

# Development of a Semi-submersible Barge for the installation of a TLP floating substructure. TLPWIND<sup>®</sup> case study.

Juan Amate<sup>1</sup>, Gustavo D Sánchez<sup>2</sup> and Gonzalo González<sup>1</sup>

<sup>1</sup> Iberdrola Ingeniería y Construcción, Av. de Manoteras, 20, 28050 Madrid, Spain

<sup>2</sup> Iberdrola Engineering and Construction, Ochil House 10 Technology Avenue, High Blantyre, G72 0HT, United Kingdom

**Abstract.** One of the biggest challenges to introduce Tension Leg Platform (TLP) technology into the Offshore Wind market are the Transport & Installation (T&I) stages, since most of TLPs are not self-stable as semisubmersible or SPAR platforms, and consequently requires additional means to perform these operations. This paper addresses this problem that has been overcome through the development of a Semi-submersible “Transport & Installation” Barge (SSB) for Iberdrola’s TLPWIND<sup>®</sup> floating support structure. The Semi-submersible Barge has been designed both through the use of numerical models and an extensive basin testing campaign carried out at the University of Strathclyde facilities. This paper also includes an estimation of the duration in time to carry out the installation process of a Floating Offshore Wind Farm, comprising 100x5MW TLPWIND<sup>®</sup> units in different scenarios.

## 1. Introduction

The development of offshore floating wind turbines is currently one of the toughest engineering challenges of wind energy. Numerous synergies have been established with Oil&Gas floating technologies (SPAR, semi-submersible and TLP) in order to determine the optimal concept designs that better matches with the conditions and constraints of the forecasted development areas worldwide.

In this sense, Oil&Gas floating technologies are designed like “one of a kind projects” that can be installed in reduced period of times and relatively short weather windows. On the contrary, the high number of units used for Offshore Wind developments require innovative systems that can perform an effective installation and operate at more severe sea states to increase the installation windows (or workable days per year). The possibility of assembling the wind turbine onshore has been determined as a major advantage for floating technologies, due to the development of a project lifecycle much more onshore based which reduces the cost and risks of a project.

SPAR designs cannot meet the requirement of assembling the wind turbine onshore due to its deep draught. TLPs have an outstanding dynamic behaviour in comparison to other floating technologies and also present a much lighter weight than Semisubmersible platforms, as well as much simpler construction processes and rated costs.

On the other hand, most of the TLP concepts present a lack of stability during the transport and installation stages, since the stability of this type of platforms is provided by the mooring system, once it has been connected. In order to solve this temporary drawback, aid systems which provide the required stability have to be used during T&I stages. The use of a Semi-submersible Barge is a solution which can efficiently address the abovementioned problem.



Previous developments for T&I based on the concept of a semi-submersible vessel have been proposed as presented in [1][2][3][4]. These concepts aim to reduce the cost of bottom fixed offshore wind technology, more specifically Gravity Based Foundations installation processes. Also, some companies have developed multipurpose semi-submersible vessels which can ease offshore operations as presented in [5]. For the floating wind sector, the development of a T&I barge for a TLP structure has been performed in the past as presented in [6], although this solution does not rely in the semi-submersible capacity but instead comprises a set of mechanical spuds to lower the platform (Figure 1).

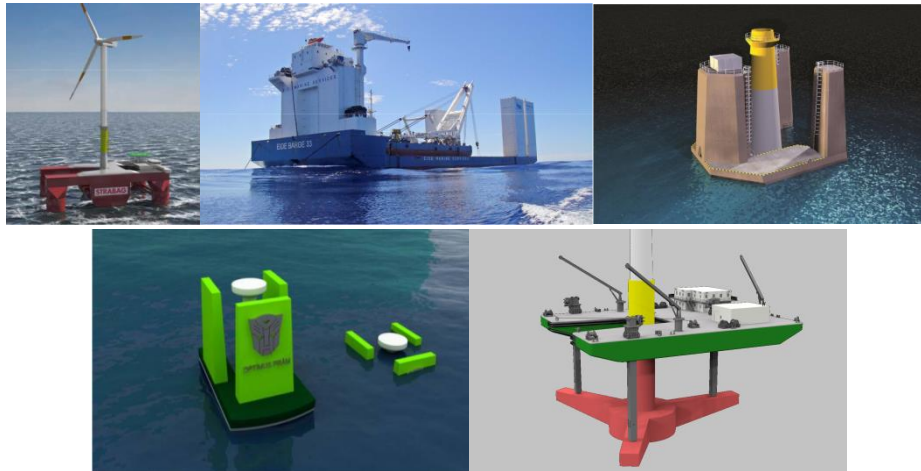


Figure 1: Strabag Carrier (Top left) [1], Eide Barge 33 (Top centre) [2], Vinci GBF (Top right) [3], Optimus Pram (Bottom left) [4], Pelastar barge (Bottom Right) [5].

