G. Hoogendoorn – BSc

Design in principle for flexible fully assembled wind turbine installation

Offshore installation of wind turbines

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Huisman
Worldwide Lifting, Drilling and Subsea Solutions

Design in principle for flexible fully assembled wind turbine installation

Offshore installation of wind turbines

By

G. Hoogendoorn – BSc

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TU Delft

Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world. *– Albert Einstein*

Preface

Dear reader,

First of all I would like to thank you for reading this report. Wind energy is an interesting form of alternative energy in my opinion. In the Netherlands, wind turbines are installed onshore in various places. These wind turbines are very large when passing by car or train. However, offshore wind turbines are typically larger in capacity compared with onshore wind turbines. Many of those cannot be seen from the coast although more wind energy is generated by offshore wind turbines compared with onshore wind turbines. The reason behind my interest in offshore wind turbines is the large and challenging installation of these wind turbines. Besides, the used transportation methods and demanding onshore logistics are also interesting.

I would like to thank all the people involved in my graduation project. Especially the supervisors who I could contact when needed and gave me the opportunity to continue during the Corona crisis. I started this project with Dr. ir. H. Polinder who I contacted for the wind program of Huisman. After an interesting discussion with ir. E. Romeijn of Huisman I got the opportunity to write my own research proposal to perform research on fully assembled wind turbine installation using cranes on a floating vessel. My daily supervisors ir. W. van den Bos of the TU Delft and ir. R. Nouwens of Huisman Equipment helped me well during the research period and gave critical but usable feedback. The team of supervisors gave me the opportunity to design and engineer new solutions for wind turbine installation. Special thanks to M. Brinkman of Huisman who helped me with finding the different vessels for wind turbine installation and who build the final model 3D model.

Furthermore, I would like to thank my family for guiding me at home. The Corona crisis forced us all to work at home which gave me the opportunity to develop and compare different concepts. I'm especially thankful to my father. His critical thinking and our discussions helped me splitting process and content in the project. Furthermore, I would like to thank my colleagues within Huisman Equipment who gave me the opportunity to ask questions for my project. I would like to thank the company in general for facilitating the graduation project.

It was interesting to use divers methods and perspectives in this project. I have not only applied tools and knowledge which I have learned from during my mechanical engineering studies but also design principles which I have learned during Design Thinking and my minor at Industrial Design. This knowledge in combination with my interest in cranes and transport methods let to the development of the proposed concept. Besides, I acquired valuable information related to offshore wind installation. The offshore wind turbine industry was more interesting and challenging than I had ever thought. I hope that my contribution to science and industry will help fulfilling future wind turbine installation demand.

Gerben Hoogendoorn
Driebruggen, July 31, 2020

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. The center of gravity of a fully assembled wind turbine is relatively low and thus lifting above the wind turbine is not necessarily for fully assembled wind turbine installation. 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. To identify these solutions, principles are proposed and compared with state-of-the-art vessels for wind turbine installations. A morphological analysis is used to identify promising solutions for fully assembled wind turbine installation. Eight concepts are compared in a scenario comparison with varying distance between nearby marshalling ports and the wind turbine park location. Several solutions show subsequent improvement in installation rates. One new concept, the PWT installation vessel, shows overall improvement in installation rates. This solution, developed by the author of this report, is proposed for flexible and scalable fully assembled wind turbine installation.

List of abbreviations

CoG	Center of Gravity
LCOE	Levelized Cost Of Energy
DP system	Dynamic Positioning System
SWATH	Small-waterplane-area twin hull
GM	Metacentric height
PWT installation	Parallelogram Wind Turbine installation

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1. 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 (Naschert, 2019). It is expected that by 2023 the amount of GW installed have doubled compared to 2018 (Ohlenforst, et al., 2019). To achieve the required goal of 450 GW in 2050, the installation rate (GW/year) in 2035 needs to be the eightfold of 2020 (Freeman, et al., 2019). 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 (Freeman, et al., 2019). In 2019, Huisman has been ordered to install the largest crane yet on a jack up vessel specific for the offshore wind turbine installation with a capacity of over 3,000 tons and unique heights (Huisman, 2019a). Still this vessel is designed to install wind turbines component for component similar to smaller comparable vessels. These vessels vessels can be upgraded to a certain extent to meet this demand but this will not be enough (Paulsson, Hodges, & Martin, 2019). 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 (Hopson, 2020) which seems to be a next step in wind turbine installation. In 2011, a 20 MW turbine seemed to be possible in the future (European Wind Energy Association 2011, 2011). These turbines will have a rotor with a diameter of of 252 meters, hub height of 153 meters and an overall weight over 3,500 tons. Comparing this with 10 MW turbines (largest state-of-the-art wind turbines at commercial scale), the overall weight is almost doubled and a rotor diameter increased by over 40%.

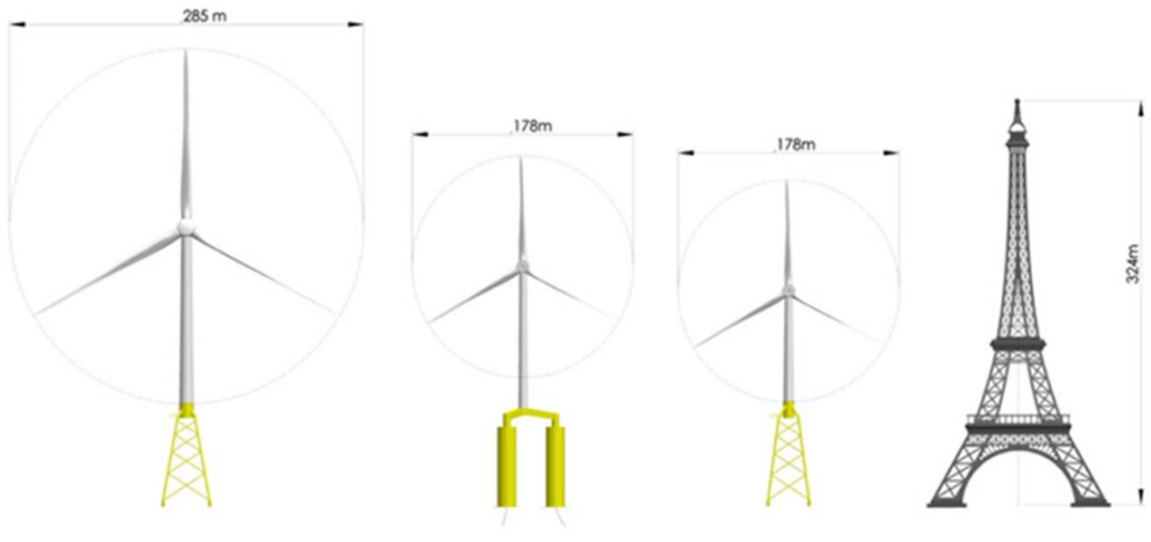


Figure 1 Wind turbine size comparison (20 MW on jacket, 10 MW on tripod, 10 MW on jacket and Eifel Tower) (TNO, n.d.)

A large gap exists between the future perspective of wind turbines and current methods of installation in terms of lifting heights and weights of components. Even the currently largest crane vessel built, the Sleipnir from Heerema, is probably just able to install a 20 MW wind turbine mainly due to the required lifting height. The size of the 20 MW wind turbine visually seen is relatively large compared with 10 MW wind turbines and the Eifel Tower (Figure 1 (TNO, n.d.)). The blade span of a 20 MW wind turbine is 123 meters (Peeringa, Brood, Ceyhan, Engels, & Winkel, 2011) which larger than the diameter of the London Eye.

Figure 2 W3G marine OWTIS wind turbine installation vessel (The Motorship, 2011)

Research has been performed to identify solutions to install large pre-assembled wind turbines offshore. One of the concepts is a monohull vessel equipped with one crane that can lift a wind turbine from the deck on the foundation with a supporting tool around the turbine. Still the motions of the vessel and the relatively low lifting point could generate problems since the CoG of the wind turbine could be relatively high and the whole turbine is free to move around under the crane. A vessel capable of single-lift wind turbine installation is shown in Figure 2 (The Motorship, 2011). Also currently used vessels have been proposed for installation a fully assembled wind turbine (Wermeskerken, 2013).

Figure 3 Huisman Wind Turbine Shuttle (Huisman, n.d.a)

There is also an interest for finding more specialized solutions for installation of wind turbines. One of them is the Huisman Wind Turbine Shuttle, capable to load, transport and install two wind turbines with a relatively high sailing speed. This vessel can transport not only wind turbines, but also other parts that are used for wind turbine installations (monopiles and jackets). The wind turbine shuttle is shown in Figure 3 (Huisman, n.d.a).

Research goal & questions

Still the mentioned vessels are scaled for lifting wind turbines up to current standards. 20 MW wind turbines seems to be a far future, but how far away are the turbines in reality? Last year, an article was published noting that a 20 MW generator needed for 20 MW wind turbines is ready within 3 years (Snieckus, Offshore wind turbine 20MW generator ready 'within three years', 2019). Installation of 50 large 20 MW turbines instead of 100 midsized 10 MW turbines could be interesting, especially when installation can be performed by just one lift. However it is uncertain to which extent wind turbines will grow and whether 20 MW is the best solution (Dobbin, Mast, & Echavarria, 2017). Therefore the purpose of this research assignment is defined using the following research goal:

Investigate and come up with promising solutions for installation of large fully assembled offshore wind turbines from vessel onto foundation with the possibility to transport multiple wind turbines on the installation vessel. The vessel itself should be scalable since the wind turbine industry can grow up to large sizes (> 20 MW), but small sizes can also be optimal (state-of-the-art turbines) and thus the proposed concept should not be dependent on this variety of sizes. Furthermore, the vessel should be flexible to be used for other applications too, especially related to offshore wind park installation (such as foundations and offshore substations).

Many different wind turbine installation vessels can be proposed within the research goal. 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 capacity 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, fully assembled wind turbine installation was set as a condition during the research, to reduce the number of liftings offshore which lead to reduced installation time. The reduced installation time due to pre-assembled wind turbine installation from a floating installation vessel is a promising 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 divers liftings 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 but this depends on the location of the cranes on the vessel. These conditions, considerations and the research goal are formulated in the following research question:

In which way is it possible to install pre-assembled large offshore wind turbines in a scalable, flexible way using a floating installation vessel equipped with one or multiple cranes?

With the following sub-questions:

1. Which size of wind turbines and wind turbine parks are foreseen for future wind turbine installation?
2. Which state-of-the-art vessels are used for wind turbine installation and which vessels are proposed to be used in future wind turbine installation?
3. Which requirements and processes are involved in wind turbine installation and how do the earlier introduced vessel relate with the fulfillment of the need for future wind turbine installation?
4. In which way can large wind turbines (up to or over 20 MW) be installed with the usage of cranes on a floating installation vessel with transport capacity?
5. In which way do the proposed concepts relate to each other compared with earlier proposed concepts?
6. Which overall concept show potential to be used in future wind turbine installation industry in terms of flexibility and scalability and in which way does it fulfill the need for the wind turbine installation industry?

Scope

Focus in this research is conceptual development of an installation vessel that is able to install large wind turbines fully assembled. In future, wind turbines can grow up to large sizes, but the concept has to be scalable with these sizes. 15 MW and 20 MW wind turbines have been announced as possible sizes, therefore first properties of the concept are based on these sizes. Furthermore, the installation of the foundations of these wind turbines is taken into account, but the main goal is installation of the wind turbine itself. The region where the concept could be used is mainly in Europe in the North Sea and Baltic Sea since these regions show large potential in wind turbine industry. The passage is the sea area Kattegat located between Denmark and Sweden. Using the difference in operational windows of these two seas (difference in wind and ice) could create a longer operational window for the installation vessel. Excluded are floating wind turbines which are required for specific areas (such as near France or Norway) due to geological circumstances. The focus of this research is on fixed foundations which can be applied in the discussed region. Rapid market change due to increase of wind turbine costs (such manufacturing) are not considered explicitly, but have something to do with the scalable property as mentioned before. Furthermore, state-of-the-art wind turbine designs and properties are assumed (tower, nacelle and blades) and no special wind turbines are involved in the research (such as multiple mini rotors on one foundation). The installation of the wind turbines is assumed to be executed feasible in terms of wind turbine properties, meaning lifted using a crane and enough strength in wind turbines for other attachments such as a gripper at the end of the tower. With this, 3D compensation is assumed to be practically applicable control wise. Mechanically, the concept should show potential to be used with 3D compensation. Wind turbines need to be installed at location, however fully assembled turbines need to be assembled elsewhere. It is assumed that there are enough larger ports that have facilities to assemble wind turbines and load them on a wind turbine installation vessel. Maintenance or repair on wind turbines, scalability of the concept and decommissioning activities are not widely involved in this research and are named secondary points.

