Design in principle of crane vessel for flexible fully assembled wind turbine installation

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Abstract— **Wind turbine industry is growing and future predictions are promising. However, a shortage of installation vessels could influence this growth in offshore wind industry. Commonly, wind turbines are installed in components using a jack-up vessel. Occasionally, wind turbines are installed fully assembled. Lifting above the wind turbine is not necessarily for fully assembled wind turbine installation due to the center of gravity of a fully assembled wind turbine. Wind turbines can be installed fully assembled using cranes in twin lift configuration to reduce required lifting capacities. The flexibility and scalability of the vessel depends on the location of the cranes on the vessel. Different vessels can install wind turbines with their advantages and disadvantages. A morphological analysis in combination with a comparison are used to identify promising solutions for fully assembled wind turbine installation. One new concept, the PWT installation vessel, shows overall improvement in installation rates. This solution, developed by the author of this paper, is proposed for flexible and scalable fully assembled wind turbine installation. Furthermore, this specific vessel is usable for other installation activities too.**

Keywords— Offshore wind turbine installation, fully assembled wind turbine installation, PWT installation vessel, crane vessel, semi-submersible vessel

I. INTRODUCTION

In 2021 the 12 MW wind turbines manufactured by General Electric Co will enter the commercial market. This wind turbine towers 260 meters high with relatively large weights which demands a large vessel to install the turbines [1]. It is expected that by 2023 the installed wind capacity is doubled compared to 2018 [2]. To achieve the required goal of 450 GW in 2050, the installation rate (GW/year) in 2035 needs to be the eight-fold of 2020 [3]. However, a shortage of installation vessels can hamper the deployment of the installation of the wind turbines. In future, a need is expected for 10 wind turbine installation vessels with capacity of 100 wind turbine installations per year, meaning an extra of 1,000 wind turbine installations a year [3]. State-of-the-art vessels can be upgraded to a certain extent to meet this demand but this will not be enough [4]. Besides an increase in numbers, wind turbines are also growing in power/size. Wind parks using up to 20 MW wind turbines are kicked off currently which seems to be a next step in wind turbine installation. In 2011, a 20 MW turbine seemed to be possible in the future [5,6]. These wind turbines will have a rotor with a diameter of 252 meters, hub height of 153 meters and an overall weight over 3,500 tons.

The state-of-the-art installation method assembles wind turbines offshore at location which is performed by jack-up vessels. These vessels cannot be used widely due to soil conditions and water depths. Furthermore, jack-up vessels need to raise themselves out of the water which negatively influences the installation rate of the vessels. A floating installation vessel can be preferable over a jack-up vessel due to the lack of the jack-up process. Besides, reduced installation time by lifting fully assembled wind turbines from a floating installation vessel is a promising method to fulfill the future installation need. The installation technique can be very different, however cranes have been proven to be flexible for offshore usage. A crane is equipped with a hook and different lifts can be performed using a hook. Apart from these three conditions, scalable and flexible installation is required. This means that the vessel should be scalable up to the wind turbine size it has been designed for. The flexible part is related to the crane usage for other applications, but this depends on the location of the cranes on the vessel.

The focus of this work was on the conceptual development of an installation vessel that is able to install large wind turbines fully assembled by one or multiple cranes. Scalability and flexibility are determined by the lay-out of the vessel and play an important role in the feasibility of the concept. Furthermore, focus of this research is on fixed foundations. The application of the concept is assumed to be in the North Sea and Baltic Sea (including passage possibilities between these two seas).

II. DESIGN REQUIREMENTS

A. Installations of a wind park

The development of a wind park consists of different processes. First, the foundation for wind turbines need to be installed. Most typical foundations are monopile, jacket and tripod. The dimensions of the foundation are problematic since monopiles are at the limit of allowed installation noise due to hammering [7]. These can be installed in different ways which all have some consequences on the operational process of the installation vessel. Currently, wind turbines are generally installed component wise, which takes a long time before a wind turbine is ready. Besides wind turbine installation, heavy lifts occur for offshore substations that convert the generated power of the wind turbines to shore.

