operating limitations of the bridge and the relative movements of the vessel and the facility.

The bridge nominal length determines the stand-off distance between the vessel and the facility. The limitations to be considered are the bridge horizontal extension and the bridge allowable swing angle. The two main factors that influence the horizontal extension and the angle are the difference in elevation between the vessel and facility due to heave, pitch and loading condition (draught) of these, and the difference in horizontal distance at the bridge height due to roll.

The RAO data for the vessel and the facility are used to determine the sea state that would lead to the operational limitation of the bridge extension or operational limitation on the bridge angle dependent on the limit that is reached first. In practice the vessel should maintain a heading that will reduce vessel roll during the transfer. The main assumption for calculations of availability is that the vessel lies in the trough of the wave and the facility is on the crest. This is considered a conservative assumption. The bridge location on the vessel is assumed to be mid-ships, hence the vessel pitch does not affect the bridge elevation. The vessel and facility's 'surge', 'sway' and 'yaw' are normally not considered since these are assumed to have a minimal impact on the calculation of the bridge limitations. For this scenario the most onerous loading condition is the condition with minimum vessel draught and this is the condition that is the basis for the determination of the Hs and the availability of the bridge transfer system.

The availability is determined from consideration of the monthly and annual distributions of non-exceedance of significant wave heights in the MetOcean design basis for the location of the wind turbine.

A walking speed of 1 m/s is considered realistic in normal circumstances and 0.5 m/s is considered a reasonable assumption for crossing the bridge in an emergency situation. The evacuation time from time of warning of evacuation to evacuation is completed depends on the evacuation possibilities from the nacelle down to the bridge support on the wind turbine support structure.

No winterization requirements for the vessel should be necessary in North Sea conditions. For wind turbines installed in northern areas where low temperatures and ice are common, vessel winterization based on the DNV standard for "Winterization for Cold Climate Operations" (DNVGL-OS-A201) [2] should apply. An important aspect of the winterization is the protection of the hydraulic system that drives the bridge and controls the bridge extension.

The use of the transfer system for evacuation under dimensioning events should be considered by reviewing the DSHAs defined by the operator, assessing the DSHAs relevant for a bridge evacuation system and determining any limitations in the use of the system.

3. Application of the bridge evacuation system

3.1 Bridge transfer system; W2W gangway

There is a number of manufactures of gangway systems and with increasing interest in their use, the number of manufactures is growing steadily.

All W2W systems are able to accommodate some motion relative to the object it is landed on. Principally, this can be achieved by two different methods:

- Active compensation through hydraulically actuated cylinders which maintain the gangway in place at its landing point.
- Passive compensation, through telescopic extension and the ability to move on its bearings vertically and horizontally to follow the relative motions between the W2W vessel and the installation it is attached to.

For the purpose of this report, it is not necessary to go into more details on vendors and manufactures of W2W systems. Most of the designs can be delivered in more than one length and with various degrees of weather protection.

We will, for *illustrational purposes*, refer to one bridge system in this report. This is an Uptime telescopic gangway [3] that is suitable for installation on a typical vessel that could function as a vessel in *rough offshore conditions*, see figure 3.1. The operational limits for the bridge are described in table 3.1. A fully enclosed bridge is considered due to the needs to protect personnel during the transfer. Other types of bridges (shorter) and vessels (having less size and therefore could be rented with a lower day-rate) could be considered in case more downtime/ waiting for maintenance crew, is accepted.

Figure 3.1 Uptime Gangway installed on a vessel (Illustration)

Table 3.1. Bridge/ gangway dimensions and operational limitation for rough sea states.

Parameter	Value	Comment
Nominal length	26 meters	
Maximum/minimum telescopic extension	10 meters (+/- 5 meters)	
Operations limit on telescopic extension	8 meters (+/- 4 meters)	The report uses the operations limit for telescopic extension as the allowable limit.
Maximum speed on telescopic movement	2.5 meters/second	
Maximum angle on bridge	+/- 25 degrees from horizontal	The report uses the maximum angle as the allowable limit.
Operational limitation on angle on bridge	+/- 20 degrees from horizontal	See figure 3.2
Maximum change in angle	5 degrees per second	
Maximum acceleration force	0.3 g in horizontal direction	
Maximum swing change	6 degrees per second	See figure 3.3
Maximum wind speed	20 m/s (39 knots)	Assumed not dimensioning

Figure 3.2 shows the bridge angle and figure 3.3 the swing angle.

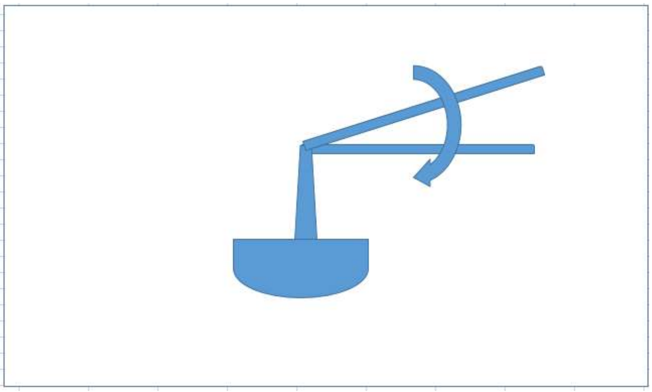

Figure 3.2 Bridge angle (front elevation).

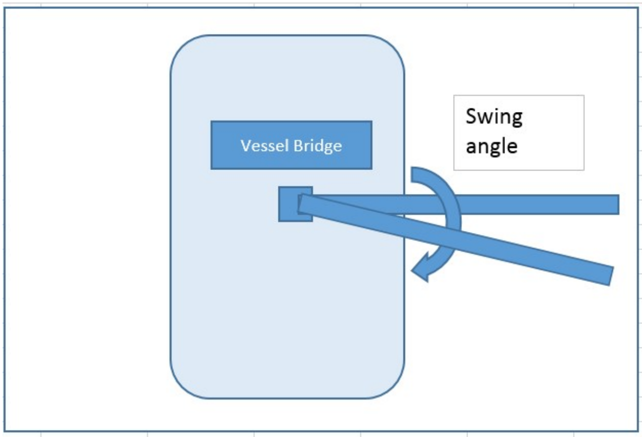

Figure 3.3 Swing angle for bridge (plan).