Outline

The following steps are foreseen to be carried out during the research:

1. Investigate the current wind industry and future demand for installation
2. Analyze installation process of wind turbine parks and define criteria for concept development
3. Define solutions using cranes to install large fully assembled wind turbines in single lift
4. Compare different concepts proposed by literature and defined in this research to identify promising solutions
5. Work out one concept in detail
6. Evaluate the investigation

The above mentioned steps are the main steps performed in this research. Due to the form of this research, concepts will be proposed and thought of interactively. The steps 3 till 5 were iterative thus were not performed in chronological order. Step 1 and 2 are discussed in chapter 2 and 3 respectively. Different solutions (step 3) are proposed in chapter 4, 5 and 6. Step 4 and 5 are discussed in chapter 7 and chapter 8 respectively. The evaluation of the investigation is discussed in the final chapters of this report.

2. State of the art

This chapter describes the state-of-the-art and future market for wind turbine parks, wind turbine sizes and installation vessels. The following sub questions are answered in this chapter:

1. *Which size of wind turbines and wind turbine parks are foreseen for future wind turbine installation?*
2. *Which state-of-the-art vessels are used for wind turbine installation and which vessels are proposed to be used in future wind turbine installation?*

Chapter outline

The current offshore wind parks and wind turbines are growing in size and capacity to fulfill the future demand. Proposed are designs of 15 MW wind turbine and even 20 MW. These need to be installed while a shortage of 1000 installations a year is identified and needs to be fulfilled in coming future. Different installation concepts using specific examples are proposed by industry. State-of-the-art vessels are discussed which can (possibly) assemble and transport wind turbines component wise. Furthermore, proposed modifications on current vessels are discussed. Finally also the proposed concepts of which some will set sail within a couple of years will be discussed. The focus is to identify the differences in wind turbine installation and it is not representative for the whole fleet of wind turbine vessels. The jack-up vessel is used commonly for wind turbine installation while a few other vessels have been used occasionally.

Offshore wind turbine market

In 2019 Europe added 3,627 MW offshore wind power of which the UK contributed most (Ramírez, Fraile, Brindley, Walsh, & Velde, 2020). Ramírez, Fraile, Brindley, Walsh & Velde (2020) also discussed that the average capacity of the wind turbines, has been steadily increasing for the last couple year, with a growth of almost 8 MW last year. Not only the size of the wind farms increased, but also its power. The average distance from shore to offshore wind farms is increased. This was in 2018 24 kilometers closer as in 2019. The average distance in 2019 was 59 kilometers. Yet it is not sure how the future of floating wind farms will look like in future. France is the only country planning to launch auctions for floating wind farms and the results will determine further conditions for auctions from 2024 on (Ramírez, Fraile, Brindley, Walsh, & Velde, 2020).

Most of the wind turbines are produced by a few manufacturers. Siemens Gamesa Renewable Energy, MHI Vestas Offshore Wind and GE Renewable Energy represent over 90% of the offshore wind turbine market connected in Europe at the end of 2019 (Ramírez, Fraile, Brindley, Walsh, & Velde, 2020) [redacted]. Furthermore 70% of the newly-installed foundations were monopiles in 2019 compared to the 30% of jackets installed (Ramírez, Fraile, Brindley, Walsh, & Velde, 2020).

MW, offshore	New installations 2017	Total installations 2017	New installations 2018	Total installations 2018
Total offshore	4,472	18,658	4,496	23,140
Europe	**3,196**	**15,630**	**2,661**	**18,278**
United Kingdom	1,715	6,651	1,312	7,963
Germany	1,253	5,411	969	6,380
Belgium	165	877	309	1,186
Denmark	0	1,268	61	1,329
Netherlands	0	1,118	0	1,118
Other Europe	63	305	0	302
Asia-Pacific	**1,276**	**2,998**	**1,835**	**4,832**
China	1,161	2,788	1,800	4,588
South Korea	3	38	35	73
Other Asia	112	172	0	171
Americas	**0**	**30**	**0**	**30**
USA	0	30	0	30

Table 1 Historic development of total installations (Ohlenforst et al., 2019, p. 29)

In total, Europe has installed most of the wind turbines compared to other countries, but country based China is on top, followed by the UK and Germany (Ohlenforst, et al., 2019) [redacted]. China is growing in terms of power of new offshore wind turbine installations, followed by the European countries Table 1 (Ohlenforst, et al., 2019). Apart from Europe and the Asia-Pacific area, no other countries worldwide have installed offshore wind turbines (Ohlenforst, et al., 2019). Ohlenforst et al (2019) predict a market increase for offshore wind turbines be doubled in 2023 relatively to 2018. By 2025, 10% of the wind energy is generated by offshore wind turbines and the market is changing to become global up to 2030 since more countries want to set up offshore wind turbines (Ohlenforst, et al., 2019). The market growth in the future is expected to be driven by China primarly together with new countries such as Taiwan, Japan and South Korea (Musial, Beiter, Spitsen, Nunemaker, & Gevorgian, 2019). Still, Europe would be 47% responsible for the total installed global offshore wind capacity.

Wind turbine parks in future

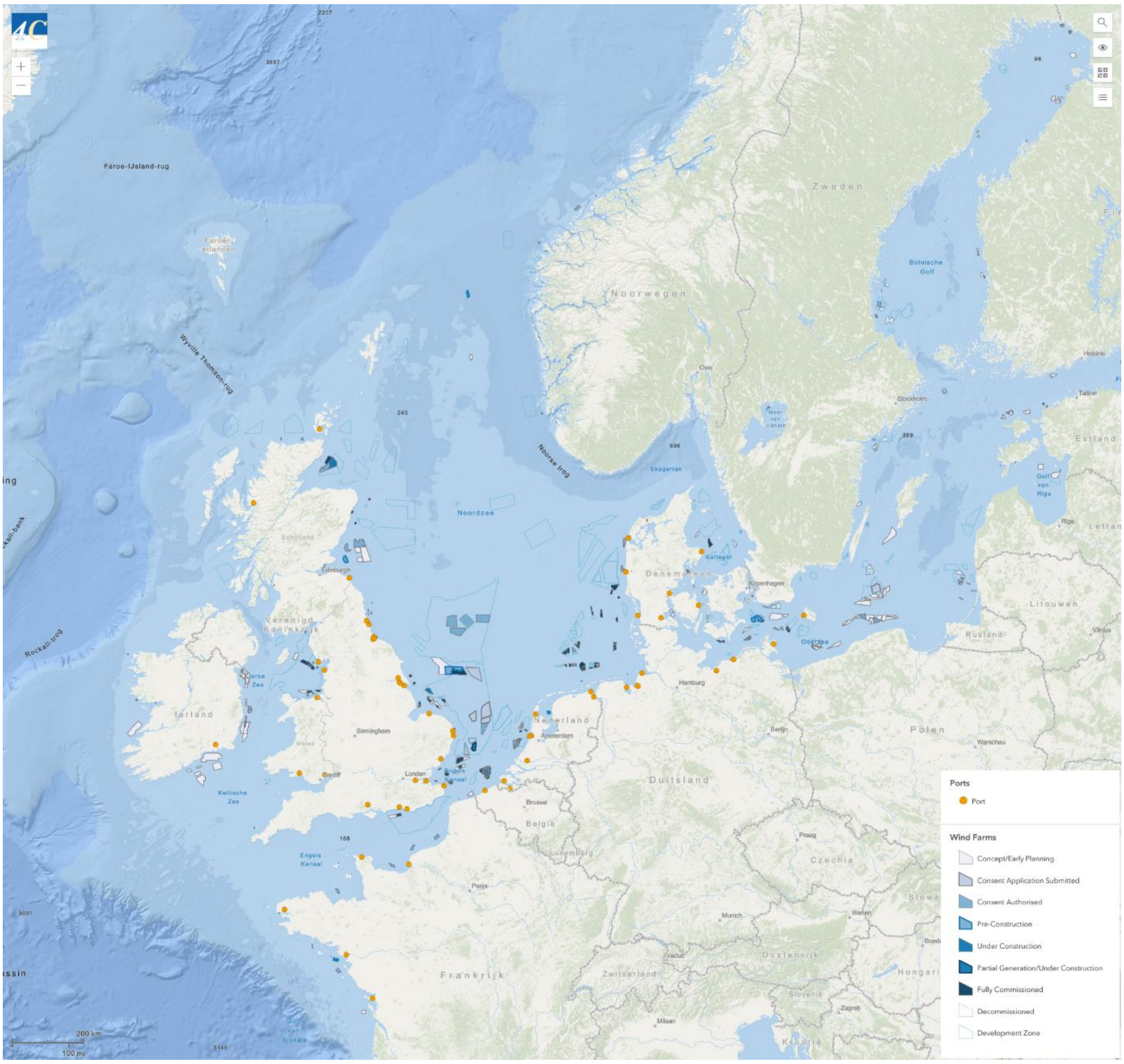


Figure 4 Offshore wind map ports and wind parks (4C Offshore, n.d.a)

Many development zones are proposed for wind turbine parks. Relatively dense areas of wind turbine parks will be located in different economic exclusive zones (EEZ) which is shown in Figure 4 **(4C Offshore, n.d.a)**. This figure is composed out of multiple maps, combining the area of the North Sea and Baltic Sea. These maps are accessible as an interactive map online (https://www.4coffshore.com/offshorewind/). Figure 4 shows all the wind parks that are marked as concepts up to fully commissioned. In the EEZ of the Netherlands, United Kingdom, Germany and Denmark many wind parks are in development. However, in the Baltic Sea there are also many wind park development zones. Wind parks are proposed around Poland, Estonia and in the northern part of the Gulf of Bothnia. Many (possible marshalling) ports are located around the southern part of the North Sea and western part of the Baltic Sea, but not all wind parks have a close connection with usable ports for offshore wind turbines.

Freeman, et al. (2019) notes that the LCOE (levelized costs of energy) are very high when the wind turbines are located further away from shore (assuming 15 MW wind turbines). Every improvement that reduces these costs is interesting for further investigation. The LCOEs of the North Sea and the

Baltic Sea are shown in Figure 5 (Freeman et al., 2019, p. 20, fig. 5). The LCOE can also be reduced using larger wind turbines (TNO, n.d.). These reduction of costs could be over 30%.

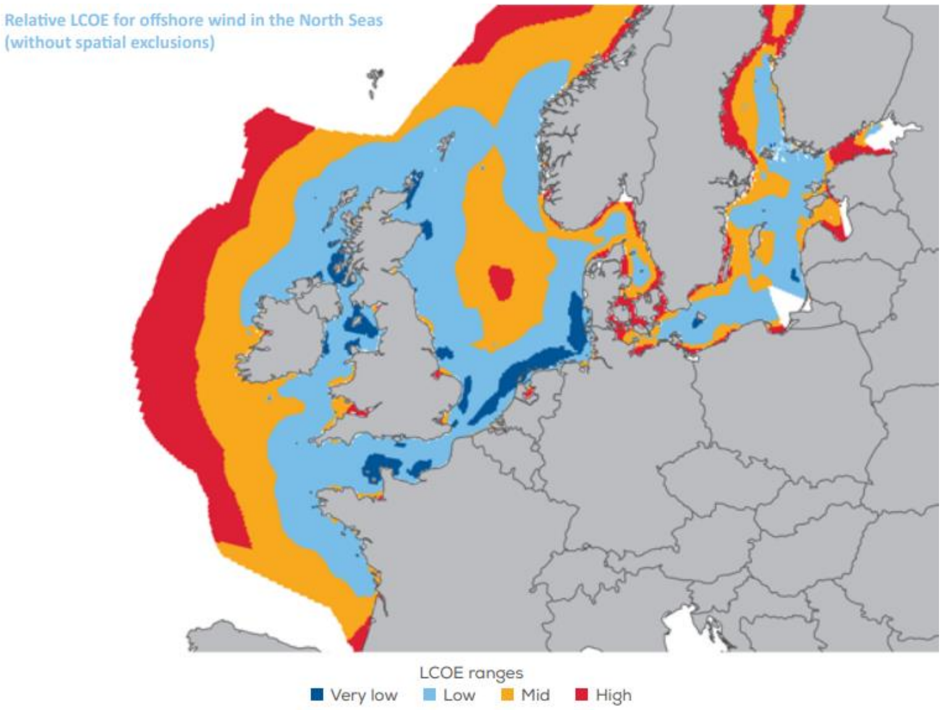


Figure 5 Levelized cost of electricity (Freeman et al., 2019, p. 20, fig. 5).