In this paper, the design philosophy and performance of a Semi-submersible barge, tailored to TLPWIND<sup>®</sup> technology, is presented continuing the work exposed in [7]. The results have proven the feasibility of the solution and the cost reduction potential that it offers not only for the installation of the wind farm, but also to perform maintenance actions and the decommissioning which represent a significant part of an Offshore Wind Farm life cycle.

## 2. TLPWIND<sup>®</sup> technology description

TLPWIND<sup>®</sup> is an innovative TLP concept designed specifically to support offshore wind turbines for very aggressive conditions in mid/large water depths. This concept is characterized by a simplified geometry (Figure 2) and light weight (900 – 1000 tons TLPWIND<sup>®</sup> 5MW) which drives to much simpler construction processes and lower costs, but it requires an ad-hoc system that provides stability during T&I phases to avoid the use of expensive Heavy Lift vessels.

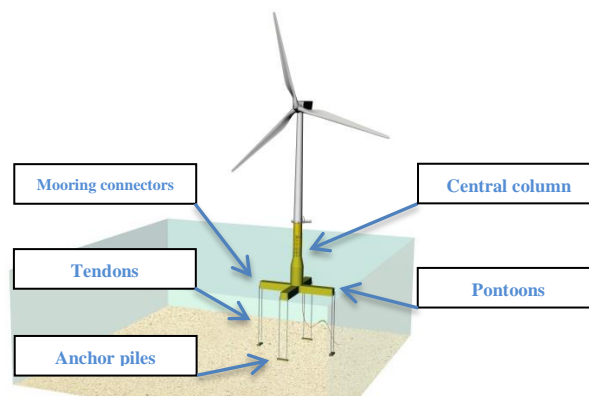


Figure 2: TLPWIND<sup>®</sup> technology main components

Since 2012, Iberdrola Ingeniería & Construcción has designed and tested at reduced scale three ad-hoc solutions for addressing this matter (Figure 3). An U-shaped barge, which can effectively perform the transport operations, a set of re-usable floaters which grant enough stability for performing both transport and installation operations, but also an U-shaped Semi-submersible barge (SSB); awarded PCT/2013/070697, that merged the advantages of the two systems formerly developed (High towing speed due to a significant low water resistance for transport operations & outstanding seakeeping capabilities at variable draughts).

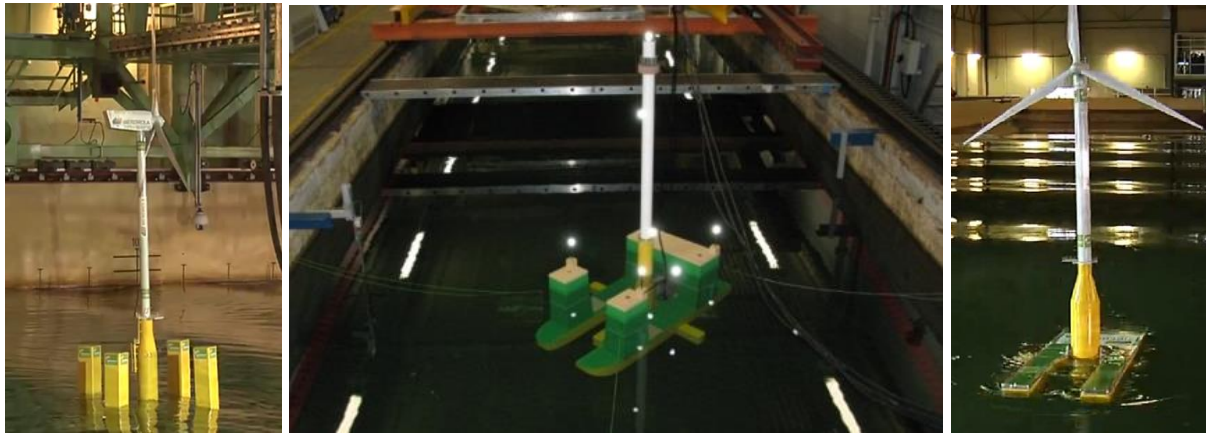


Figure 3: TLPWIND® T&I solutions. Auxiliary floaters (left), semisubmersible barge (centre) and U-shaped barge (right)

### 3. TLPWIND® transport and installation operation

This section covers the development and detailed study of the Transport & Installation operations and the necessary means to perform these operations with the TLPWIND® floating platform in a safe manner.