The operational limitation on the bridge angle is a mechanical limitation and is intended to give a good margin from the maximum bridge angle. No limitation has been set on the bridge angle based on the safety of personnel crossing the bridge. For personnel using the bridge the main challenge will be the bridge movement and rapidly changing bridge angle. We should refer to ISO 14122 Part 2 [4] for slopes on access ways:

Subclause 4.2.4.7, Slip hazards, refers to floorings being designed and manufactured to reduce the risk of slipping and ramps of pitch angles between 10° and 20° to which ribs can be attached with widths between 10 and 20 mm and heights of 10 to 20 mm.

However, great care should be taken with ribbed ramps, bearing in mind that ISO 14122 also states:

Subclause 4.2.4.4, Trip hazards, states that 'the greatest difference between the tops of neighboring floor surfaces shall not exceed 4 mm in height.'

The design of the bridge and the need for ribs to aid crossing should be addressed in more detailed studies. Indeed, it should be studied whether limitations due to human factors, including, but not limited to slope, acceleration of movement and trip hazards, could impose stricter limitations than the physical limits of the bridge. Involvement of human factors specialists should be part of the operational design of

For the purposes of this report, it is assumed that the maximum wind speed is not exceeded for the periods the system is available within the Hs limits. A review of NORA10 data base [5] shows that occurrences with wind speed above design criterion and wave height below are extremely rare for most locations on the Norwegian Continental Shelf. Wind speed is, therefore, not considered to be dimensioning for the availability of the bridge mounted on the vessel.

The location of the pedestal for the bridge is in the center of the vessel both related to length and breadth see figure 3.4. This position reduces the impact of roll and pitch on the bridge operability. It also allows the vessel to position with the facility on port and starboard with the same standoff distance. The optimal elevation for the bridge is the same elevation as the elevation on the landing area on the facility.

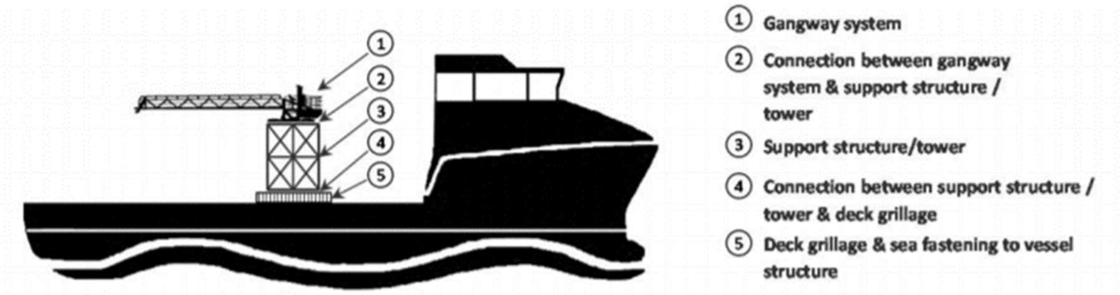

Figure 3.4 Bridge and pedestal location on vessel.

For a Stril Barents vessel equivalent, with the referenced Uptime bridge, the stand-off distance from the facility will be 17 meters, calculated from a bridge nominal length of 26 meters and a distance of 9 meters from the pedestal to the beam of the vessel see figure 3.5. The main assumption is that the DP system on the vessel maintains a distance of 17 meters and the relative movement of the vessel and the facility due to surge is compensated by the allowable swing angle. The bridge angle and the telescopic extension/ retraction limits should not be exceeded.

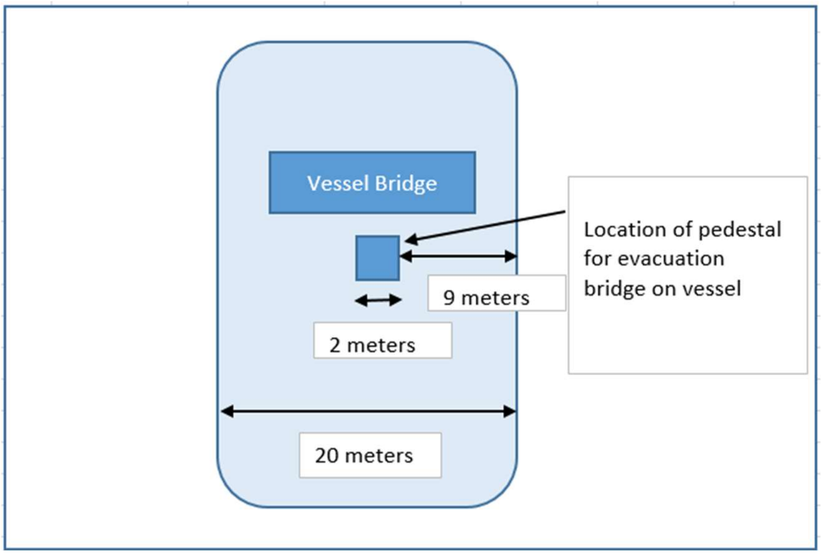

Figure 3.5 Location of pedestal on the vessel

The availability of the bridge evacuation system is determined by the following steps:

- Assessment of the elevation distance between the bridge location on the vessel and the bridge location on the facility
- Assessment of the impact of roll on the bridge angle and extension/retraction limits
- Assessment of the sea state condition that results in a limitation on the bridge extension or the bridge angle

The impact of surge on the swing angle and the impact of sway and yaw on the extension of the bridge are assumed to have low impact compared with heave and roll.