B. Installation of wind turbines

Installing relatively large assemblies can be performed by first installing the whole tower and afterwards the nacelle and rotor (including blades) in one lift. This installation is proposed where the Thialf is installing the nacelle rotor assembly on a dummy tower [8]. Another way is installing first a part of the tower (for example half the tower) followed by the rest of the tower, nacelle and rotor [9]. The installing technique on which this study is focused is fully assembled wind turbine installation. Since this has been done a few times before, the CoG (Center of Gravity) of the wind turbines installations is estimated in order to be able to have some specific requirements for the turbine installation vessel [10,11,12]. This estimation of the CoG (schematically shown in Fig. 1) is used in a later stage of this research when detailed properties are needed for lifting. Larger assemblies used for installation mean a lower CoG of the assembled components but larger weights.

Installing a fully assembled wind turbine in one lift is possible. When lifting at the right points, this operation can even make the wind turbine less complex since it does not have to withstand every separate installation procedure. The CoG of the assembly is relatively low, but the installation requires large lifting capacities. It is not needed to specifically lift fully assembled wind turbine above the wind turbine which requires large hook heights. The location of the CoG of the wind turbine makes it possible to lift wind turbines from the side. Instead of one crane lifting, two cranes can be used of a smaller size. Two smaller cranes can possibly better control the wind turbine. Furthermore, two cranes limit the lifting height of the vessel, which is positive for the vessel movements. For twin-lift installation it is estimated that a hook height for a 20 MW wind turbine of 150 meters is enough for wind turbine installation on top of a jacket. Furthermore, there needs to be enough clearance during lifting between the wind turbine and foundation. Note that the fully assembled wind turbine installation on top of a 20 MW jacket requires a hook height of over 140 meters, which is possible with the estimated 150 meters for wind turbine installation.

C. Operational area and vessel passage

The focus area for offshore wind turbine installation is the North Sea and Baltic Sea. Many development zones for wind parks are foreseen in the North Sea and Baltic Sea [13]. 4C Offshore has developed a map on which wind turbine parks can be seen in different stages. The distances vary from near shore up to 300 kilometers offshore at the Doggersbank. The Baltic Sea and the North Sea are separated and only accessible via different Danish Straits for large vessels. One of the strait is the Great Belt which has a limited height and deepest draft of the Danish Straits [14]. The other large strait is the Øresund which has no height restrictions once the draft of the vessel is limited for passage over the Drogden Tunnel [15]. Øresund and The Great Belt passage do have a relatively large open area for a large vessel to maneuver through both large passages.

D. Criteria

Different criteria or vessel properties need to be taken into consideration for concepts for fully assembled wind turbine installation. The following criteria has been formulated for the concepts:

1) Size of vessel - Length and width of vessel hull

2) Operational window - Different installation methods result in different workabilities

3) Stability - Location of cranes influences stability of vessel (side or stern)

4) Scalable - Variety of wind turbine sizes and upgrades concept with time

5) Flexible - Usability in different applications of concept

6) Logistical challenges - Offshore logistics influence onshore logistics, balance important