This includes the characterization and analysis of the steps to follow in order to perform the installation of a platform, initially focusing in a single platform to later consider a full wind farm scale (100x5MW TLPWIND® units) and the impact of having repetitive operations. The results for this study are presented at the end of this paper.

In this regard, fifteen operations were identified for a single unit which can be summarised in six main stages (Figure 4) starting from the required port operations (1 & 2), followed by a transport stage (3), installation of the TLPWIND® platform (4) and final recovery of the SSB (5) and tow back to port (6).

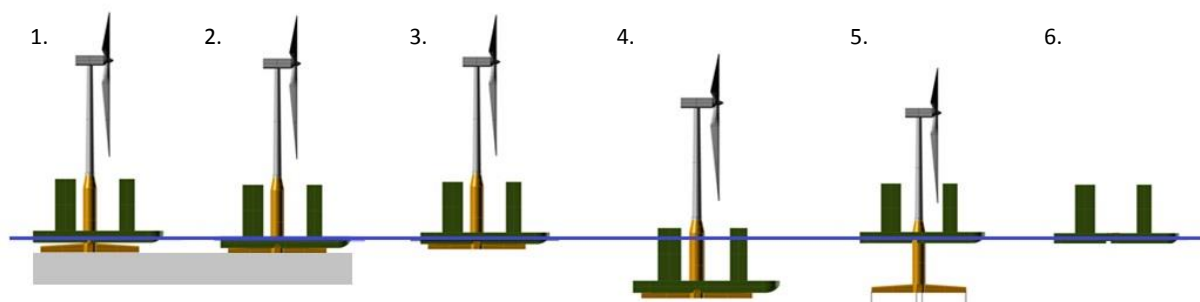


Figure 4: Transport and Installation stages

On a second step, the design of the ad-hoc SSB was carried out, taking into account the stability, towing resistance, dynamics and seakeeping characteristics of the vessel to comply with the requirements imposed by the wind turbine, the navigational limits and installation tolerances at each of the several draught conditions achieved during the whole installation operation.

#### 4. TLPWIND® Semi-submersible Barge design & analysis methodology

Since the first stages of development of the TLPWIND® concept, and in parallel to the design of the TLP platform, the creation an auxiliary system that allows reducing the T&I operations complexity as well as the associated cost has been one of the key tasks of the TLPWIND® design team. Subsequently, the development of a design methodology that allows adjusting the characteristics of the SSB to each specific TLPWIND® geometry (defined depending on selected site characteristics) has been established.

Following the typical naval design spiral, the methodology that has been used for the first loop in the development of the SSB is shown in Figure 5.

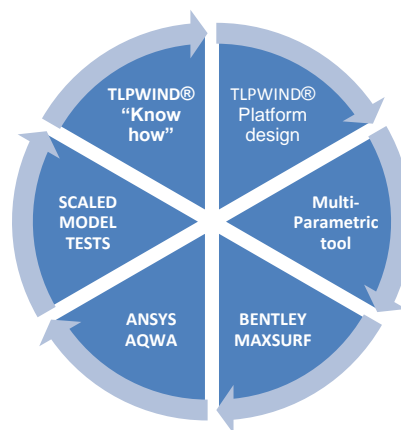


Figure 5: SSB Design Methodology scheme

On a first step an in-house Multi-parametric tool is used for achieving several preliminary configurations that meet the stability and dynamic performance requirements for a simple approach. Since the SSB is suited to a specific TLPWIND® geometry, the dimensions of the TLP platform have been taken into account to match both elements and the necessary footprint. Secondly, the use of commercial software like Maxsurf or Ansys AQWA allows verifying in the detail the stability and dynamic behaviour identifying the hydrostatic curves, static and dynamic stability, eigen periods and RAOs among many other parameters that define the performance of the system, thus this detailed analysis provides information that enables refining the design of the SSB.

For the selected design scaled model tests are carried out, which include a wide range of tests covering all the single stages that would happen during the T&I process apart from tests that help to characterize the SSB. A short list of the tests that have been performed is shown as follows:

- Free decay tests
- Semi captive towing tests in calm water and in waves for the SSB and SSB+TLP assembly
- Wired towing tests in calm water and in waves for the SSB and SSB+TLP assembly
- Seakeeping tests in regular and irregular waves

The results of the tests were correlated with the numerical simulations in order to validate the design and obtain additional information that allows once again performing a re-engineering process and improving even further, the design and performance of the SSB.

Consequently, it is worth highlighting that, the optimum solution will be reached by means of an iterative approach, where the design loop is repeated until the no significant improvement is achieved

More details on the results achieved from the development and scaled model testing of the SBB are presented in the following sections.