A rapid growth of the installation rate is expected for offshore wind turbines (Freeman, et al., 2019). They show that this year (2020) an installation rate of approximately 2.5 GW/year is expected which should grow up to more than 20 GW/year in 2035 (eightfold of 2020). The installation rate needs to be very high to achieve 450 GW offshore wind in 2050, shown in Figure 6 (Freeman et al., 2019, p. 30, fig. 8) and Table 2 (Freeman et al., 2019, p. 30, tab. 2). The European Commission estimates that between 240 up to 450 GW offshore wind power is needed to keep temperature rises below 1.5°C (European Commission, 2020).

The wind power plays an important role to achieve the renewable energy targets by 2050. The discussed GW/year numbers can also be converted in number of wind turbines. If 2020 has a foreseen 2.5 GW/year installation rate assuming 10 MW wind turbines, 250 wind turbines need to be installed in one year. If in 2035 the state-of-the-art wind turbine is 20 MW and an installation rate of over 20 GW/year, it means installation of 1000 wind turbines a year of 20 MW or over 1300 wind turbines a year of 15 MW. A growth is foreseen from 2035 on the installation rate on repowered sites of 0.4 GW/year steadily up to 2.0 GW/year in 2050. There is a large market in offshore wind turbine installation for over more than 30 years of which repowering is relatively small. For future demand of installation Freeman, et al. (2019) note that at least 10 new installation vessels are required, capable of installing over 100 turbines a year including some heavy-lift deep water installation capable vessels. Floating wind turbines and innovative installation procedures can decrease this demand for new installation vessels (Freeman, et al., 2019).

	AVERAGE RATE					
	2019 to 2025	2026 to 2030	2031 to 2035	2036 to 2040	2041 to 2045	2046 to 2050
Installed on new sites (GW/year)	5.0	8.2	14.8	20.7	20.5	15.8
Installed on repowered sites (GW/year)	0.08	0.20	0.39	0.72	0.88	2.03

Table 2 Required installation rate for achievement goal 2050 450 GW (Freeman et al., 2019, p. 30, tab. 2)

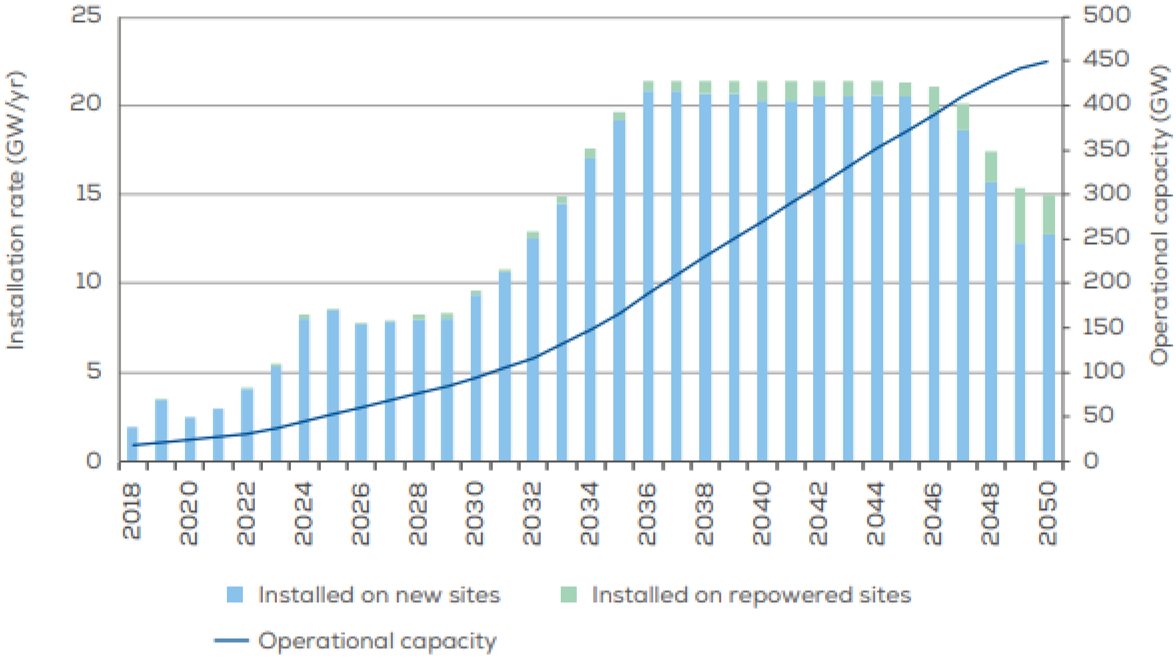


Figure 6 Required installation rate for achievement goal 2050 450 GW (Freeman et al., 2019, p. 30, fig. 8)

Growing offshore wind turbines

Wind turbines are growing in size. The largest wind turbine that is used for offshore purposes is the GE Haliade-X 12 MW prototype which is installed at Rotterdam-Maasvlakte last year. General Electric will be starting serial production second half of 2021 (GE Renewable Energy, 2019). One of the turbine installation companies, Jan de Nul, mentions wind turbines of 16 MW within the coming 5 untill 10 years which are larger than the currently introduced 10 MW market models (Spoelstra, 2020). Even the earlier mentioned wind turbines of 20 MW can be larger since new technologies can lead to a generator applicable on 25 MW wind turbines (Snieckus, New-look generator opens door to 25MW offshore wind turbines, 2019). [redacted] Developers are taking the advantage of inceasing wind turbine sizes and will generally select the largest wind turbine available for projects for cost advantages (Musial, Beiter, Spitsen, Nunemaker, & Gevorgian, 2019). The proposed detailed designs of 15 MW (published in 2020) and 20 MW (published in 2011 and 2017) are discussed further since for these turbines estimated properties are published in detail.

Future 15 MW wind turbine

Based on the direct drive GE wind turbine, a reference turbine is formulated with an estimated power of 15 MW (Gaertner, et al., 2020). This direct drive wind turbine is an open design to enable collaboration between industry and research institutes. The turbine has an hub height of 150 meters and a rotor diameter of 240 meters. Furthermore the monopile has a diameter of 10 meters and weighs 1318 tons. Figure 7 (Gaertner et al., 2020, p. V, fig. ES-1) shows the properties of the 15 MW reference wind turbine. The properties of the 15 MW wind turbine compared with the 10 MW wind turbine are shown in Table 3 (Gaertner et al., 2020, p. IV, tab. ES-1).

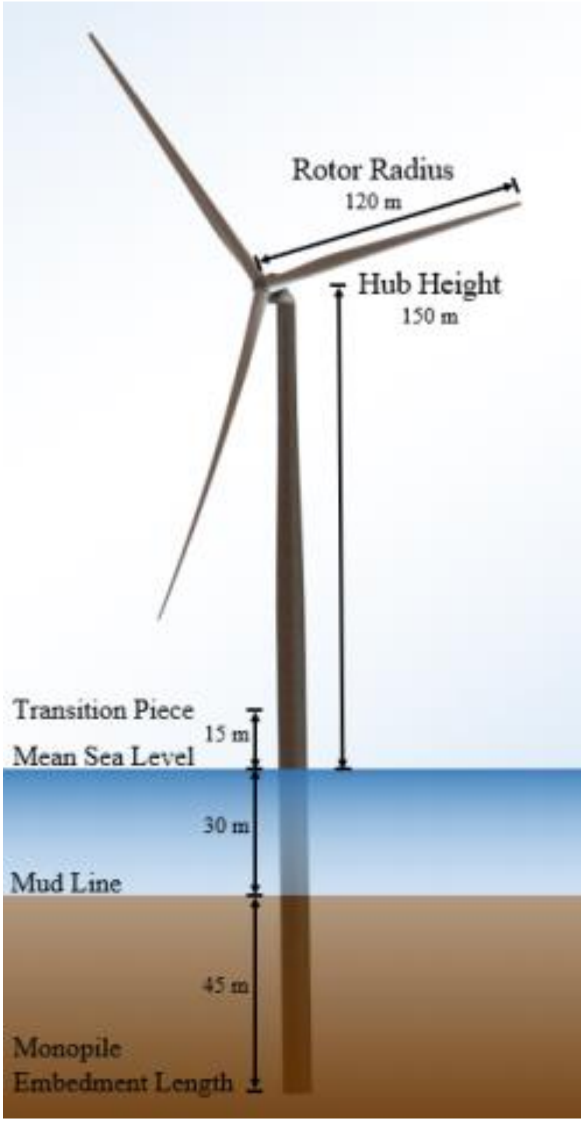


Figure 7 IEA 15 MW reference wind turbine (Gaertner et al., 2020, p. V, fig. ES-1)

Parameter	Units	DTU 10-MW Turbine	IEA Wind 15-MW Turbine
Power rating	MW	10	15
Turbine class	-	IEC Class 1B	IEC Class 1B
Specific rating	W/m^2	401	332
Rotor orientation	-	Upwind	Upwind
Number of blades	-	3	3
Control	-	Variable speed	Variable speed
	-	Collective pitch	Collective pitch
Cut-in wind speed	m/s	4	3
Rated wind speed	m/s	11.4	10.59
Cut-out wind speed	m/s	25	25
Rotor diameter	m	178.3	240
Airfoil series	-	FFA-W3	FFA-W3
Hub height	m	119	150
Hub diameter	m	5.6	7.94
Hub overhang	m	7.1	11.35
Drivetrain	-	Medium speed	Low speed
	-	Multiple-stage gearbox	Direct drive
Design tip-speed ratio	-	7.5	9.0
Minimum rotor speed	rpm	6.0	5.0
Maximum rotor speed	rpm	9.6	7.56
Maximum tip speed	m/s	90	95
Gearbox ratio	-	50	—
Shaft tilt angle	deg	5	6
Rotor precone angle	deg	-2.5	-4.0
Blade prebend	m	3.332	4
Blade mass	t	41	65
Rotor nacelle assembly mass	t	674	1,017
Tower mass	t	987	860
Tower base diameter	m	8	10
Transition piece height	m	10	15
Monopile embedment depth	m	42.6	45
Monopile base diameter	m	9	10
Monopile mass	t	2,044	1,318

deg	degrees	rpm	revolutions per minute
m	meters	t	metric tons
m/s	meters per second	W/m^2	watts per square meter
MW	megawatts		

Table 3 Parameters IEA 15 MW reference wind turbine compared with 10 MW wind turbine (Gaertner et al., 2020, p. IV, tab. ES-1)

Future 20 MW wind turbine

Even though the 15 MW wind turbine is a very large turbine compared to the state-of-the-art turbines, larger wind turbines are proposed in detail. This larger wind turbine is a 20 MW wind turbine discussed in 2011 and later in 2017. In a later project, Innwind, the 20 MW wind turbine is analyzed in more detail. An overall weight of 3,510 tons is estimated for the 20 MW wind turbine, Table 4 (Pontow, Kaufer, Shirzahdeh & Kühn, 2017, p. 28, tab. 5-1). Still, some of the variables are relatively low compared with the estimations published 6 years ago. "It is unclear whether a 20MW turbine will be able to yield lower cost of energy than a 10 or 15 MW wind turbine and it is highly site dependent. Innovations in the component and system design can bring down the cost of energy. Wind turbine OEMs will have to design, develop and test prototypes before bringing any products on the market." ((Dobbin, Mast, & Echavarria, 2017), p. 19 & 20). This means that a specific type of vessel only suitable for 20 MW turbines can have the opposite effect, being not effective. Which large MW wind turbine is the most profitable is yet unknown. The comparison between the 10 MW wind turbine and the 20 MW wind turbine is shown in Figure 8. Compared to the overall weight of the 20 MW wind turbine, the foreseen jacket is relatively small and light. Table 5 (Pontow, Kaufer, Shirzahdeh & Kühn, 2017, p. 11, tab. 2-1) indicates that the jacket weighs around half the weight of the 20 MW wind turbine.