7) Acceptance - New concept should be accepted to be developed

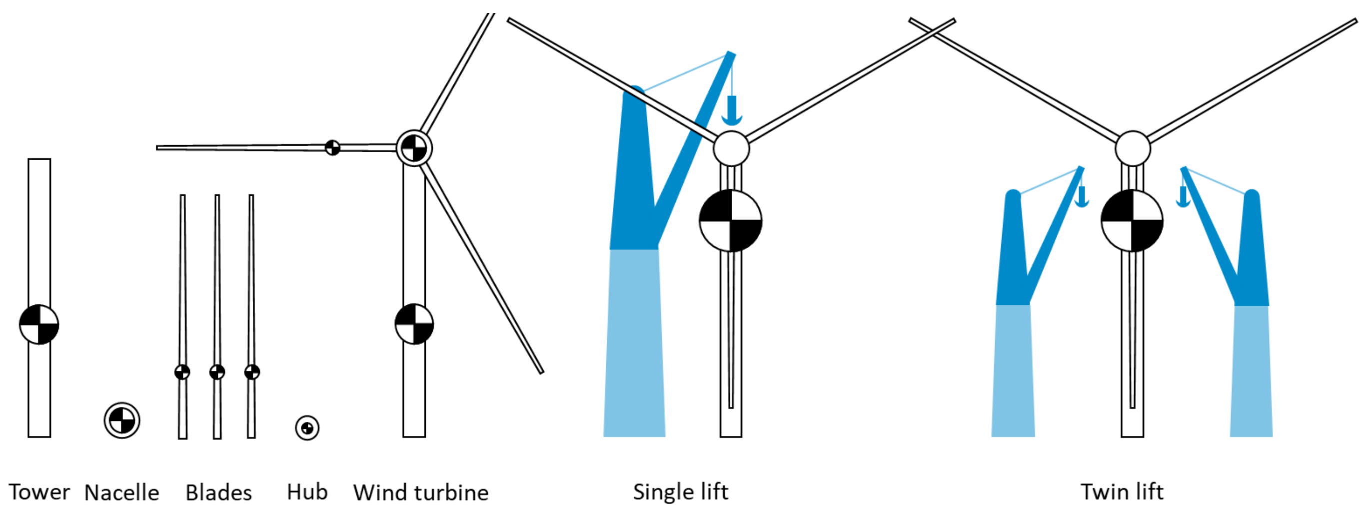

Fig. 1 Single crane or double crane wind turbine installation

E. Morphological analysis

To identify the large differences in solutions, specific solutions of the vessels (such as transport capacity and lay-out) are organized in a morphological overview. A combination of solutions forms a concept, marked in colors in Fig. 2. The following five operations (1 till 5) with different solutions (a till d) are identified for the investigation for (fully assembled) offshore wind turbine installation:

1) *Solutions for assembling operation*
   a) *None*
   b) *Onshore*
   c) *Crane vessel*
   d) *Jack-up vessel*
2) *Solutions for (un)loading operation*
   a) *Vessel equipment*
   b) *Crane vessel*
   c) *Barge exchange*
3) *Solutions for transportation operation*
   a) *2 Wind turbines*
   b) *4 Wind turbines*
   c) *8 Wind turbines*
   d) *Supply vessel*
4) *Solutions for sailing operation*
   a) *Barge*
   b) *Monohull*
   c) *Multi-body*
5) *Solutions for installation operation*
   a) *Vessel equipment*
   b) *Crane vessel*

III. Performance

Different concepts are introduced and explained based on the morphological analysis. These concepts are compared in relation to the installation rate. The installation rate is formulated in the 'Day per turbine' number.

A. Overview of concepts for comparison

Assembling, loading, transportation, sailing and installation

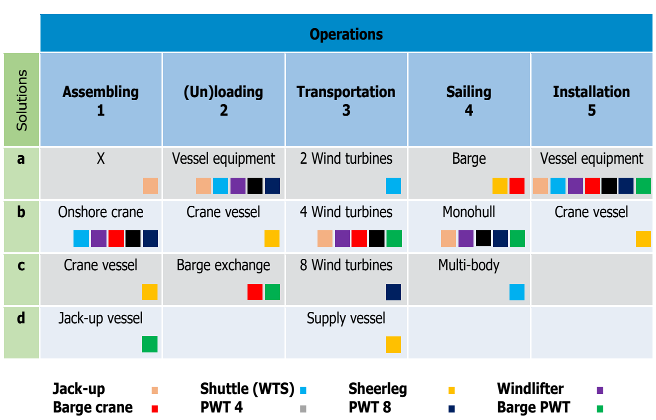

Fig. 2 Morphological overview of concepts

solutions are used in the morphological analysis (Fig. 2). The eight concepts for comparison are based on the morphological analysis. The barge exchange concepts make it possible to assemble wind turbines on the barge which can be seen as a temporary quay.