#### 4.1. SSB behaviour in transport operation

The Semi-submersible Barge introduced in this paper presents a significantly low drag resistance, which leads into a reduction of the capacity needed to tow the SSB+TLP to the installation point (commonly known as Bollard Pull).

This low drag makes possible to perform the transport operation just using conventional tug boats and avoiding the need of the expensive vessels used currently used for the Oil&Gas sector.

To determinate the towing drag and dynamic behaviour of the SSB barge, towing tests were performed in Kelvin Hydrodynamic Laboratory (University of Strathclyde) by means of two different methods: an accurate semi-captive system, used for characterizing the towing resistance of the SSB+TLP assembly, and a wired towing system, which allowed to characterize in a more realistic way the seakeeping behaviour during the towing operation in still water, regular and irregular waves. These tests provided the technical background for the decision on operational limits for the towing operation. The towing resistance was evaluated both in the transport as well as in return condition, once the TLPWIND<sup>®</sup> platform has been installed and only the SSB is towed (Figure 6).

In both conditions, the SSB presents an extraordinary low towing resistance even at high towing speed, due to the optimized shapes developed, which minimizes viscous drag and wave formation components.

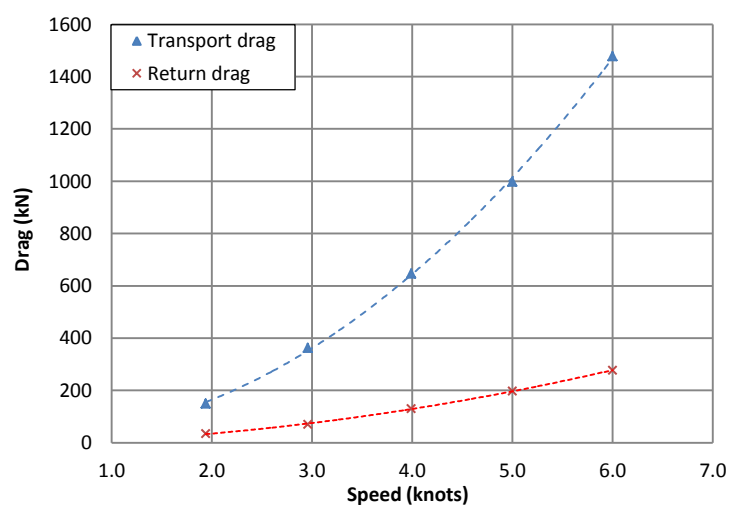


Figure 6: Calm water resistance with semi-captive system

As mentioned previously, this low towing drag leads into a reduction of the overall installation time, driving down the overall LCoE due to the shorter duration of the installation campaigns as well as the cost of the installation means needed.

Nevertheless, on a real scale operation, the transport operation would be performed with a towing wire (one line or various, depending on the specific transport scenario). In this sense, the position of the towage point may have a notable influence in towing resistance as well as in trim angles, which could lead into excessive tilting angles and loading over the nacelle, endangering the integrity of the wind turbine components.

Two different towing points were then considered for determining the best way to carry out this operation. Consequently, a precise tracking of the SSB's behaviour was required in these tests, which used an optical tracking system (*Qualisys*) to register the motions of the SSB. Also, the tension on the towing line was acquired by means of a load cell which connected the towing carriage and the towing wire that pulled the model.

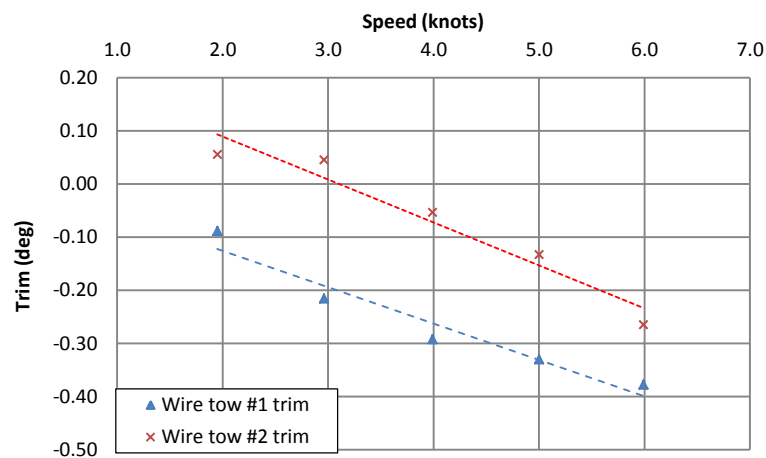


Figure 7: Calm water trim from wired tow tests

Difference between drag forces obtained using the different towing points are almost negligible; however, the SSB's trimming presents notable differences as shown in Figure 7. Towing point 1, located at the middle of the bow of the barge, develops almost twice trimming than the achieved when performed using tow point 2, which is located at the top of the bow of the barge.