Wind turbine data		
Wind turbine model		Upscaled 20MW
Rated electrical capacity	MW	20.0
Number of blades	-	3
Hub height	m LAT	+167.9
Rotor diameter	m	252.2
Blade Length	M	122.14
Design Extreme Thrust Value	kN	9600
Rated wind speed	m/s	11.4
Minimum rotor speed	rpm	4.45
Maximum rotor speed	rpm	7.13
Weight of rotor (hub and 3 blades)	t	632
Weight of nacelle without hub and blades	t	1098
Weight of support–tower incl. internals (onshore tower)	t	1600-1780
Distance from the tower upper flange plane to the hub	m	4.76
Tower outer diameter at top of tower (preliminary tower)	m	7.78
Tower outer diameter at interface level (+26 m LAT) (preliminary tower)	m	11.74
1st natural frequency (onshore)	Hz	0.18 - 0.21Hz

Table 4 Main data of 20 MW wind turbine (Pontow, Kaufer, Shirzahdeh & Kühn, 2017, p. 28, tab. 5-1)

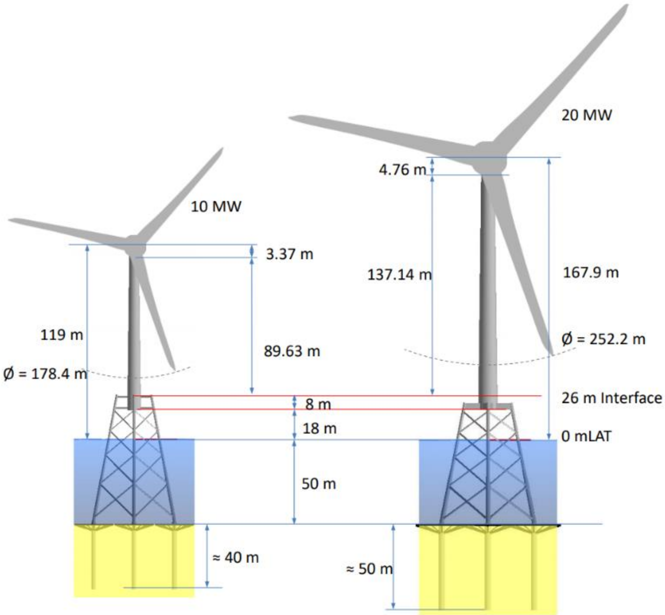


Figure 8 Comparison dimensions 10 MW and 20 MW wind turbine (Chaviaropoulis et al., 2017, p. 65, fig. 5-1)

Parameter	Unit	Reference jacket for 10MW	Estimated jacket for 20MW
RNA mass	[t]	676[1]	1730
Interface level	[mLAT]	26	
Water depth	[mLAT]	50	
Width at mudline[2]	[m]	33	38
Width at top[2]	[m]	16	20
Total height[3] of assembled jacket	[m]	~82	~82
Lifting mass	[t]	900-1100	1600-1700

[1] according to INNWIND.EU reference wind turbine [4]
[2] with respect to center of leg, neglecting appurtenances
[3] including leg extension below mudline

Table 5 Size and weight of jacket for 10 MW and 20 MW wind turbine (Pontow, Kaufer, Shirzahdeh & Kühn, 2017, p. 11, tab. 2-1)

Comparison 10, 15 and 20 MW wind turbine

The 15 MW reference wind turbine is based on the 12 MW direct drive wind turbine located at Rotterdam-Maasvlakte. A 15 MW wind turbine is probably the next large step in wind turbine manufacturing, followed by the 20 MW wind turbines. Comparing some typical numbers of the wind turbines (Table 6), it is shown that the dimensions are scaled relatively comparable, from the 10 MW to 15 MW and from the 10 MW to 20 MW. Interesting for the 15 MW wind turbine is the usage of a monopile while for the 20 MW wind turbine jackets are proposed. The monopile for the 15 MW wind turbine is based on the shallow water depth of 30 meters. This shallow water is a difference compared with the jackets shown in Figure 8 (Chaviaropoulis et al., 2017, p. 65, fig. 5-1). This 10 MW wind turbine is assumed to be installed in 40 meters water depth.

The 20 MW wind turbine is formulated in 2011 and 2017 while the 15 MW is based on state-of-the-art wind turbine prototypes. Current estimate is up to 3,510 tons, but if the weights grow in the same manner as 15 MW, the overall mass can be relatively low, just over 2,000 tons. For this research, the weight of the tower of the 15 MW wind turbine is assumed to be proportional with 10 MW and 20 MW growth. The proportional 15 MW wind turbine is indicated by the 15 MW* in Table 6 (Peeringa, Brood, Ceyhan, Engels, & Winkel, 2011), (Pontow, Kaufer, Shirzahdeh, & Kühn, 2017) & (Gaertner, et al., 2020). If in future the wind turbine has different properties, requirements for the concept need to be adapted on the changing properties.

Parameter	**Units**	**10 MW**	**15 MW**	**15 MW***	**20 MW**
Power rating	MW	10	15	15	20
Number of blades	-	3	3	3	3
Rotor diameter	m	178.3	240	240	252
Hub height	m	119	150	150	168
Tower diameter	m	8	10	10	12
Blade mass	t	41	65	65	99
Nacelle mass	t	240	631	631	1098
Nacelle incl. rotor mass	t	674	1017	1017	1730
Tower mass	t	987	860	**1300**	1600-1780
Overall mass	t	1661	1877	**2317**	3510

Table 6 Comparison 10, 15 and 20 MW wind turbine (Peeringa, Brood, Ceyhan, Engels, & Winkel, 2011), (Pontow, Kaufer, Shirzahdeh, & Kühn, 2017) & (Gaertner, et al., 2020)

As indicated before, the turbines could grow further beyond the 20 MW wind turbines. However, the limitations in fabrications can influence its development. For this research, the typical 10 MW, 15 MW* and 20 MW wind turbines are taken as the turbines for the analysis. Since the final solutions should be scalable and flexible, the exact numbers do not influence the principle design, it only changes some properties of the concept.

State-of-the-art installation vessels

Different types of installation vessels exist on the offshore market. The goal of this section is to provide an overview of installation vessels with cranes that use floating wind turbine installation. This is often valid for the vessels except for the jack-up vessel (which is the state-of-the-art installation vessel). Furthermore, there are variety of installation methods. The state-of-the-art vessels often install wind turbines assembly wise while some vessel have performed fully assembled wind turbine installation. These vessels which performed fully assembled wind turbine installation are discussed in this overview. However, there are exceptions such as the Windlifter which does not use a crane for wind turbine installation. The reason to include this installation method is to provide a more complete overview of the installation vessels.

Jack-up vessels

The commonly used type of installation vessel for wind turbine installation offshore is a jack-up vessel. These vessels have often four jack-up legs to raise themselves out of the ocean to take away the motions of the ocean. The vessel is equipped with a large crane. Which can install both foundations for the wind turbine and wind turbine components. Furthermore, the vessel has a relatively large deck area to transport multiple wind turbines components and is equipped with an accommodation for the crew. Jack-up vessels are often equipped with a bridge to let people safely move to the wind turbine, a helicopter deck for employee transportation and a gripper that helps installing the components. The legs of a jack-up vessel need to support the whole vessel once out of the water including the lifting forces. Relatively strong seafloors and relatively quiet shallow waters are the areas where these installation vessels can operate. Critical is the moment the legs touch the seafloor, this need to be done gently to prevent large impacts on the legs.

Goliath

The Goliath is an earlier jack-up vessel constructed in 2009, shown in Figure 9 (Roo, 2016). This vessel is equipped with a 400 tons crane and a deck pay load of 1,400 tons. This vessel is one of the early self-propelled jack-up vessels that was built at that time for the company Hochtief. The vessel was built for 5 MW offshore wind turbines (Sun & Wind Energy, 2009). The vessel has four legs of 60 meters to be able to work in depths up to 45 meters.

Figure 9 Goliath jack-up vessel of DEME (Roo, 2016)

Aeolus

The Aeolus was built in 2014 and needed several modifications for future usage. In 2018, the vessel was modified to grow with future wind industry. One of the modifications was upgrading the lifting capacity of the vessel's crane. Currently, the vessel is equipped with a Huisman crane with 1,600 tons main hoist and 100 tons auxiliary hoist capacity (Van Oord, n.d.a). Furthermore, the vessel is equipped with a helicopter deck. This jack-up vessel is used for offshore wind industry, both for installation of foundations and wind turbines. As shown in Figure 10 the vessel can transport several assemblies of the wind turbine. The vessel typically installs the tower, nacelle and blades separately (Figure 10 (Van Oord, n.d.b)).

Figure 10 Aeolus of Van Oord installing wind turbines (Van Oord, n.d.b)

Bokalift

Another type of vessel that is used for wind turbine installations is a floating crane vessel (Figure 11 (Boskalis, n.d.)). These vessels are fitted with a relatively large crane with a high capacity. These vessels can often easily transport multiple components, even the larger jackets. This type of vessels is extensively used for wind park installation. Bokalift 1 is used for wind turbine foundation installation. The Bokalift 1 is equipped with a 3,000 tons Huisman crane and dynamic positioning system of the type DP2. The dynamic positioning system is a combination of different rotatable screws which are controlled from the deck to maintain an initial position. In general, a DP system has an accuracy in meters or decimeters. The crane and DP system enables the vessel to be used in industries such as transportation and installation of the foundations in offshore wind (Boskalis, n.d.). The Bokalift 1 has also potential to be used for wind turbine installation due to the relatively high hook height of the auxiliary hook. This results in possible usage of the vessel for wind turbines installation similar to state-of-the-art jack-up vessels. However, the Bokalift 1 must compensate for the movements of the vessel due to the lack of the stabilization of jack-up legs.

Figure 11 Bokalift 1 of Boskalis transporting jackets (Boskalis, n.d.)

Sheerleg

Furthermore, sheerlegs are used to install components for wind turbines. Vessels equipped with a single crane require hook heights above the lifting components, such as the tower and nacelle of a wind turbine. A vessel equipped with two (similar) cranes, can lift the load between the booms. This means that the hook height can be lower compared with vessel with a single crane. Sheerlegs do not have a large deck area to transport components by themselves, but they have relatively large lifting capacities. In offshore wind industry, they are used for foundation and offshore substation installation. Sheerlegs can be used for installation of wind turbines in one move. Due to the lack of deck area for wind turbine components, they need supporting vessels/barges to feed themselves. Besides, these cranes are floating and have to withstand ocean movements (also during operation). Additional systems are used for motion compensations such as a ballasting system. The base of a sheerleg is a barge sized hull which typically has worse workabilities offshore compared with a monohull vessel.

<u>Rambiz</u>

The Rambiz is a sheerleg which is built in 1996 and has performed fully assembled wind turbine installation in the past (Huisman, n.d.b). This vessel uses the area between the two crane masts for the top part of the wind turbine as shown in Figure 12 (Huisman, n.d.b). Special rigging was made that let the wind turbine been lifted from the bottom of the tower while holding it stable above the CoG (center of gravity) of the wind turbine.

Figure 12 Rambiz floating crane installing wind turbine (Huisman, n.d.b)

Semi-submersible crane vessels

Another type of floating cranes are semi-submersible crane vessels. These type of vessels are often used for decommissioning of oil platforms or pipe laying. High decks, relatively low transition speeds but great stability are key points of these vessels. These vessels originate from semi-submersible oil platforms and some early build vessels already reached their life time and are already scrapped.

Saipem 7000

Some of these semi-submersible vessels are sometimes used in wind industry such as the Saipem 7000 for the project Hywind. The vessel installed fully assembled wind turbines on floating foundations in the harbor of Stord Norway shown in Figure 13 (Saipem, n.d.) (BigLift, 2017).

Figure 13 Saipem 7000 twin-lift fully assembled wind turbine installation (Saipem, n.d.)

The strongest heavy lift vessel, the Sleipnir, could be used for large wind turbine installations. The vessel has a hook height capable to lift wind turbines between the boom of the crane. Due to the lay-out of the vessel, the cranes are unable to pick-up a large fully assembled wind turbine from the deck of the vessel. The hook height of the Sleipnir is 135 meters, which could be enough for fully assembled wind turbine installation in the same way as the Saipem 7000 (Heerema, n.d.). Installing wind turbines in components is also possible for the Sleipnir, since the auxiliary hook has a lifting height of up to 165 meters, which is close to the hub height of the 20 MW wind turbine.

Shun Yi 1600

Another wind turbine installation vessel is the Shun Yi 1600. [redacted] The vessel is capable of transporting multiple components of a couple of wind turbines on its deck as indicated in Figure 14 (4C Offshore, n.d.b). The difference with other state-of-the-art vessels is the usage of a single crane on top of a vessel with a semi-submersible hull. The crane is located relatively close to the middle of the ship which positively influences the stabilization during lifting. This vessel is already in operation.

Figure 14 Shun Yi 1600 Semi-submersible crane vessel (4C Offshore, n.d.b)

Modifications on state-of-the-art vessels

Some vessels are adapted or will be adapted in the near future for wind turbine installation applications. Other concept modifications are proposed for wind turbine installation. The vessels are originally constructed for other applications. The modifications for wind industry applications are discussed in this section.