3.2 Sea State Data

While the need for preventative maintenance can be planned for periods with as far as possible optimal conditions for accessing the wind turbines, corrective maintenance may need to be carried out at short notice and at the prevailing conditions for the season.

However, for preventative maintenance, it would be useful for planning purposes to assess average availability per season or month.

At the planning stage little data exists on the variation in wave data, windspeeds and directions and so forth. To identify the average availability per month of a year, it is essential to have access to historical data, to calculate averages and maximum/minimum for a given period.

There are two ways these can be obtained:

- Historical MetOcean data collected by a nearby installation
- Use of hindcast data

3.2.1 MetOcean data

On the Norwegian continental shelf, the network of manned oil and gas installations are by regulation obligated to collect and record MetOcean data at site. For developments in the same area as records exists, these can be obtained.

However, there is a number of caveats to this approach:

- While there is reasonable correlation over some distance, uncertainty will invariably increase with distance to the closest data point
- While there may be installations present in the area of interest, they may be fairly recent installations and thus the longevity of the record may be less than desired to capture variability.

3.2.2 Hindcast data

Hindcast data can be obtained from the NORA10 database [See 5]. The data in this database has been created by using atmospheric fields from the European Weather Forecasting Agency (ECMWF) as input to the atmospheric model HIRLAM and the wave model WAM. The datapoints are generated with a temporal resolution of 3 hours and a spatial resolution of 10 km.

Data which can be obtained from the NORA10 database are listed in table 3.2 below.

Table 3.2 NORA10 database

Type	Abbrevation	Explanation	Unit
DATE & TIME	YEAR	Year	-
DATE & TIME	M	Month	-
DATE & TIME	D	Day	-
DATE & TIME	H	Hour	-
PRESSURE	MSLP	Mean sea level pressure	hPa
TEMPERATURE	T2m	Temperatures 2 meters above sea level	Degree Celsius
	RH2m	Relative Humidity 2 meters above sea level??	%
	RR	Rapid Refresh	
WIND SPEED	W10		m/s
WIND SPEED	W50		m/s
WIND SPEED	W80		m/s
WIND SPEED	W100		m/s
WIND SPEED	W150		m/s
WIND DIRECTION	D10		Degrees
WIND DIRECTION	D100		Degrees
WIND DIRECTION	D150		Degrees
TOTAL SEA	HS	Significant wave height	m
TOTAL SEA	TP	Peak wave period	s
TOTAL SEA	TM	Mean wave period	s
TOTAL SEA	DIRP	Peak wave direction	Degrees
TOTAL SEA	DIRM	Mean wave direction	Degrees
WIND SEA	HS	Significant wave height	m
WIND SEA	TP	Peak wave period	s
WIND SEA	DIRP	Peak wave Direction	Degrees
SWELL	HS	Significant wave height	m
SWELL	TP	Peak wave period	s
SWELL	DIRP	Peak wave Direction	Degrees

The availability of the gangway system is based on information as follows, see figure 3.6:

- The geometry of the vessel – gangway – landing point on the installation
- Wave conditions
    - Significant wave height
    - Wave direction
    - Wave period
- Response to wave conditions (RAOs). Note that the vessel and installation will have different RAOs
    - Vessel with gangway
    - Floating wind installation

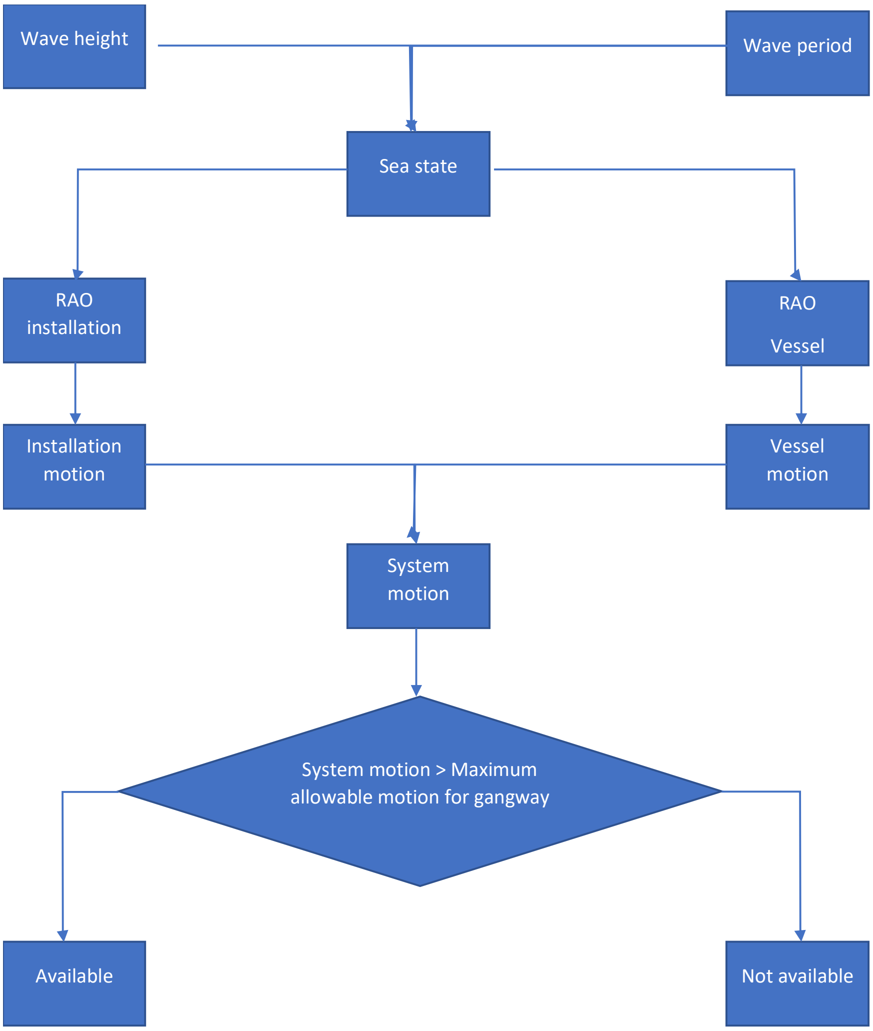

Figure 3.6 Gangway system availability

3.3 Wind-Float facilities

The layout and dimensions of the facilities and the RAO data for the facilities must be established and used in the transfer analysis. The forces of the tower, the nacelle and the rotor as caused by the wind loading must be taken into account when establishing the RAO data.