The SSB has presented an extraordinary towing behaviour in calm waters; however, the transport operation tests have to be validated in realistic conditions, where waves are also taken into account.

The added resistance in waves was calculated for regular waves with a period ranging from 6 to 20 seconds (in real scale), with a nominal height of 1 meter.



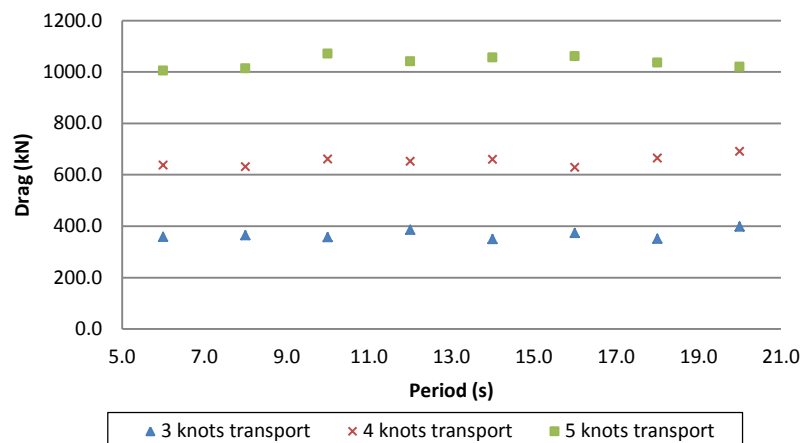


Figure 8: Transport operation resistance with waves using semi-captive system

The mean resistance is calculated in this section of the testing campaign integrating over a number of wave cycles, and the added resistance is obtained calculating the difference between this and the resistance calculated for calm water. Again, these tests were conducted for the transport and return condition. From these tests, it is obtained that the wave forming resistance increases the total resistance in between 2% and 6% depending on the specific wave period and towing speed as shown in Figure 8.

In the same way it was done for the calm water runs and aiming to represent a realistic behaviour of the barge on the towing operation, the tests for regular waves were repeated using a wired tow attachment.

With this wire towing configuration, it was noticed that the model develops a small directional instability and oscillates slightly from side to side (fish-tailing). This effect makes the resistance vary with the lateral oscillation. This phenomenon pointed that it seems to be more advisable to perform the towage of the TLPWIND<sup>®</sup> SSB platform using two tug boats and two towing lines rather than a single line.

On the other hand motions of the SSB in transport conditions seem to be appropriated for performing this operation in safe conditions. In the figure below (Figure 9), heave and pitch RAO resulting from testing the SSB in unitary height regular waves are plotted, presenting a good degree of reliability.

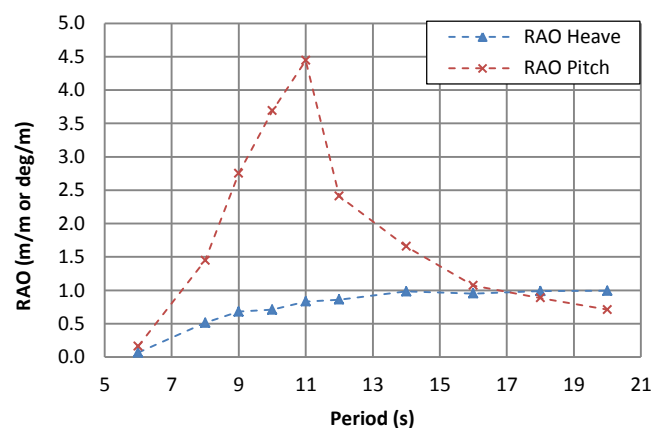


Figure 9: Towing test RAOs, regular wave with wire-tow system

As for most of the ships and conventional barges, heave RAO does not present any peak within tested range of wave periods, avoiding any undesired resonance and excessive motion in this degree of freedom. Therefore, the SSB+TLP assembly will just tag along the waves when towing in large period waves. On the other side, regarding pitch RAO, it is showed a maximum, corresponding to the pitch eigen period. In this sense, it is crucial to ensure this peak does not match with the most probable excitation periods that may occur during the transport operation, if not it is advisable to move this pitch eigen period above characteristic wave periods.

One of the aims of the design was to achieve pitch eigen periods above 10s, since sea state wave periods higher than that value are not expected during the transport operations for the selected location in this study, thus avoiding resonant phenomena.