Svanen

The heavy lift vessel Svanen is currently owned by Van Oord who uses the vessel in combination with the Aeolus to install wind turbine parks. The Svanen is used to install wind turbine foundations where the Aeolus is used for wind turbine installation. The Svanen was originally built to install the Storebælt bridge across the Great Belt in Denmark (Gusto MSC, n.d.). The vessel has been upgraded a couple of times to perform new projects according to Gusto MSC (n.d.). Figure 15 (Wermeskerken, 2013, slide 11) shows a special adapter on the Svanen to install wind turbines fully assembled in one lift. The vessel is not capable to transport multiple wind turbines to the location of installation, therefore the vessel needs to be fed with another vessel.

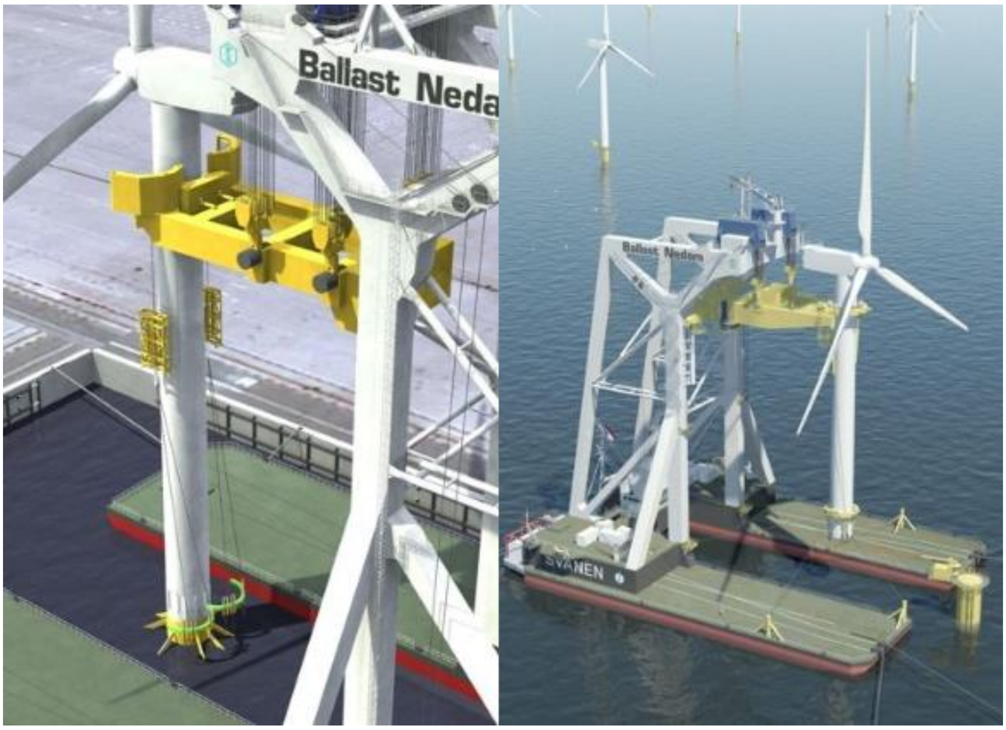


Figure 15 Svanen with special adapter to install wind turbines (Wermeskerken, 2013, slide 11)

Thialf and Balder

Another type of possible usage of a semi-submersible crane vessel such as the Saipem 7000 is related to the project Arcadis Ost 1 in the Baltic Sea. Due to the challenging soil conditions, another method is proposed for the installation of the wind turbines (Heerema, 2019). This method uses the Thialf vessel as an assembly vessel equipped with a dummy tower. On top of the dummy tower, the nacelle, hub and rotors are assembled using the cranes of the vessel. The complete construction can than be placed on top of the already installed tower at once (Heerema, 2019). The operation is visualized in Figure 16 (Tacx, 2019).

Figure 16 Heerema Thialf wind turbine installation method using dummy tower (Tacx, 2019)

The special semi-submersible crane vessels can also be used for both foundation and wind turbine installation. An example is proposed using the Balder which is shown in Figure 17 (Patent No. WO2019245366A1, 2019, p.73, figure 12). The portside crane is primarily used to assemble and install wind turbines with assisting equipment such as the original pipelay tower on the vessel. The starboard crane is used to install the foundations which are lifted from an assisting feeder barge (Patent No. WO2019245366A1, 2019).

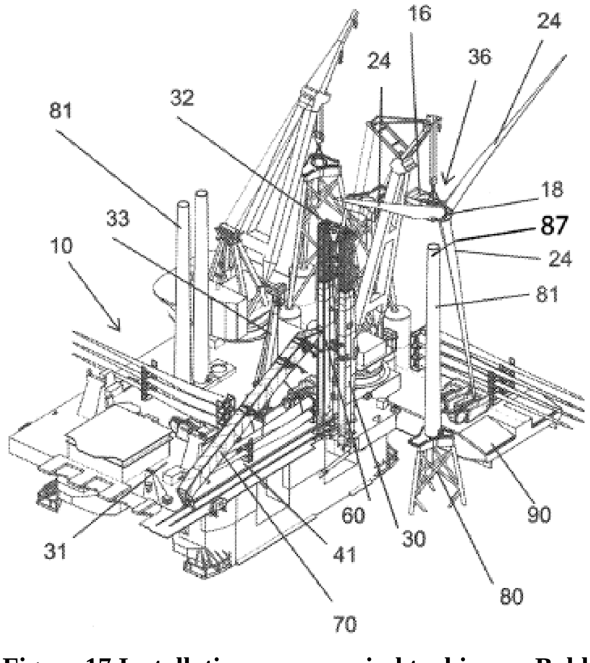


Figure 17 Installation process wind turbine on Balder (Patent No. WO2019245366A1, 2019, p.73, figure 12)

Future concepts for wind turbine installation

Different vessels are proposed for wind turbine installation applications. Some are developed in detail and some are still concepts. In the coming years, some of the vessels will be developed and operational. Different vessels have been proposed with interesting wind turbine installation methods, especially during the last 10 years. This section is focused on the process of wind turbine installation of those vessels and will not go into detail about the technical differences of the vessels. The main goal is to identify the solutions which have a distinctive value to the installation process of the vessel itself. Most of the proposed crane vessels do have cranes similar to the state-of-the-art designs of the cranes nowadays. New cranes are in development for wind turbine installation such as the Tetrahedron crane (Patent No. WO2020060394A1, 2020).

Voltaire

A new jack-up vessel will be built within coming years which is able to install the largest wind turbines component wise. The new type of vessel is the Voltaire of Jan de Nul shown in Figure 18 (Jan de Nul, n.d.). The Voltaire has approximately double capacity of state-of-the-art jack-up vessels combined with a maximum lifting height (from the seafloor) of 325 meters (which is as high than the Eifel tower).

Figure 18 New generation jack-up vessel Voltaire of Jan de Nul (Jan de Nul, n.d.)

The Voltaire of Jan de Nul is announced to be ready in 2022 having a lifting capacity over 3,000 tons. Once lifted out of the water, the vessel is 325 meters high (Lievens, 2019). The distance between the first and third floor of the Eifel Tower is comparable to the lifting height of the crane from the water level up to the main hoist (Figure 19 (Lievens, 2019)). This distance is over 200 meters, which is higher than the largest discussed wind turbine of 20 MW. Due to the large size of the Voltaire, it is one of the few vessels that is capable to install these large wind turbines with a single crane.

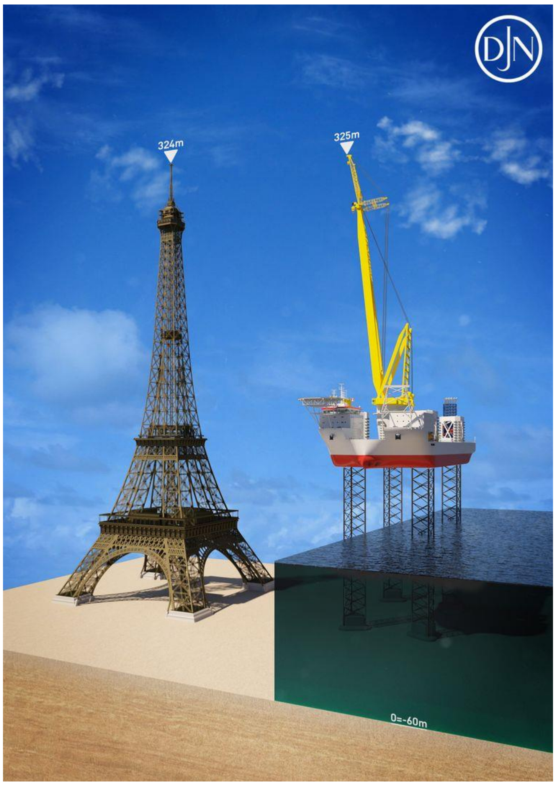


Figure 19 Voltaire and Eifel Tower (Lievens, 2019)

OWTIS

One of the concept vessels for wind turbine installation is the OWTIS of W3G Marine (W3G Marine Ltd, n.d.), shown in Figure 20. This vessel can install both the foundations and the wind turbines in one lift respectively. The 1,500 tons 100,000 tm crane is equipped with a special top section that enables the nacelle of the wind turbine to be lifted relatively close to the crane (West, Dziedzicka, & Olafsson, 2014). West, Dziedzicka & Olafsson (2014) explained that this concept is also able to install wind turbines with weights up to 720 tons with a hub height of 80 meters. They further mention that the allowable ship motions at turbine hub are longitudinal 0.38 g, vertical 2.0 g and transverse 0.74 g. This concept would than be able to work with significant wave height of 2.5 meters, 30 meters from the centre of the crane. The crane is placed in the middle of the vessel for transport capabilities and load-in activities in the port. The location of the crane also minimizes the motions of the foundation or wind turbine during lifting operations.

Figure 20 OWTIS™ - Offshore Wind Turbine Installation Ship - W3G Marine Ltd (W3G Marine Ltd, n.d.)

Windlifter

Another way of wind turbine installation and transportation performed by one vessel is the Ulstein Windlifter (Figure 21 (Ulstein, n.d.)). 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 coupled with the wind turbine foundation while the vessel moves with restricted motions (Ulstein, n.d.). The vessel will compensate the motions itself for safe wind turbine installation. This vessel for wind turbine installation can be used on fixed and floating foundations.

Figure 21 Ulstein Windlifter (Ulstein, n.d.)

SWIV

Another totally different installation vessel is proposed by Leenaars BV. This is a semi-submersible vessel equipped with spud poles for stabilization (Leenaars BV, 2018). The vessel has a triangular design which enables the crane to lift around the center of the vessel, which is shown in Figure 22 (Leenaars BV, 2018, p.10). The crane has 1,200 tons capacity and the vessel has a service speed of 10 knots. The vessel has a relatively deep draught during operation compared with the previous concepts. Furthermore, a limited number of wind turbines can be transported with this vessel. However, this vessel can transport both foundation and wind turbine and install them piece by piece. The lay-out of the vessel is interesting since the accommodation is located under the slew mechanism of the crane which results in a compact vessel. This concept can handle +5 MW wind turbines (Leenaars BV, 2018). The loading of the vessel is explained in detail in the report, which is used as a reference and shall not be explained further in this report.

Figure 22 SWIV - Semi-submersible wind turbine installation vessel - Leenaars BV (Leenaars BV, 2018, p.10)

Shuttle (WTS)

Huisman proposed the Wind Turbine Shuttle (WTS) to improve the efficiency of the offshore wind turbine installation. The vessel has a SWATH (Small-waterplane-are twin hull) hull which results into fast sailing without much influence of ocean waves. The vessel is dynamically positioned which enables it to install the wind turbines directly on the foundation while arriving with a speed of 14 knots from shore (Huisman, n.d.a). Sea states up to 3.5 meters significant wave height are acceptable. The vessel can transport two fully assembled wind turbines from shore to the offshore location. The loading of wind turbines is shown in Figure 23 (Huisman, n.d.a).

Figure 23 Wind Turbine Shuttle of Huisman (Huisman, n.d.a)

Other concepts

Other future concepts are proposed which are only visualized. These concepts consist of combinations of jack-up/monohulls, cranes/lifting device and single or twin lift configurations (Horst, 2011) & (Harst, 2013). One of these concepts is shown in Figure 24 (Horst, 2011, slide 16). This concept uses a single crane in combination with several controlling devices along the tower. The concepts of Figure 24 and Figure 25 (Harst, 2013, slide 6) are numbered from left to right, first row and second row. Therefore, the single lift wind turbine installation is number 1 (Figure 24), the monohull special crane single lift is number 2 in Figure 25 and the double crane foundation installation in Figure 25 is number 4 for example. These five concepts will be discussed later using the names Future Concept 1 till 5.