There should be two landing points on the facilities to ensure no conflict with the rotor during the transfer (the rotor is of course at standstill when personnel access the facilities). The space required on the facilities will be determined by an evaluation of the required availability for personnel transfer, taking into account the swing angle of the bridge and the horizontal movement of the bridge.

The basis for the calculation of the bridge landing point elevation on the facility is the mean of the maximum and the minimum. Thus, the greatest elevation difference between the bridge on the vessel and the bridge on the facility is determined. During an emergency situation in case of needs to evacuate the facilities, the vessel will normally be positioned with a heading into the waves.

Heading into the waves minimizes the roll of the vessel, however, it may not be possible to ensure minimum roll for all evacuation scenarios, so a 60-degree heading could be assumed as a worst case for the determination of the bridge limitations.

The calculation of the vertical movement considers the component of heave of the vessel and the facility and the component of pitch of the facility.

3.4 To perform access evaluations

The optimum bridge elevation for the operational limitations is that the bridge is at the same elevation on the vessel and the facility. The geometry of the installation to be serviced is the main dimensioning factor for the W2W gangway:

- Height above MSL relative to the gangway on the service vessel
- The layout of the installation and location of landing points

Obviously, the gangway must have a length and height of pedestal enabling it to reach the landing point on the installation while accommodating the sea state affecting the motion of vessel and installation, figure 3.7.

It is also advantageous that the installation can cater for multiple landing points for the gangway. This will increase availability as the vessel can use the landing point which enable the most favourable heading with regards to wind and wave conditions, e.g., ideally the vessel would position itself downwind of the installation (to reduce collision risk) and heading into to the waves (to minimise roll motions).

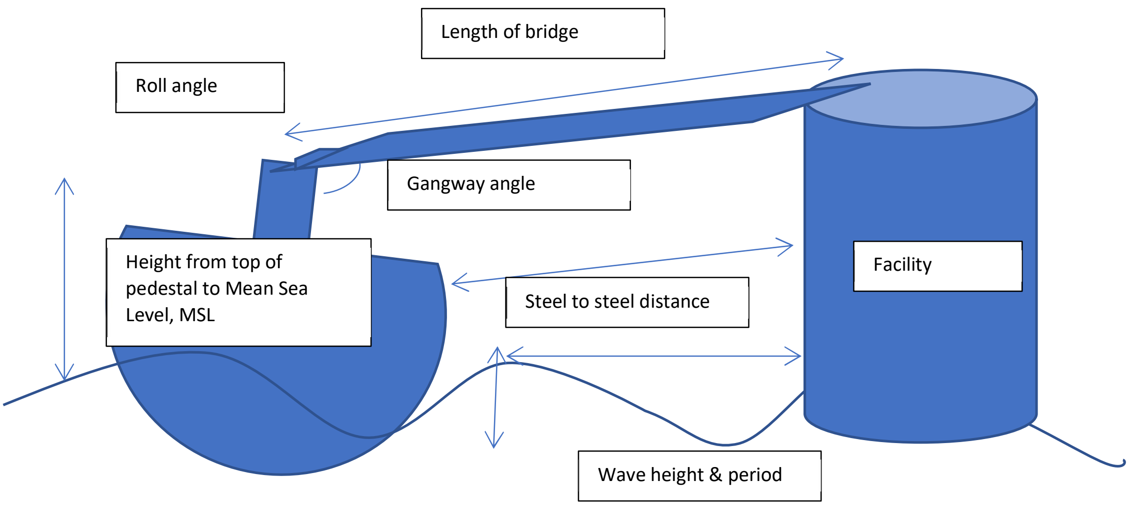

Figure 3.7 Illustration of the dynamic interaction between bridge/ gangway, service vessel and facility.

As is evident from figure 3.7, access to an installation with a W2W system can be modelled as a dynamic geometrical problem. Most of the variables in the figure are constant, however, the motion of the vessel and the installation are variable, driven by the sea state which is transferred via the RAOs for the respective units to actual motions.

An estimated Hs for the limitations of personnel transfer is to be identified, so a relevant wave period is to be assumed for selection of the RAOs. Note that a check must be made for the case of swells when the vessel is in resonance with e long-crested swell waves. The vertical movement of the vessel is calculated from the RAO for heave. The roll of the vessel is calculated from the RAO for roll for a 60-degree heading. The RAOs for heave and roll are taken from the RAO displacement results available for the vessel and the facility.

The horizontal movement has two components. The extension required to accommodate the vertical movement and the extension associated with the roll of the vessel. The most onerous scenario for the bridge limitation could be vessel heading 60 degrees and facility in minimum draught condition.

If the relative motion of the vessel and installation exceeds the gangway's ability to compensate, the operation will have to be aborted and the installation is unavailable to visits using the W2W system. It should be noted, that establishing a connection, may require calmer conditions than operating/maintaining the connection once it has been established.

Based on knowledge regarding wave data at the location, the availability to access the facility could be determined for each month of the year for different types of vessels. Then, based on a cost benefit analysis, the optimum vessel could be selected, taking into account the cost of hiring the vessel and the loss of income to delay repair or needed maintenance.