#### 4.2. SSB behaviour in installation operation

Installation operation in a TLP structure is probably one of the most critical and sensitive operations to be planned within its development. In this sense, designing an auxiliary installation mean that greatly eases this operation and increases the installation weather window is a crucial issue when developing a large scale Offshore Wind Farm.

A set of four elastic lines (soft moorings) were connected at each of the corners of the SSB to keep the model in place. The evaluation of the seakeeping behaviour of the SSB has been carried out through analysis of the motions RAOs over a range of different draughts that will occur during the installation operation and subsequent ballasting. This evaluation started from the transport draught (lowest draught) and ended up for the draught at which the connection of the mooring system is performed (deepest draught).

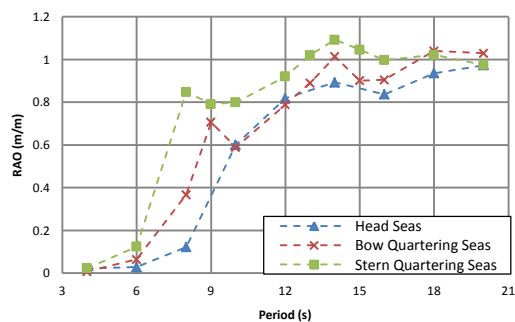


Figure 10: Zero forward speed Surge RAOs at transport draught (7m)

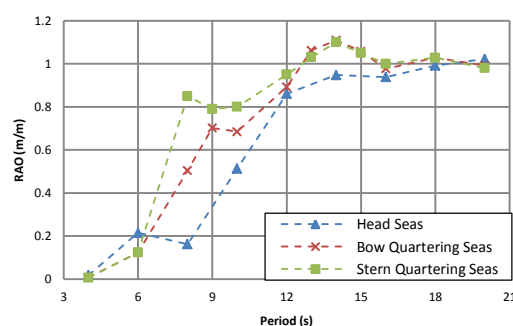


Figure 11: Zero forward speed Heave RAOs at transport draught (7m)

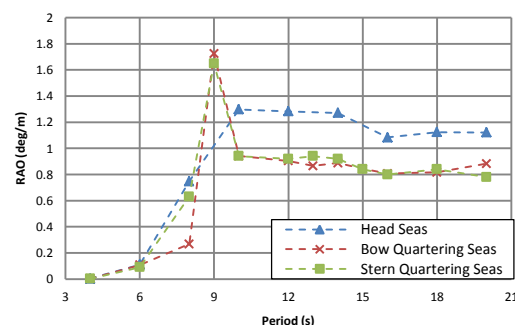


Figure 12: Zero forward speed Pitch RAOs at transport draught (7m)



These tests were carried out with three different wave headings (head, bow quartering and stern quartering waves) but same wave height of 1 meter and range of periods from 4s to 20s to make it comparable. Results for the initial installation stage (the one corresponding to the transport draught) are shown on Figures 10 to 12.

To ensure assure a good dynamic behaviour of the SSB and avoid undesired resonances or noise in the recorded signals, the mooring system is selected with a natural frequency far away from the generated wave frequencies and SSB natural frequencies.

The same evaluation of the stability and dynamic behaviour of the SSB was performed for the deepest draught or tendon connection draught (Figures 13 to 15). It is important to highlight that this condition requires a deeper analysis due to the sensitivity of this operation at which the platform is connected to the pre-installed mooring system.

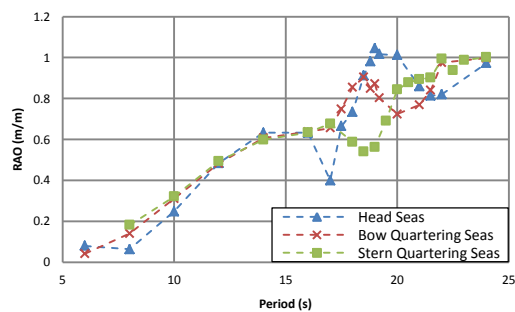


Figure 13: Zero forward speed Surge RAO at the connection draught (35.5m)

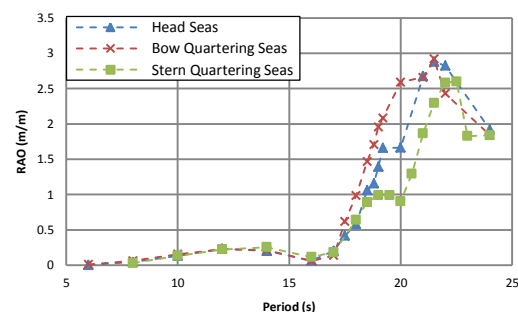


Figure 14: Zero forward speed Heave RAO at the connection draught (35.5m)