Figure 24 Single lift wind turbine installation with stabilization arms (Horst, 2011, slide 16)

Figure 25 Wind turbine installation concept vessels (Harst, 2013, slide 6)

Summary

The offshore wind turbine market is a dynamic and fast-growing sector. The wind parks are increasing in size and volume. Wind parks are foreseen on different locations varying from the Doggersbank till the Gulf of Bothnia in Europe. Wind turbines themselves are increasing in power and the Levelized cost of energy are increasing with distance from shore. It is expected that the installed wind turbine capacity in 2035 increased eightfold relative to 2020. Furthermore, a need for over 1000 extra wind turbine installation a year is identified (Freeman, et al., 2019).

Different new milestones have been published in wind turbine industry. Two of those are the 15 MW and 20 MW wind turbines. State-of-the-art wind turbines are over 200 meters high and increasing in size. [redacted] A 20 MW wind is expected to weight double the weight of the 10 MW wind turbine. The nacelle height of a 20 MW wind turbine is up to 170 meters from the waterline. The 15 MW wind turbine is estimated to weigh less than 2,000 tons while 3 years ago the 20 MW is estimated on around 3,500 tons. This is a large difference, which only can be answered in future. For this research, the weight of 15 MW is assumed to be proportional with the discussed 10 MW and proposed 20 MW. This results in a possible overestimation of the weight, on which easily can be anticipated since the eventual solution should be scalable and flexible.

The range of state-of the art installation vessels is broad and diverse. In this study the choice was made to focus primarily on floating crane vessels which are used for wind turbine installation. Typical state-of-the-art installation vessels are jack-up vessels although different installation concepts have been executed occasionally. Various crane vessels could possibly install large wind turbines although few are ready for 20 MW wind turbine installation. Some other vessels show potential (such as the Bokalift 1), but due to usage of single cranes, the hook needs always to be raised above the nacelle of the wind turbine. Specific crane vessels (semi-submersible vessels) can be used to install large capacity wind turbines. These vessels can lift the turbines from the side using a spreader system to lift the turbine, but often do have a relatively high deck. Therefore, these vessels need to be fed separately to install wind turbines fully/large assembly wise.

Based on currently used crane vessels, modifications are proposed for offshore wind turbine installation. One of the modifications is the gripper for the Svanen to install fully assembled wind turbines. Semi-submersible crane vessels are also proposed for modifications. The main purpose of these modifications is to create larger assemblies of wind turbine components to reduce lifting of the wind turbine components on the foundation. Different new vessels have been proposed of which the Voltaire becomes real within the coming years. There is a variation of installation techniques which all have advantage and disadvantages. Different proposed vessels are specialized for wind turbine installation itself, which is interesting for the installation methods. Furthermore, special components on the crane or the smart usage of deck space are typical for the proposed concepts. Overall, most of the proposed vessels use fully assembled wind turbine installation.

3. Wind turbine installation

Since the development of offshore wind turbines, different installation procedures have been suggested of which jack-up installation of wind turbine parts is the most dominant in industry. State-of-the-art sheerlegs and semi-submersible vessels have been installing wind turbines fully assembled occasionally. This chapter discusses requirements and processes for wind turbine installation and relates the introduced vessels with the future wind turbine installation market. The following sub question is answered in this chapter:

3. *Which requirements and processes are involved in wind turbine installation and how do the earlier introduced vessel relate with the fulfillment of the need for future wind turbine installation?*

Chapter outline

In the following section of this chapter the wind turbine installation process is described based on the Gemini Wind Park. The installation process is discussed in more detail in the following sections using figures. The installation of fully assembled wind turbines is discussed in relation to the CoG (Center of Gravity) of the wind turbine components and assemblies. Besides, maintenance or repair is briefly introduced in this chapter since this is part of the process of the wind turbine. Furthermore, an overview is made relating to the state-of-the-art, modifications on and future installation vessels. This overview is later used to identify different solutions for fully assembled wind turbine installations. From the overview, criteria are introduced for development of solutions for fully assembled wind turbine installations. Finally, some vessel properties are introduced which are important for the solution development.

Gemini Wind Park

The Gemini Wind Park is taken as an example to explain the installation or development of wind parks. The wind park is shown in the video Highlights of Gemini Offshore Wind Park by (Van Oord, 2016). This offshore wind park is located in the North Sea in the region of the Netherlands above the Wadden Sea (Graaf, n.d.). This wind park is located 85 kilometers from the Groningen coast and has a total power output of 600 MW. For this wind park, an onshore station is built, two offshore substations and 150 wind turbines of 4 MW on average.

Onshore, a high voltage substation was built to connect the produced energy of the wind park with the power grid of Groningen. From this onshore substation, cables are laid onshore, in the intertidal zone and in the ocean. Offshore, two large substations are built on top of jackets, installed by the sheerleg Rambiz. These offshore substations (OSS) are used for collecting the power/energy/oid generated by the wind turbines and transfer/transport? it to the onshore substation.

To prepare the soil for monopile installation, a fallpipe vessel is used to cover each location with rocks. The monopiles are transported by the installation vessel and upended on the ship (Figure 26 (Van Oord, 2016)). In vertical position, the monopiles can be installed one by one using a gripper. The gripper can make small adjustments to install the pile at the right location. The monopile needs to be hammered in the seafloor which produces a lot of noise. Hammering is cancelled by sending noise that counters the noise of hammering. In this way the noise is minimized. After the monopiles are installed, the transition piece is put on top of it and connects the monopile to the future wind turbine. This piece should be located precisely to let the wind turbine stand straight up. Early methods without gripper usage allowed large tolerances for the monopile in terms of installation. This unwanted effect needs to be counteracted with high accuracy installation of the transition piece. State-of-the-art methods such as grippers make tolerances for monopiles smaller so that the tolerances for the transition pieces are not as strict as before. The monopiles are connected to cables with the offshore substations. Three monopiles and three transition pieces are transported in one move, after which the vessel needed to sail back to load the next monopiles and transition pieces.

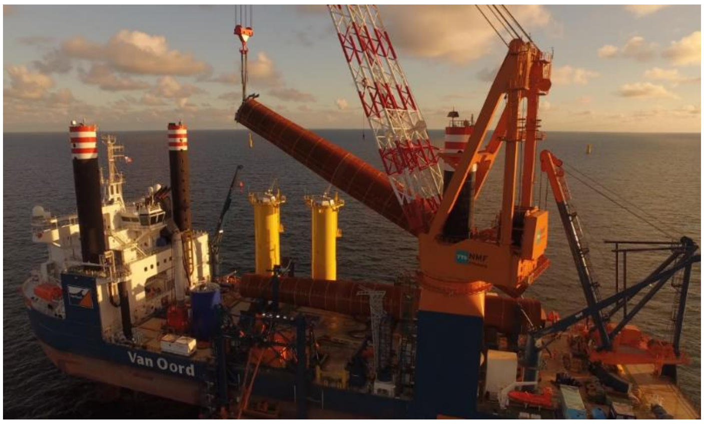


Figure 26 Monopile upending by Van Oord Aeolus Jack-up vessel (Van Oord, 2016)

After the foundations are installed, the tower is first to be installed. This tower of a 4 MW wind turbine weighs 280 tons and has a height of 68.8 meters. The following installation is the nacelle (186 tons), which is put on top of the tower. After the nacelle, the hub is installed on the nacelle. The hub is used to connect the blades with the nacelle. The hub with blades is called a rotor. On the hub, all the blades were installed separately. Components for three turbines are transported by the vessel in one move. After installation of those three turbines, the vessels sails back to the harbor to load the next three wind turbines. The transportation of wind turbines needs to be repeated 50 times before all wind turbines are installed.

Installation of foundation

Currently, three types of foundations are used for fixed offshore wind turbine installations: the monopile, the jacket and the tripod. The monopile is the smallest and most used type of foundation. The jacket and tripod are other foundations which are used less common. The foundations are visualized in Figure 27.

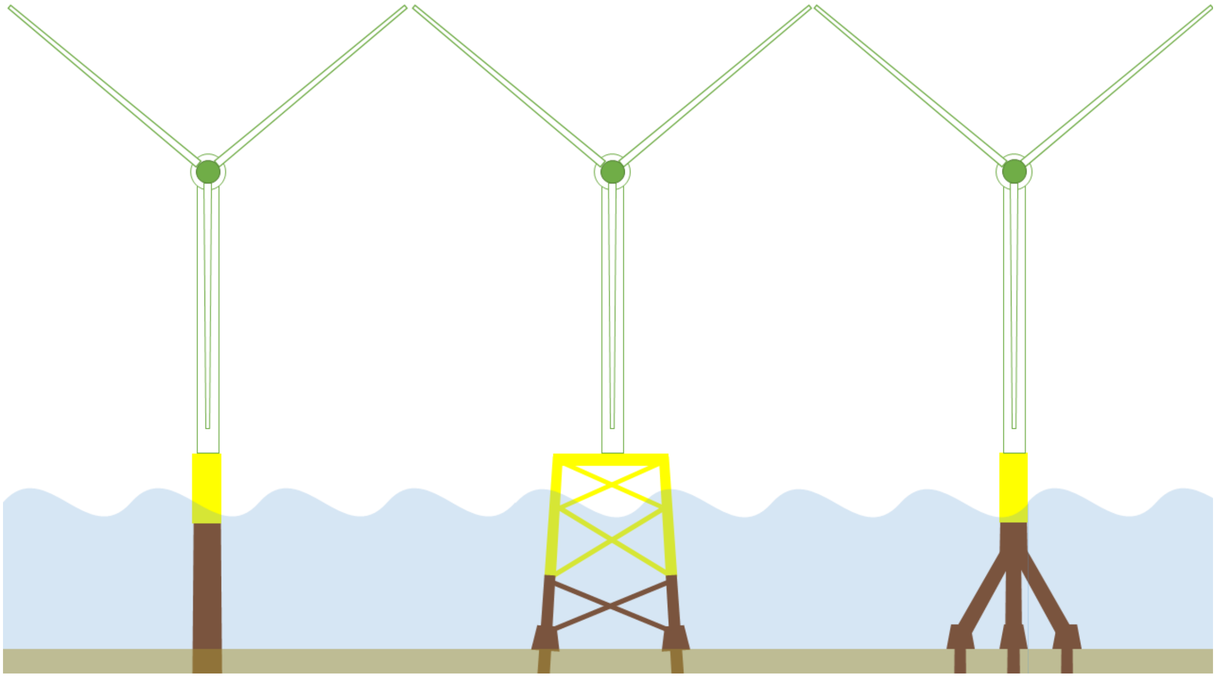


Figure 27 Foundation types offshore wind turbine

The monopile is installed by using a hammer to drill it in the seafloor. This is shown in Figure 28. Initially, the monopile is lifted in the water after which the hammer is put on top. After the hammer has drilled the monopile deep enough in the seafloor, the transition piece is put on top. This is a very vulnerable piece of the foundation since it needs to connect the foundation with the wind turbine precisely. Furthermore, vulnerable attachments (ladders, docking) are connected on this component. The monopile foundation is complete and the wind turbine can be installed.