3.5 Evacuation duration

The time required to evacuate the facility has been determined by considering 3 phases for the evacuation process:

- The time required to sail to the facility, maneuver the vessel into position and deploy the bridge.
- The time required to transfer the persons from the facility to the vessel.
- The time required to disconnect the bridge.

When the vessel is required for providing an emergency response, it is assumed that the normal sailing position of the vessel will be just outside the wind-farm safety zone. It is also assumed that the weather conditions are within the limitations for the use of the bridge. The time required to sail to the facility, maneuver the vessel and deploy the bridge is estimated as 15 minutes. The deployment of the bridge includes swinging the bridge from its normal position, connecting the cone to the landing area, setting up the DP for station keeping and setting up any bridge instrumentation and alarms. This is an area that will require further assessment including discussions with the shipping companies.

The time to transfer the people is based on an estimate of walking speed 0.5 m/s and 15 persons on the bridge at any one time, i.e., a group of 15 can cross the bridge in approximately one minute, given a bridge length of 27.5 metres. However, allowing for some spacing and for injured people including stretchers, time to transfer should be approximately 4 minutes for 15 persons. This is considered a conservative estimate.

The time to disconnect the bridge is estimated as 1 minute. Total time 20 minutes.

4. Availability

For the purpose of this report, availability is defined as the percentage time that the bridge is available for immediate use to transfer personnel from the vessel onto the facility and vice versa. There are several factors that will influence the availability of the bridge.

- Maintenance requiring the gangway to be out of service
- Winter conditions with icing, snow, freezing temperatures
- Sea state and vessel response
- Wind and wind loading

4.1 Maintenance

Maintenance will be required on the bridge; however, this is assumed not to impact the bridge availability. Minor maintenance can be carried out with the bridge still available, while major maintenance and modifications would be planned when the vessel is in harbor or in dock.

4.2 Winterization

The bridge will be exposed to the challenges when it is used in cold temperatures.

To achieve normal, or close to normal operation under these conditions, certain technical and operational measures will have to be taken, this is usually called *winterization*. It is reasonably evident that there is a correlation between the amount of winterization and availability in winter conditions.

For the purpose of the availability, it has been assumed that the gangway can be winterized to the extent that this will not be the constraining factor on availability.

4.3 Sea-state and vessel/installation response

The governing factor for availability will be the sea-state and the associated response of the vessel and the facility (the wind turbine support structure).

The gangway operation consists of:

- Establishing connection with the installation, landing the gangway and making connections.
- Transfer of personnel with the gangway attached
- Retrieving the gangway

For the latest generation bridges, there is virtually no difference between the sea state in which the bridge is able to operate and the sea-state required to establish the connection. Hence, for the purpose of this report, we could only consider the effect of the sea state on the ability to safely maintain the gangway attached and continue transferring the personnel.

The basic premise is that a certain sea state defined by significant wave height (Hs) and wave period will produce a certain predictable response of the vessel and the facility.

4.4 Wind and wind loading

In case the bridge will be fully enclosed for effective protection, this will increase the wind loading compared to an open structured bridge. The normal position for the bridge will be perpendicular to the prevailing wind, assuming the prevailing wind is in the same direction as the prevailing seas. This will give the maximum loading for any wind case. As the bridge is to be fixed at both ends, to the pedestal on the vessel and through the cone connection of the facility, then the wind loading forces are supported at both ends. The wind loading is unlikely to limit the availability of the bridge for winds speeds associated with the sea states that limit the bridge operation. Torsion on the bridge due to wind loading is also unlikely to limit the bridge operation. Further work on wind loading should be carried out including the pitching effect of the facility due to wind on tower, nacelle and rotor.

5. Functional Requirements for the vessel

A Hazid on the bridge evacuation system should carried out as part of the selection of vessel. Some of the points *relevant to the vessel*, are addressed in this section.

The vessel should be suitable for the accommodation of the personnel to be transferred to the wind turbine.

The vessel should have dynamic positioning class DP 2. This ensures redundancy so that no single fault in an active system will cause the system to fail.

Loss of position should not occur from a single fault of an active component or system such as generators, thruster, switchboards, remote controlled valves etc., but may occur after failure of a static component such as cables, pipes, manual valves etc.

The vessel should be capable of accommodating a bridge pedestal in the center of the vessel to support a bridge with the required nominal length and a potential extension of, say 5 meters, for additional safety. The vessel should be able to provide the utilities required for the bridge to function.

The vessel's RAO characteristics must be carefully determined.

The hazardous area classification for the vessel should not different from a normal supply or standby boat. The fuel stored on the vessel and the use of the fuel should ensure safe vessel operations. Particular concerns with respect to fire and explosions should be taken in case batteries or hydrogen be used as fuel.

6. Functional Requirements for Bridge Evacuation System

A Hazid on the bridge evacuation system should carried out as part of the selection of bridge evacuation system. Some of the points *relevant to the bridge*, are addressed in this section.

The bridge and pedestal should be constructed from Aluminum to minimize the weight on the vessel and the facilities. Construction should be carried out in accordance with the appropriate standards and with the required QA/QC standards applied.

The bridge connection to the facility will be with a cone that locates into a point on the landing area(s). The provision for the landing area on the facility should be 4 meters by 4 meters for a large size bridge discussed in this report. A muster area for personnel is required.

The bridge, pedestal and bridge connections should be designed for a wind loading based on a wind speed at least 10% higher than the maximum wind speed associated with the Hs that will limit the bridge operation.

The pedestal, bridge and bridge operative systems should be subjected to a failure mode effects and criticality analysis (FMECA) to determine the probability of failure against the severity of consequence. The analysis performed should be at a functional level. The bridge design should account for accidental and deliberate disconnection during an evacuation. In an evacuation this could happen if the incident escalates severely and the vessel integrity and safety of personnel are compromised. In this case it is assumed that evacuation would be stopped and that everybody on the bridge would be allowed to reach the vessel. In the event there are personnel on the bridge when the disconnection is made, then the hydraulic system must be able to support the bridge when it disconnects.