1) Jack-up ■

The jack-up vessel installs wind turbines in components and can transport four wind turbines in total. This solution is included to compare other solutions with the nowadays commonly used wind turbine installation method.

2) Shuttle (WTS) ■

The Huisman wind turbine shuttle can transport two fully assembled wind turbines and is specialized for this application [16]. The specialization of the vessel in combination with relatively small transport capacity is interesting and therefore the wind turbine shuttle is included in the comparison.

3) Sheerleg ■

The sheerleg cannot transport multiple wind turbines. For further comparison in logistics, the sheerleg is assumed to be at location and only picking up wind turbines from other vessels/barges and install them offshore. This solution is included in the comparison to identify whether it is interesting to have a specific crane vessel at location that only installs wind turbines while being fed by other vessels. Loading the wind turbines in the harbor can possibly be performed by using another sheerleg. Due to the usage of two sheerlegs, the installation rate and related numbers need to be doubled in the further comparison.

4) Windlifter ■

The Windlifter has an assumed normal transport capacity of four wind turbines. This vessel is capable to transport multiple pre-assembled wind turbines and install them by sliding them over the stern over a special bridge. The vessel is connected with the wind turbine foundation while the vessel moves with restricted motions [17].

5) Barge crane ■

One of the concepts using the barge exchange is the barge crane. The purpose of this concept is to identify the usability of the barge exchange. It is assumed that the barge exchange is taking place at the port (sheltered waters) where the wind turbines are assembled. Another crane can directly assemble the wind turbines on the barge. Note that an assembly crane is needed for most of the concepts that install fully assembled wind turbines. Every barge exchange solution requires at least two barges for efficient usage of the mechanism. These barges are not self-propelled and only consist out of a metal frame which is simple to build. Therefore, it is assumed that two barges with barge exchange vessels is valid to be compared with one other vessel.

6) PWT 4 ■ *and PWT 8* ■

PWT 4 and PWT 8 concepts are using the technical solution PWT crane configuration in combination with different transport capacity. PWT installation (Parallelogram Wind Turbine installation) or cranes in PWT configuration are in a diagonal position and based on a four-bar linkage system. It is observed that with this set-up the cranes can slew approximately 90 degrees without any trouble (Fig. 3).

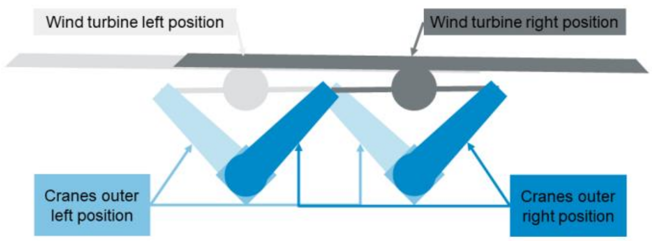

Fig. 3 Lifting wind turbines sideways

A transport capacity of four wind turbines is assumed to be the standard transport capacity on the installation vessel but the question is whether this number is the best transport capacity. PWT 8 can transport 8 wind turbines which is the double transport capacity of all the 4 wind turbine installation concepts. Furthermore, it is the quadruple transport capacity of the wind turbine shuttle. PWT 8 is included in the comparison to identify whether it would be interesting to scale up the transport capacity of the wind turbine installation vessels. It would not be a total fair comparison to compare PWT 8 with the Windlifter. Therefore, the PWT 4 is included in the total comparison.

7) Barge PWT ■

The new concept uses barge exchange with an optimized travel speed. The barge exchange limits the possible choices for twin-lift crane configurations due to the semi-submersible properties of the vessel. Both (small hull and barge exchange) are required for a good performance and thus this sets the limits for the development of (technical) solutions. Since the configuration of the Parallel Wind Turbine Installation (or PWT installation) can be placed on a slender vessel with promising properties for scalability and flexibility, it is included for further comparison as an extra concept for turbine installation. The wind turbines on the Barge PWT concept do not have to be moved over the cranes and the vessel should be able to install all wind turbine sizes up to its maximum installation capacity. No other crane arrangement is found for a vessel with a small hull without wind turbines moving over the cranes.