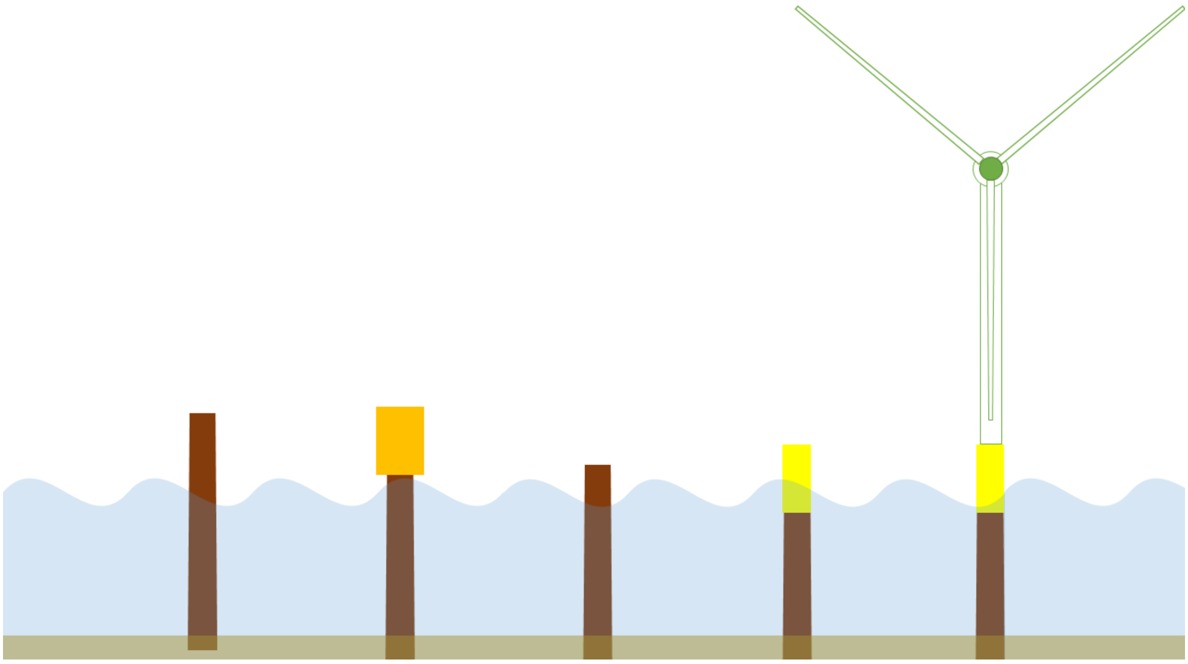


Figure 28 Monopile foundation installation process

The jacket can be installed in two different ways. One way is lowering a template on the seafloor with which piles are drilled in position in the seafloor. After the piles are installed, the template is replaced by the jacket and the foundation is complete. Another way is lowering the jacket in the ocean and drilling the piles in the seafloor using jacket. After this, the foundation is complete. The template installation is shown left in Figure 29 and the other installation is shown right.

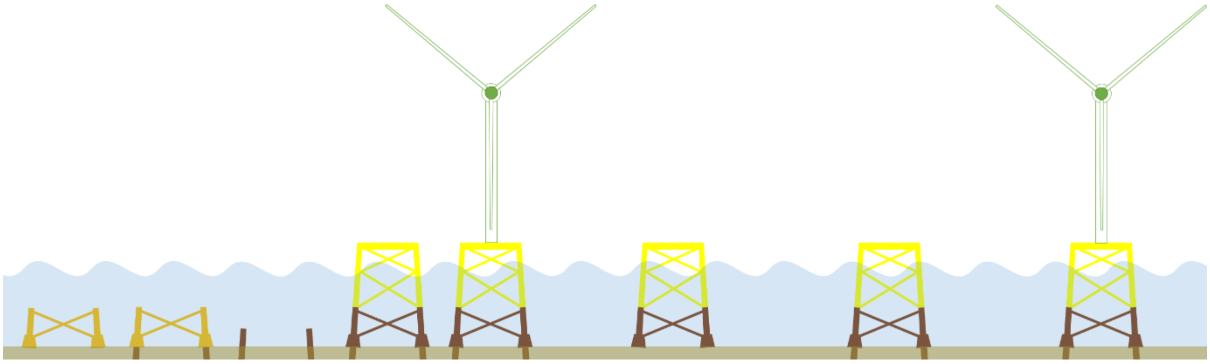


Figure 29 Jacket foundation installation process

The tripod can be installed in the same way as the monopile and the jacket. Therefore, also the suction version is included, which can also be used for the other foundations. The suction method pumps the water out of the piles which results in suction of them in the sea floor. The tripod combines features of both the monopile and the jacket. The area is relatively large while it consists of more standard parts that do have similarities with the monopile. The tripod installations are shown in Figure 30.

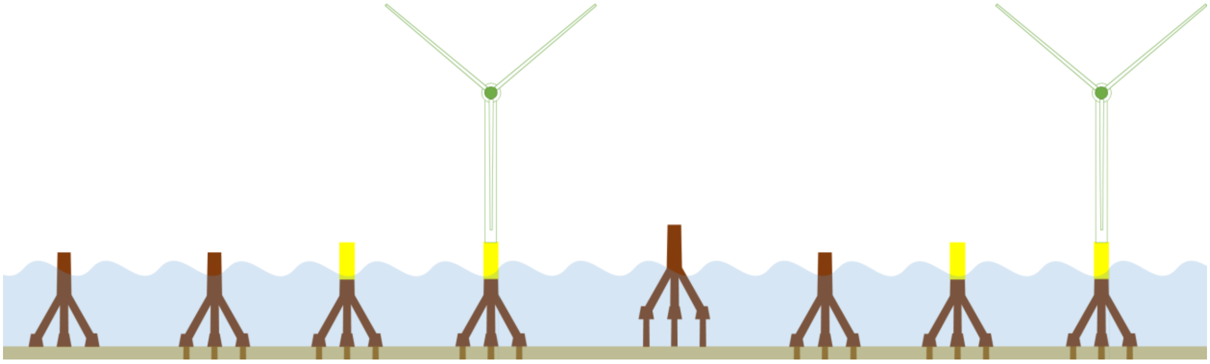


Figure 30 Tripod foundation installation process

Monopiles are foreseen to be used for 15 MW wind turbines while jackets are foreseen for 20 MW wind turbines. Figure 31 (Rumes, Erkman & Haelters, 2016, p. 42, fig. 2) shows the sound level during hammering of monopiles From the figure can be concluded that the green line (exposure of sound level) is nearly at the allowed threshold value of Belgium (red line) and exceeding the Dutch allowance (upper orange line) (Rumes, Erkman, & Haelters, 2016). The required 10 meters monopile for 15 MW wind turbines cannot be hammered taking the sound depicted below into account (Gaertner, et al., 2020). Compared with the monopiles, the jacket pile diameters can be relatively small, therefore are relatively less influenced by the noise problem during hammering.

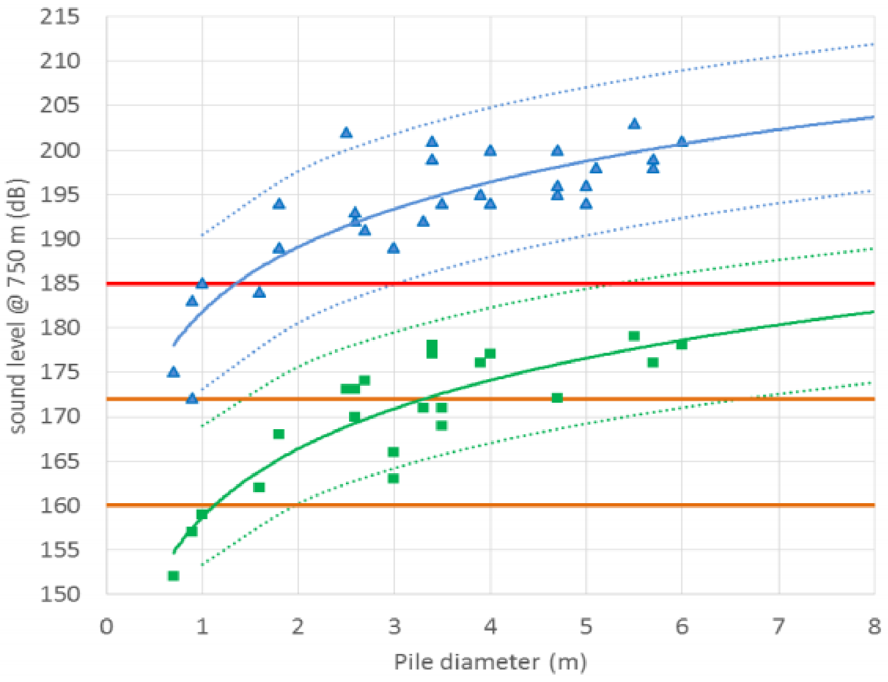


Figure 31 Sound Pressure Levels (blue) and Sound Exposure levels (green) and Belgian threshold (red) and variable Dutch SEL threshold (orange) (Rumes, Erkman & Haelters, 2016, p. 42, fig. 2)

Installation of wind turbines

Wind turbines can be installed in various ways. The installation procedure can differ much, from all components separately up to just one installation movement. The larger installation methods as used today are explained in this section.

Installation processes

A couple of different processes are taken as examples. One of them (S1) is introduced in the explanation of the Gemini Wind Park. In Figure 32 the left process (S1) is installing the components one by one which can easily be performed by a crane with a large lifting height and average lifting capacity. The components are relatively light but need to be lifted at hub height. Every lifting process requires installation time and many components require relatively large assembly time. This is the typical current installation method. The right process indicates installation of the tower, followed by the nacelle and finished by the rotor (blades and hub pre-assembled), indicated with S2 in Figure 32.

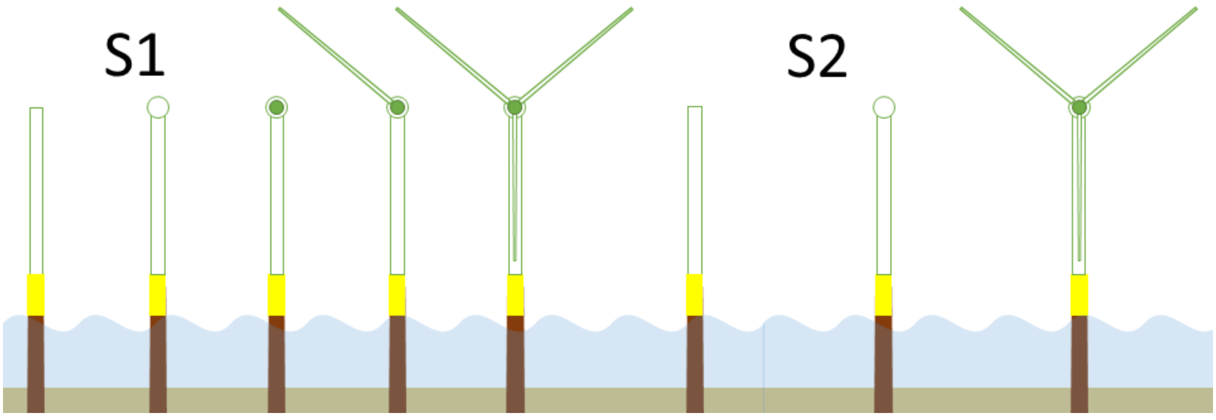


Figure 32 Installation process of wind turbines small assemblies

Installing relatively large assemblies can be performed by first installing the whole tower and afterwards the nacelle and rotor in one lift (L1 in Figure 33). This installation is discussed earlier in Figure 16 where the Thialf is installing the nacelle rotor assembly on a dummy tower. 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 (L2 in Figure 33). The complete wind turbine assembly installation (L3 in Figure 33) is also shown.

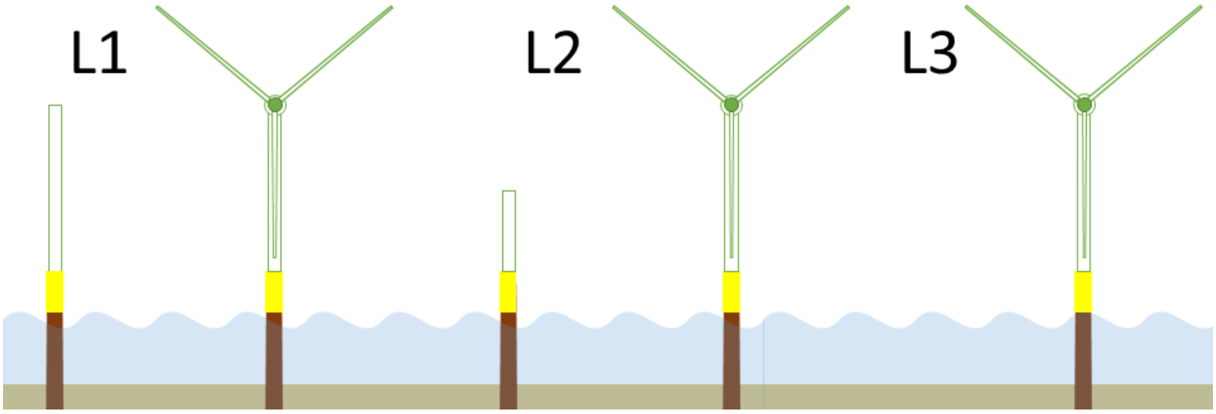


Figure 33 Installation process of wind turbines large assemblies

Center of Gravity of components

The Center of Gravity (CoG) of the individual components is important for lifting. To estimate the differences between large wind turbine installations, the CoG's of the components are estimated. The CoG of wind turbine components is visually indicated in Figure 34 below. The tower and nacelle are the heavy components. The nacelle and blades need to be installed on top of the tower. The blades are relatively light weight. Due to their size these can be difficult to handle during installation. The hub rotates with the blades and is connected to the nacelle.