In the event of accidental disconnection of the bridge through failure of the cone system on the facility landing area, the hydraulic system should be able to maintain the bridge level in order to people to escape to the vessel. Accidental disconnection of the bridge at the vessel end is not considered likely in case of adequate design. In this event the end of the bridge will fall into the sea.

In the event of failure of the hydraulic system, then the bridge cannot be deployed. The bridge will therefore be unavailable. Hydraulic failure after the bridge is deployed is considered unlikely. In this event the bridge would be disconnected once all personnel have been evacuated and the bridge will be disconnected and be allowed to fall into the sea. This is not considered an event that will compromise the vessel integrity.

7. Conclusions

A bridge transfer system for floating offshore wind turbines is feasible for both normal transfer and evacuation. The availability of the system will depend on the motion characteristics of the vessel and the wind turbine support structure.

The availability of the bridge personnel transfer system has to be determined from calculations based on certain assumptions for the relative positions of the vessel and facility, taking into consideration the varying loading conditions that impact the draught of the vessel and the facility. The effect of wind and personnel weight loading on the bridge availability should be considered in the design and operation of the facility. Further occupational work limits should taken into account with regards to exposure during the transfer as well as human factor limitations on angles, movement and trip hazards while walking over the bridge.

Dynamic simulations and/or model testing will be required to confirm the availabilities of potential bridge transfer systems. Limitations on the vessel's approach to the facility and maneuverability of the vessel while transfer or evacuation takes place are dependent on the decisions of the vessel master. These limitations may be more onerous than the design limitations calculated for the bridge itself. Further discussions with the shipping companies will be required to develop procedures for the use of the bridge evacuation system in an emergency situation.

The combination of dense fog and high waves is unlikely; therefore, the bridge transfer system should have a high availability in fog conditions.

There are some DSHAs where the bridge evacuation system could be deployed without compromising the vessel integrity or the safety of the crew members. A walk to work system has been used in an emergency situation following an explosion and with a fire ongoing on the facility while the system was deployed. This is possible if the sea and wind conditions are suitable and there is adequate protection for evacuation.

The availability of the bridge could be improved by optimization of the bridge design and the elevations of the landing areas on the vessel and facility and consideration of the most likely load conditions for the facility in operation. The less the displacement of the facility varies in operation, the higher availability can be achieved for the bridge evacuation system.

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Appendix A. Wind turbine foundation solutions

A.1. Bottom fixed solutions, reference [A.1].

Bottom fixed installations for offshore wind generation are known technology from the installation and operation of such installations at several places in the world. The harshest weather conditions are found in the North Sea, where a large number of such facilities have been installed in Denmark, Germany and the United Kingdom.

An offshore wind farm consists of several turbines with a foundation, a tower with a nacelle and rotor as well as cables for control and transmission of power to the transformer station for further transmission to land. The most well-known type of turbine is mono-towers, where a pile with a diameter of several meters is driven into the ground using pile hammers. This pile is the foundation for the turbine. A tower that fixed by grout to the pile is installed, and then the nacelle and rotor are lifted in. The work requires the use of equipment that can operate and be relocated under limited wave conditions. Jack-up platforms are often used for the work, and a lot of commercial equipment is available. The concept of using mono towers depends on whether the ground allows piling to a sufficient depth and that the erosion around the pile at the seabed does not become too large. Most often, the concept is limited to use in water depths up to 30m. In several cases, the transition between the pile and the tower has been exposed to fatigue damage.

Along the coast of Norway there are only a few places where such facilities can be installed, as in shallow water there are only a few places where the ground conditions are acceptable. An alternative would be concrete structures that are placed on the seabed. This technology is used in inland waters in Denmark where drifting ice can occur and which monopiles can hardly resist. Also, in cases where there is a danger that breaking waves can hit the facilities with great force, it is relevant with concrete structures so that the forces and the moments from the wave forces can be distributed over a larger foundation area, figure A.1. For both monopiles and concrete foundations, stone embankments are usually used around the foundations to protect them from erosion from the effects of waves and currents.

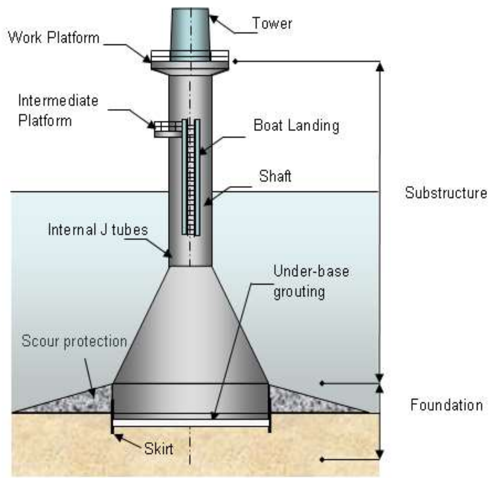

Figure A.1. Possible foundation for wind turbine in shallow waters. From reference [A.1].

For deeper water, it is relevant to mount the wind power turbine on a steel truss construction that is piled to the seabed; a "jacket", as used in the oil and gas industry. Such foundations can be installed at rather great depths; in the North Sea, such platforms have been installed at depths over 200m. But in the context of wind power, the costs quickly become too great with the use of this technology, which is possibly limited to 80 to 100 m water depth.

A.2 Floating offshore wind turbines

A.2.1 Requirement to floating offshore wind turbine

Floating offshore wind turbines must be used where facilities mounted on a single pile (up to approx. 30m, depending on the wave conditions and geotechnical properties of the seabed) or where other types of supporting structures fixed to the seabed, are not possible or cost-effective (up to approx. 100m depending on the cost of the foundation structure).