B. Comparison

The concepts identified in the previous section need logistical data (such as loading and sailing properties) to be analyzed in further comparisons. Since the amount of public information is limited for these concepts and some concepts are older (older technology), data is estimated for all the concepts.

The data of the jack-up vessel and Huisman wind turbine shuttle are based on a recent thesis related to comparison of wind turbine installation vessels and a joint interdisciplinary project of Delft University of Technology both in cooperation with Huisman Equipment Schiedam [18, 19]. Other data of the concepts is estimated based on the foreseen improvements of the different concepts relative to state-of-the-art installation vessels. The installation rate or Day per turbine is a good comparison to identify which concept has subsequent installation improvement over the jack-up vessel. Loading, sailing and installing are included in the data, all multiplied with the weather factor which takes the workability of different vessels in consideration. The data is absolute, but a relative comparison is made since the data is estimated. More details about the comparison and the different concepts can be found in [20].

The installation rates of the concepts are calculated for several distances: 0 kilometers up to 500 kilometers (Fig. 4). The sheerleg is an interesting solution for wind turbine installation. It is independent of distance from port to wind park. The overall performance of the sheerleg is not ideal due to the usage of two sheerlegs (port and wind park) which are needed for loading of supply vessels. A crane vessel with supply vessels at location is not interesting over a regular self-loading vessel. The wind turbine shuttle and barge PWT have a relatively good installation rate. The Windlifter shows potential for wind turbine installation since the day per turbine is comparable with the wind turbine shuttle. The difference between the shuttle and the Windlifter are the installation method and usability of the vessels, in favor of the wind turbine shuttle due to usability in both wind turbine and foundation installation. The barge crane has a relatively high day per turbine rate, mainly due to the low transit from marshalling port to the wind turbine park. Noticeable is the relatively low loading time of the barge concepts (compare PWT 4 and barge PWT at 0 kilometers). The Barge PWT is relatively quick compared with the PWT 4 solution. The barge exchange solution is beneficial for the installation performance. The PWT 8 efficiency is increasing over distance and comparable with the barge PWT in case of larger distances. The difference between PWT 4 and PWT 8 is marginal. The difference increases with the distance from marshalling port to the wind turbine park. Doubling the transport capacity does not immediately lead to a subsequent increase in efficiency due to the effect that every wind turbine needs to be loaded individually.

IV. PWT Installation Vessel

The small hull and barge exchange are combined in the Barge PWT concept which shows similar installation rates with the wind turbine shuttle (WTS). These two concepts have the best installation rate of all concepts. Since the wind turbine shuttle is less flexible and scalable than the barge PWT due to the vessel layout, the barge PWT is overall best performing.