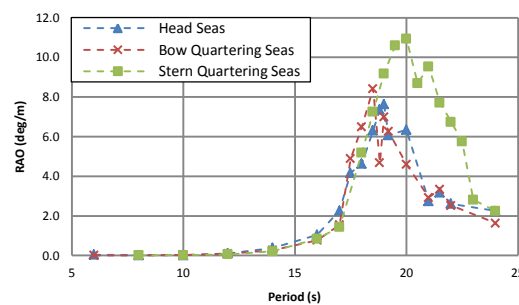


Figure 15: Zero forward speed Pitch RAO at the connection draught (35.5m)

For this tendon connection condition, other factors play an important role such as the need of accuracy in the positioning of the SSB+TLP assembly and the need of restricting as much as possible any displacement and rotation in the six degrees of freedom of the floating structure. Accordingly, the positioning methodology must be properly evaluated.

In order to evaluate this matter, a range of different stiffness for the elastic lines was tested, simulating the variation from a soft system (which was not expected to modify the behaviour of the SSB) to a stiff system (with approximately three times the stiffness of the abovementioned soft system).

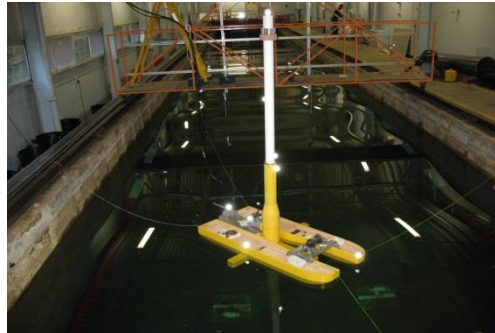


Figure 16: Position keeping system arrangement during the installation operation.

It is important to highlight that although the model from Figure 16 does not have the columns fitted to make towing easier, the mass properties were reproduced accurately so that the model behaved in all aspects as if the columns were present.

From the results of the tested performed, it can be concluded that that the less stiff the position keeping system is, the larger the operational offset will be (meaning the SSB is displaced from the initial position). However, there is not a notable influence in the amplitude of motions of the system due to this stiffness change.

The only exception to this conclusion is the pitch rotation, where the position keeping system proved to have a notable influence, reducing the amplitude of the motion at the eigen period of the SSB considerably as shown in Figure 17.

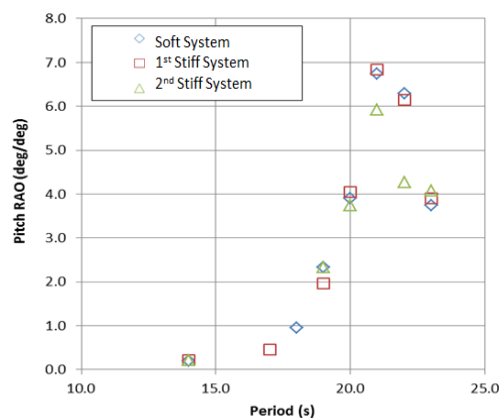


Figure 17: Pitch RAO comparison for three position keeping configurations tested

Nevertheless, since pitch eigen period of the SSB is intended to be higher than 20 s and well above the characteristic wave periods of the installation location (furthermore considering the operational limits for the installation operation), it can be concluded that the SSB at the connection draught is not very sensitive to variations introduced in the position keeping system.

## 5. Operational limits

The results obtained from the scaled model tests were used to evaluate and define realistic operational limits for the whole T&I operation.

This study showed that towing operations for the SSB+TLP can be performed up to a significant wave height ( $H_s$ ) of 2.5 meters at a towing speed of 5 knots, while most of the remaining operations can be carried out in significant wave height sea state up to 2 meters except for the most critical tendon connections operations that may require a less severe sea state of around 1.5 meters of significant wave height. However, as this operation has a very short duration compared to the whole T&I process, the impact on the overall averaged operational limit is small. As an example in Scottish waters, the averaged operational limit for the whole T&I operation is close to 2.4 meters considering Aberdeen coast as the wind farm site and its associated wind & wave characteristics, besides of a towing distance of 217 km from a port in Cromarty Firth to the selected site.

## 6. Overall installation time and cost reduction

Having defined the operational limits for each of the T&I stages and calculated the ideal duration of each of them, weather climate effect was considered by completing a study of the weather conditions for three UK waters representative locations. The operational limits for each step along with the associated duration were contrasted against the sea state probability of exceedance for the selected sites, resulting in the estimation of the necessary weather windows and expected weather downtime. The three sites are represented through the corresponding three annual mean wave heights.