Floating offshore wind turbines are characterized by:

- That foundations are produced in a dry dock.

- That the turbines are completed at the quay or in deeper water (a fjord), depending on how much draft is required for towing.

- That the turbines are installed by connection to a pre-laid anchor system. The anchor system can consist of synthetic fiber rope or wire connected to chains which in turn are connected to an anchor (for example a suction anchor). Several turbines can be connected to the same anchor to save costs. Note that anchor lines and anchors restrict the seabed from fishing with several types of gear, including trawling. The restricted area will depend on which anchor solution is chosen and on the water depth. If a tether solution is chosen, the area being restricted is significantly reduced. Each individual plant can have its anchoring solution, but for Hywind Tampen it is e.g., planned 19 anchors, of which 9 will act as a common anchor for two or three turbines.

- That the cable for electrical transmission and a separate cable for controlling turbines are connected to a transformer station.

- That a substation already has been installed as part of the wind power farm for receiving alternating current from the wind turbines and transforming it into direct current. This reduces power loss when transmitting over long distances to a new transformer station on land where the power is transformed into alternating current again. In the case of any plant near land, electricity can be fed to land as alternating current without a transformer station.

A.2.2 Types of floating wind turbines

Several types of offshore floating turbines are proposed. In the further, some examples are discussed.

a) Hywind Scotland, figure A.2.

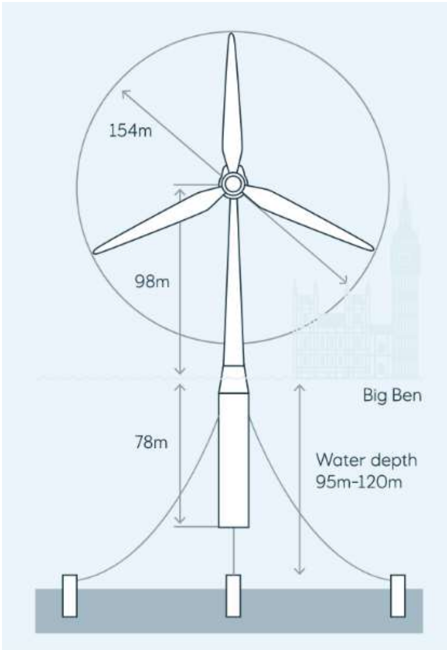

Figure 3.2 Hywind Scotland, 5 turbines, each 6 MW, total 30 MW, installed 2017, from [A.2].

The Arrangement of the wind farm is shown in figure A.3.

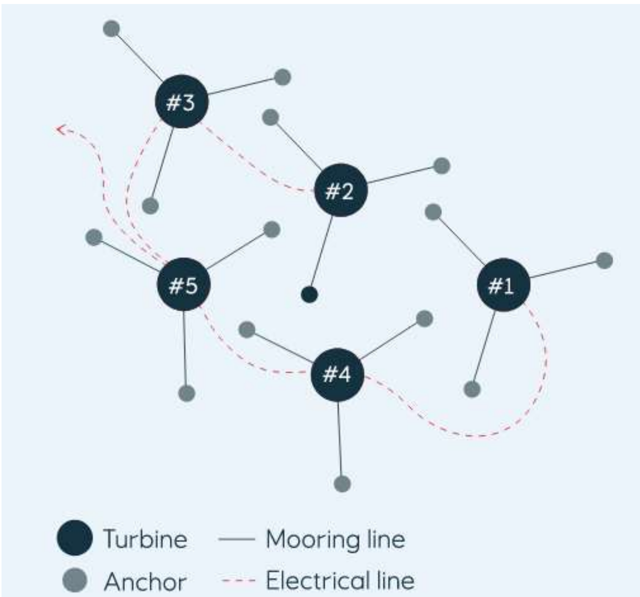

Figure A.3 Arrangement of the wind farm Hywind Scotland, consisting of five turbines [A.3].

b) Hywind Tampen; 11 turbines, each 8 MW, total 88 MW.

This wind power plant will produce electricity for the oil and gas platforms located on the Tampen area in the North Sea. The finalization of the foundations (in concrete) will be cast in early 2022. For information, see references [A.4] and [A.5].

Note that the cost of construction and installation is estimated at 500 million Euros. In this case, no transformer station is included since the electricity to be produced is used in the immediate area. For the construction and installation phase, see video [A.6].

The foundations are cast in a dock at Stord (figure A.4) and completed at the quay at Dommersnes in Ålfjorden. The foundations are then towed to Gulen for installation of the tower, nacelle and rotor before the turbines are towed out to the Tampen area.

Figure A.4 The lower part of the foundations for Hywind Tampen is cast in the dock at Stord before the foundations are towed to Ålfjorden for completion (Figure from Equinor).

c) Wind Float

Internationally, the Wind Float concept has received the most interest, Figure A.5. The reason why this concept is chosen is that there are few places where you can find deep enough fjords for construction and towing of wind power turbines of the Hywind type. It is preferred that the turbines are produced and completed in a dry dock and at the quay, so that work at sea in deep water is avoided, [A.7].

Towing takes place using a few tugs, figure A.6, taken from [A.8]. Note from figure A.4 that the anchor system will be significant if the turbine is installed in deep water. For operational purposes, it is easier to transfer personnel to Wind Float than to a Hywind solution as there are three columns in the waterline to anchor to. It may also be possible to use a helicopter that will land on top of one of the pillars when the rotor is at a standstill.