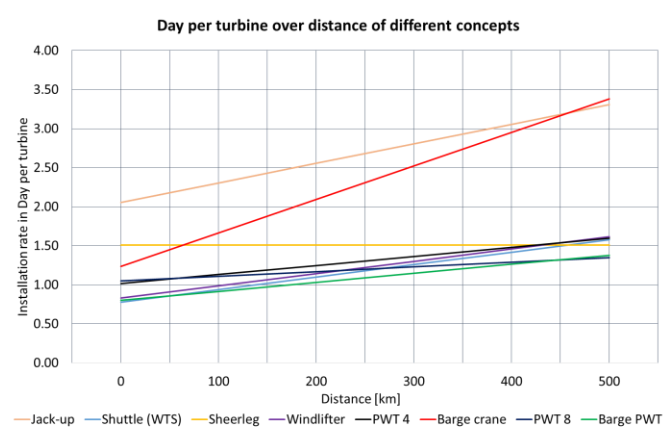

Fig. 4 Installation rate (Day per turbine) over distance for all concepts

An overview of applications of the Barge PWT or PWT installation vessel (Parallelogram Wind Turbine installation vessel) are schematically drawn in Fig. 5 and Fig. 6. The figures show how the base of the vessel and the applications could look like. The base of the vessel (Fig. 5) is shown left in the figure and the other applications from left to right are large wind turbine installation, jacket installation and small wind turbine installation. Furthermore, the offshore substation (OSS) with its jacket is schematically drawn on the right. The wind turbines are located in the center of the barge for stability during (un)loading. Additionally, a motion compensation system of the PWT installation vessel is proposed and explained in Fig. 7. A 3D model is made of the PWT installation vessel which shows various applications in offshore wind industry (Fig. 8). More details can be found in [20].

V. Conclusion

The wind turbine industry is growing and new installation methods can satisfy the growing installation demand. The grow rate can increase rapidly in terms of power and number of wind turbines. At the start of this research it was unknown if there was a possibility to find a new solution for wind turbine installation to fulfill future installation demand.

A combination of a small hull width for sailing, barge exchange mechanism for quick (un)loading and PWT (Parallelogram Wind Turbine) crane configuration show good installation performance. Cranes are used for the installation in a new set-up or PWT crane configuration. The result of combining the small hull and barge exchange with the PWT crane configuration is a flexible and scalable wind turbine installation vessel. This specific combination makes it possible to install wind turbines (and foundations) in combination with offshore substations. The absence of wind turbine lifting over the cranes makes it possible to install all wind turbine sizes up to the maximum lifting capacity. Furthermore, it is possible to scale the vessel up to the wind turbine size of that time. Another advantage of the barge exchange is the possibility to use existing jack-up vessels for wind turbine assembly on the barge in the harbor. Additionally, the adaptability of the barge exchange is a sustainable way to grow with the offshore wind market (Fig. 6). The concept only requires one installation vessel and can be used in many applications. The overall combination of existing techniques in a new arrangement makes the concept feasible to fulfill future needs.

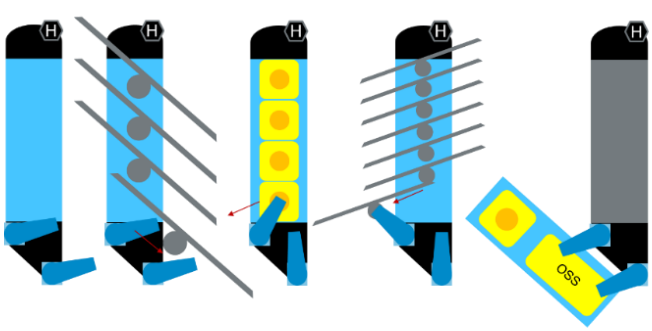

Fig. 5 Schematic drawing of PWT installation vessel base and diverse applications