The insights obtained from the previous studies were implemented for a complete Offshore Wind Farm project scale considering 100 units. This thorough study allowed estimating the total duration for the installation process of a 500 MW floating Offshore Wind Farm based on 5MW TLPWIND<sup>®</sup> platforms in different scenarios varying the staging port to site distance, weather conditions and the use of one or two SSB for the T&I strategy. This study also takes into account that T&I procedures are to be repeated numerous times, involving many man-driven operations which will have a learning-by-doing improvement. This effect was captured with the application of learning rates for each different operation when applicable (ballasting operations would not have a variation in terms of the duration of the operation).

If a single SSB is considered and a continuous installation process starting in April is assumed for the installation of the whole Offshore Wind Farm, the total estimated duration obtained for the installation of 100 units is shown in Table 1.

100 units T&I duration (days)		Annual mean wave height		
		1.0 m	1.5 m	2.0 m
Port to site distance	100 km	225 days	241 days	264 days
	250 km	365 days	397 days	425 days
	400 km	492 days	524 days	577 days

Table 1: Overall installation time with one SSB, 100x5MW TLPWIND<sup>®</sup> units

Also, if two SSBs are considered for an equal continuous installation process starting in April for the installation of the whole Offshore Wind Farm, the total estimated duration obtained is reduced by more than half since some severe weather months could be avoided.

100 units T&I duration (days)		Annual mean wave height		
		1.0 m	1.5 m	2.0 m
Port to site distance	100 km	110 days	121 days	130 days
	250 km	175 days	185 days	197 days
	400 km	245 days	262 days	290 days

Table 2: Overall installation time with two SSB, 100x5MW TLPWIND® units

Due to the outstanding dynamic behaviour of the SSB even with seas up to wave height ( $H_s$ ) of 2.5 meters, the overall installation time can be reduced which leads into a reduce of the overall LCoE of the wind farm project.

The application of TLPWIND® technology and the proposed T&I installation method has the potential to provide LCoE values of around £95/MWh by 2025 when considering a 500MW Offshore Wind Farm composed on 100 x 5MW TLPWIND® platform under Aberdeen conditions. An increase in the turbine size that would lower the number of installations to be performed could reduce the LCoE even further to values of £77/MWh by 2050 under the same conditions. Last, if additional reductions are considered like learning curves for the technology and market development LCoE values could reach £64/MWh by 2050.

## 7. Conclusions

The use of a semi-submersible barge for performing the transport and installation of TLP substructures supporting a wind turbine pre-assembled onshore is a technically and economically feasible solution. In this regard, a design of semi-submersible barge has been performed, which can efficiently carry out the abovementioned tasks reducing the overall installation process duration and costs. Also, the designed barge reduces the risks associated with the transport and installation operations besides of showing an outstanding performance in both transport and installation conditions.

The SSB has an exceptional navigation capability, even at seas with  $H_s=2.5\text{m}$ , with very low pitching angles, nacelle accelerations and towing drag ( $< 100$  tons) at 5 knots or even higher. Towing back operations after the installation can be carried out at 8 knots or even higher if higher bollard pull vessels are used.

As for the installation operations, the TLP+SSB assembly shows very good seakeeping characteristics and dynamic behaviour, especially for the lowest draught which represents the most critical installation operation.

Installation with the SSB presents high number of workable days per year, since offshore operations are minimized. Installing a 100x5 MW windfarm in less than 8 months is possible in sites with mild weather conditions and relatively close to a staging port (100 km) with just one SSB.

Finally, all the above mentioned advantages of the SSB, will not just apply for the transport and installation phases, but also for the maintenance and decommissioning phases of the Offshore Wind Farm, turning the SSB into a new concept of an asset which can provide evident benefits throughout the whole project life cycle. Thus, the extended exploitation of the SSB can provide a further cost reduction and even lower LCoE figures.

Due to the SSB's low drag characteristics and the enhanced dynamic behaviour, marine operations can be done using standard vessel like an AHT (20-35 k€/day) assisted by standard tugs (8-15 k€/day) and a WROV (8-12 k€/day) to carry out tendon connections, instead of expensive specialised vessels (150-500 k€/day). This reduction on the installation costs compensates the fabrication of the Semi-submersible Barge, leading into an overall LCoE reduction.

The application of TLPWIND® technology and the proposed T&I installation method has the potential to break the £100/MWh barrier in the near future and could offer a significant cost reductions in the long term to achieve very competitive LCoE values of £64/MWh by 2050.

## Acknowledgement

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