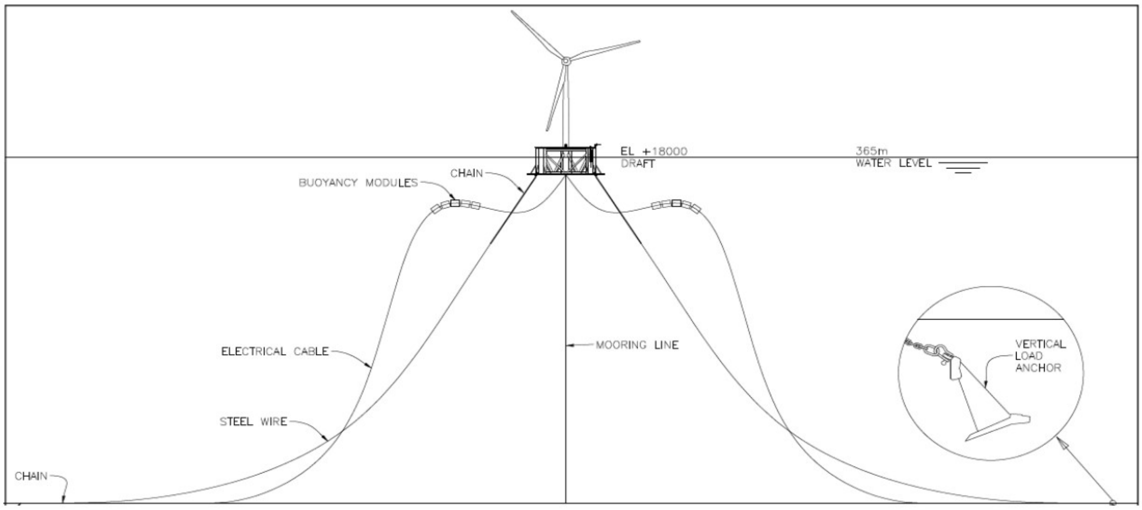

Figure A.5 Wind Float wind turbine; figure showing geometry as planned installed. from [A.9].

Figure A.6 Tow-out of the type Wind Float, 2019, from [A.8].

d) Tetraspar

Shell and partner RWA are looking at a further simplified concept; Tetraspar, see figure A.7.

Although the foundation is simplified, it may seem risky to transfer maintenance personnel to the facilities due to risk of collision between vessel and foundation.

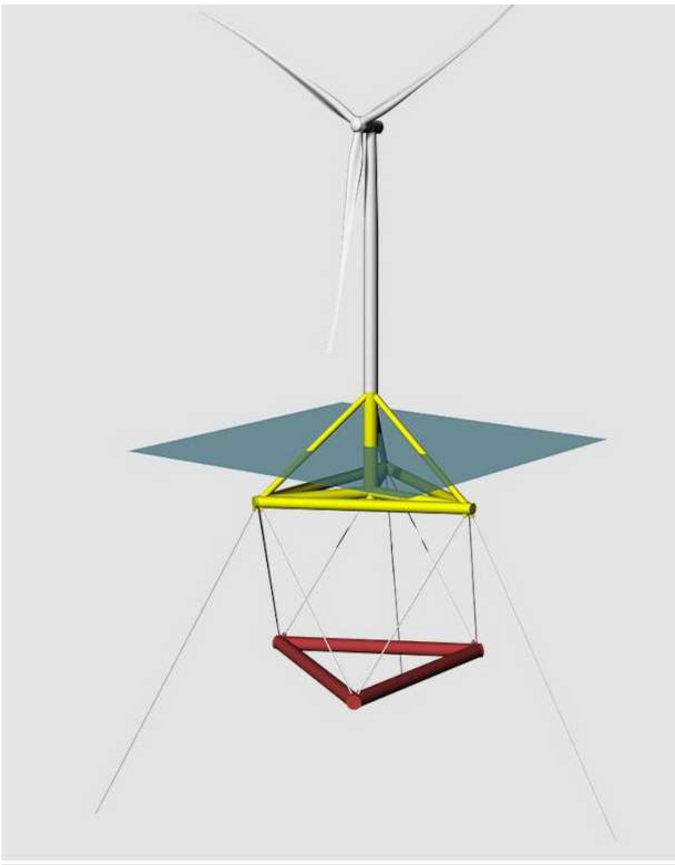

Figure A.7 Floating wind power turbine of the type Tetraspar is presently under testing, see [A.10].

A.2.3 Concept selection

For the choice of floating wind turbine concept, several factors will have to be taken into account, here are mentioned:

- The movements of the concept during waves and adaptation to the actual wave conditions at the location so that the movements lead to minimal time where shutdown is necessary. In particular, large angles of inclination (pitch) will be problematic for the rotor with subsequent shutdown.
- Available depth in the dock and at the quay and along the towing route are critical parameters for choose of concept.
- The diameter / extent of the anchor system can be critical for other industries that will be excluded in case large safety zones are required.
- Access for maintenance staff must be secured under harsh weather conditions for maintenance work to be possible throughout the year. The safety of workers must be in line with the requirements of other maritime industries.
- The investment costs will greatly influence the choice of concept. Operating costs must also be critically assessed.

A.3 Cables and transformer stations

Floating offshore wind turbines require electrical cables to be installed in the same way as risers and cables for offshore oil and gas installations.

Transformer substations to transform the current to direct current, see [A.11], are required to prevent power loss if the current is sent as alternating current. The weight of the transformer systems is significant and the transformer stations must be installed on separate floating installations of the submersible floating unit type or the like. If possible, the transformer stations can be placed on fixed steel truss platforms in shallower water nearby. There may be a need for operators to be present on these facilities for shorter periods of maintenance, and they must therefore be designed in accordance with the requirements for oil and gas platforms as there is risk of fires and explosions associated with transformer stations. Potentially, access could be with use of helicopters.

A.4 Operating and service centers for offshore wind turbines

Operating centers for offshore wind arms should be established where it is possible to easily keep in contact with the facilities, preferably near the coast. Maintenance personnel must have access to all equipment necessary for maintenance. The maritime industry is well acquainted with requirements for maintenance of offshore facilities.

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