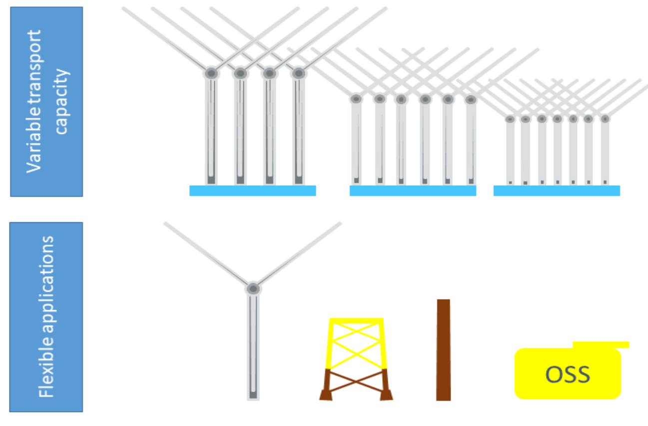

Fig. 6 Variable transport capacity and flexible applications

A concept has been proposed for wind turbine installation with preliminary designs for wind turbine installation. The combination of solutions could contribute to the need for wind turbine installation in the future. Three recommendations for further investigation are identified. First of all, a wind turbine installation vessels performs well if all the related logistical processes are working efficient. If the onshore activities do not fulfill the requirements for offshore installation rates, the solution cannot perform ideal. The onshore logistics for assembling of wind turbines for the PWT installation vessel need to be investigated. Assembling a 20 MW wind turbine in future requires a large crane. Possibly, older jack-up vessel can be used for this purpose. Secondly, the semi-submersible part of the vessel should get enough strength to withstand the PWT configuration stern. Detailed analysis is needed of motion compensation systems, vessel structure, crane configuration and barge exchange design. Lastly, efficient wind turbine installation can improve if different manufacturers are collaborating. Small adjustments in the design of a foundation or wind turbine can speed up the installation. If fully assembled wind turbine installation is used offshore, the manufacturers can change the design up to the requirements for onshore assembly of components and offshore installation of the wind turbine. If manufacturers of the wind turbine industry and installation industry collaborate well, installation processes can increase in efficiency.

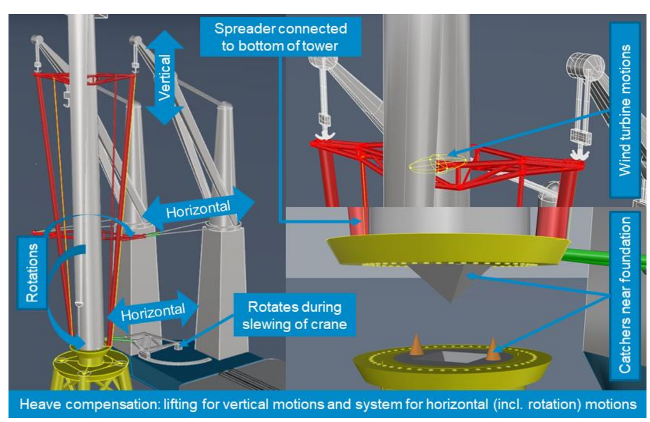

Fig. 7 PWT crane configuration functionalities

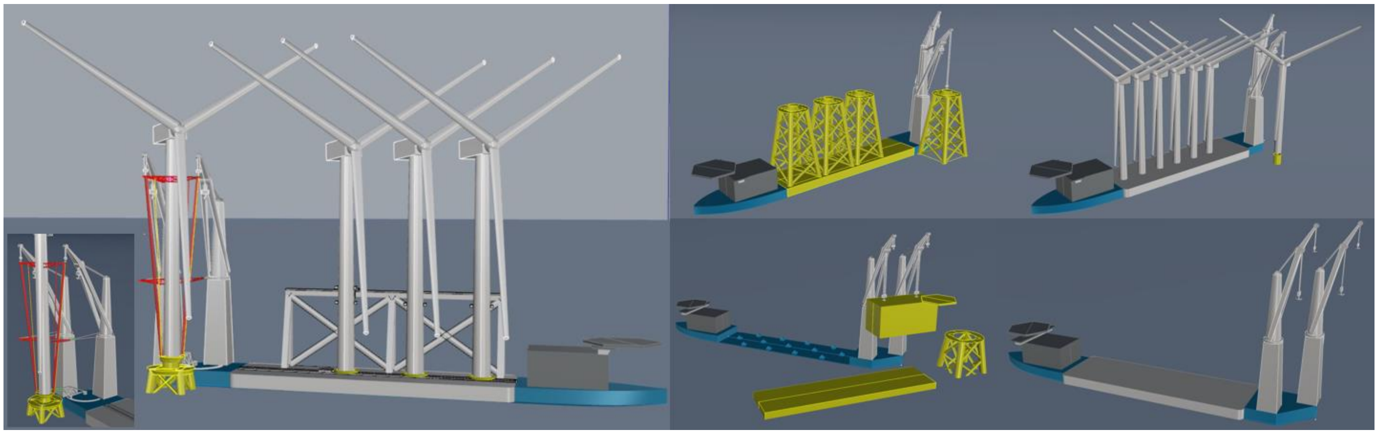

Fig. 8 Overview applications of PWT installation vessel

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