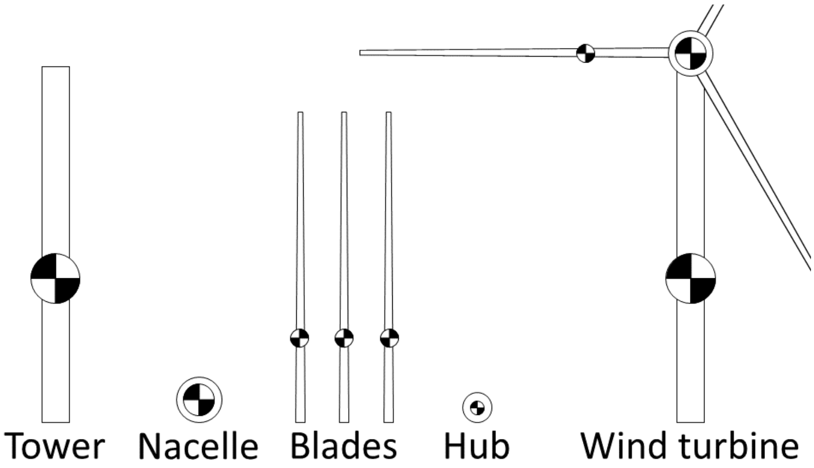


Figure 34 Center of Gravity (CoG) of the components of a wind turbine

Based on the estimated numbers of 10, 15 and 20 MW as indicated in Table 6, the CoG of the different components is estimated which corresponds to the CoG in the figure above. Since one of the concept vessels (SWIV) discussed before uses the assembly of half the tower including foundation and half the tower including nacelle and rotor, also the CoG values of two tower sections each half the length of the tower are shown. The estimated masses are shown in Table 8, the bottom half of the tower is estimated to have 60% of the mass of the tower and the top half 40%.

CoG (m)	Lengthscale (-)	10 MW	15 MW*	20 MW
Blade	0.33	20	25	28
Tower	0.40	48	60	67
Tower bottom	0.40	24	38	42
Tower top	0.40	83	105	118
Nacelle incl. rotor (see example)	Center	119	150	168

Table 7 CoG heights of 10, 15 and 20 MW wind turbine components

Mass (t)	10 MW	15 MW*	20 MW
Blade	41	65	99
Tower	987	1300	1780
Tower bottom	592	780	1068
Tower top	395	520	712
Nacelle incl. rotor mass	674	1017	1730

Table 8 CoG masses of 10, 15 and 20 MW wind turbine components

The components combined have different center of gravities which are indicated in Figure 35. Three different ways of installing the wind turbine in larger components are shown in the figure. The most left assembly has relatively the highest CoG during installation while the most right has relatively the lowest. However, the most left is the lightest assembly while the most right is the heaviest. Each assembly has advantages and disadvantages. The CoG's shown are estimated and based on the values in Table 7 and Table 8. The location of the CoG of the assemblies and the combined masses Figure 35 are shown in Table 9 and Table 10 respectively.

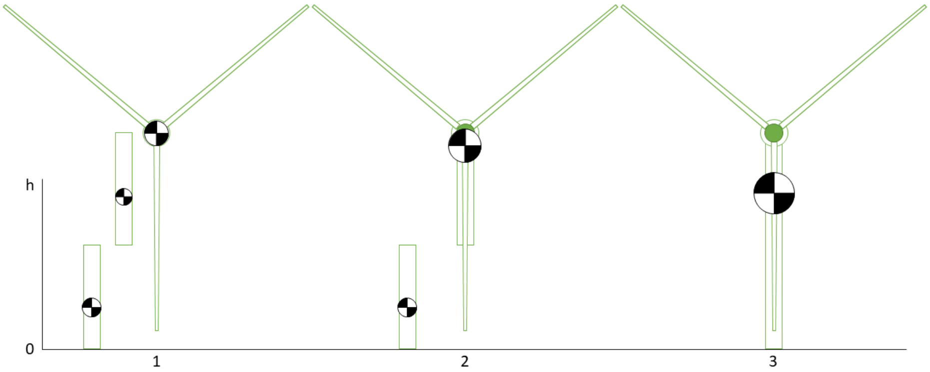


Figure 35 CoG of different combined components of wind turbine installation

	CoG (m)	h	10 MW	15 MW*	20 MW
1	Tower bottom	m	24	38	42
	Tower top	m	83	105	118
	Nacelle including rotor	m	119	150	168
2	Tower bottom	m	24	38	42
	Tower top incl. nacelle rotor	m	106	135	153
3	Tower nacelle rotor	m	77	102	119

Table 9 CoG heights of different combined components of wind turbine installation

	Mass (t)	10 MW	15 MW*	20 MW
1	Tower bottom	592	780	1068
	Tower top	395	520	712
	Nacelle including rotor	674	1017	1730
2	Tower bottom	592	780	1068
	Tower top incl. nacelle rotor	1069	1537	2442
3	Tower nacelle rotor	1661	2317	3510

Table 10 CoG masses of different combined components of wind turbine installation

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 costly since it has not to endure 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 (Figure 36). 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 20 MW of 150 meters is enough for wind turbine installation on top of a 20 MW 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.

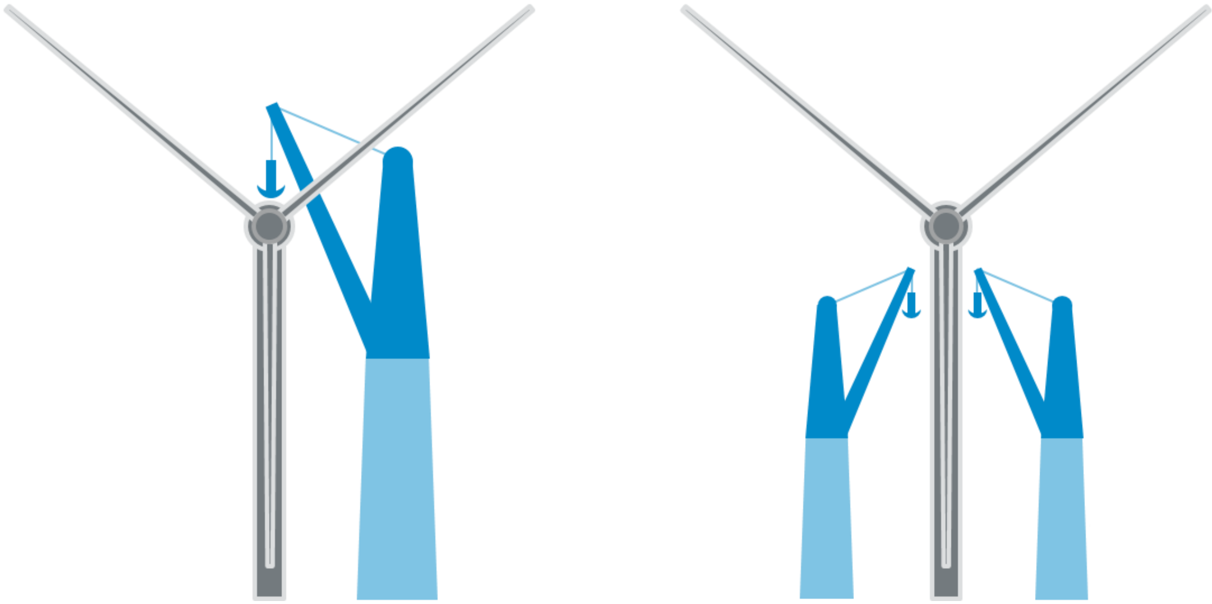


Figure 36 Single crane or double crane wind turbine installation

Maintenance and decommissioning

Offshore wind turbines are less accessible than onshore wind turbines. Some wind parks are located several dozen kilometers from the coast. A possibility to access a turbine is via small vessels pushing against the transition piece which is a dangerous activity. People need to step from a moving vessel on the fixed foundation of the wind turbine. Another way to access the turbines is via a special gangway from a larger vessel. The gangway connects the moving vessel with the stationary turbine shown in Figure 37 (SMST, n.d.). A third possibility is to use an helicopter to access the nacelle. For small repairs or regular maintenance these forms of transport are sufficient. All the tools and spare parts need to be transported by people or other equipment.

Figure 37 Gangway to access wind turbine (SMST, n.d.)

However, heavy storms can cause sudden collapse of large parts in the wind turbine. This could too lead to a need for component replacement. Future wind turbines are relatively high and state-of-the-art jack-up vessels could perform some repairs, if the water is not too deep. Such a vessel is shown in Figure 38 (Huisman, 2020). A floating installation vessel could offer possibilities for the replacement of components at heights. Future turbines could be over 170 meters high. Accessing the nacelle of a 20 MW wind turbine means a hook height up to 200 meters from the water level.

Figure 38 Foldable offshore crane for Operations and Maintenance (Huisman, 2020)

After the lifetime of the wind turbines has been reached, or the wind turbines need to be replaced for larger turbines, they need to be decommissioned. As with the installation, it is most easy to not break up the wind turbine in pieces but decommission them in one piece. If this is not possible, the turbine can be split up in pieces. Larger wind turbines will be built in a later stage, this means that decommissioning of wind turbines will mostly be performed on the small, aged turbines. Quick removal reduces risks and is safer. If a wind turbine installation vessel is suitable to install large turbines, it can also be used for small ones, probably even more easily.

Grouping wind turbine installation vessels

The previously discussed vessels are a few examples that are currently used or proposed. Some of those vessels will be used in the coming years. Besides their differences, all vessels are still being used for the same purpose which is wind turbine installation. To sort the different concepts, groups are proposed to categorize the main characteristics. The following groups are proposed for hull, installation and process wise.

Hull design (A)

First category is the hull of the vessel. The vessel can be categorized in different hulls based on found installation vessels. It is a general categorization with the focus on the differences between groups during the wind turbine installation process. The following shapes are identified:

1. Jack-up (including leg-stabilized)
2. Monohull (including sheerleg)
3. Semi-submersible
4. Multi-body (such as swath hull and catamaran hull)

The first group is the jack-up vessels. This group consist of all vessels that use legs to stabilize themselves or even lift themselves out of the water to increase lifting height. Typically, is the jack-up process which takes time. The stabilization gives them great stability with reduced influence of ocean currents. The second group is the monohull group which consists of all vessels that have one vessel structure which let them install wind turbines while floating. Semi-submersible vessels is the third group. Typical is the difference in draught in sail and operation to reduce resistance and decrease wave sensitivity. The final group is the multi-body group which includes swath hulls and catamaran hulls. Every vessel that consists of two or more hulls without the semi-submersible property is categorized in this group.

Installation device (B)

Different installation devices/tools are used for wind turbine installation. Based on the analyzed concepts/existing vessels, the following groups are identified:

1. Single rotatable crane
2. Double rotatable crane
3. A-frame (single/double crane not rotatable)
4. Specialized lifting
5. Horizontal movement

The single or double rotatable crane is a common group. Every type of rotatable crane with a hook for lifting is categorized within one of these two groups. The following group is the A-frame which is especially applicable on pontoon cranes. These vessels have a lifting frame which can luff but not to rotate: to rotate the crane the whole vessels needs to rotate. A different group is the group specialized lifting which is specified as a lifting device that can have a hook but is not rotatable and has a special construction specifically designed for a specific kind of installation. The Huisman wind turbine shuttle is an example of this category. Lifting the wind turbine on the foundation is not always needed as indicated by the Windlifter concept. Moving the wind turbine vertically over special rails or beams is also possible.

Installation process (C)

The hull with the installation device determines the process of wind turbine installation. Especially deck size has influence on the ability of transporting wind turbines to the wind park location. However, special designs are proposed to make it possible to assemble parts of the turbine offshore on a vessel. For the process the following groups are identified:

1. Assembling wind turbine on foundation including transportation
2. Assembling wind turbine on foundation with separate feeding
3. Assembling wind turbine onshore (or near shore) including transportation
4. Assembling wind turbine onshore (or near shore) with separate feeding
5. Assembling wind turbine on vessel reducing number of lifts on foundation

The wind turbine can be assembled on location directly on the foundation as currently performed by jack-up vessels. The first group describes this state-of-the-art installation method. It is also possible to use a crane vessel on location for wind turbine assembly direct on the foundation with separate feeding. Onshore assembly of wind turbines for fully assembled wind turbine installation can be performed in two ways. Vessels such as the wind turbine shuttle and Windlifter can load the wind turbines to install them on site. The fourth group consist of the Rambiz and Saipem 7000 installation which require extra feeding due to lack of transport capacity. The Thialf and Balder use assembly of wind turbine components on the vessel to install the wind turbine in larger assemblies.

Categorization of discussed installation vessels

The named groups (hull design, installation device and installation process) are put in Table 11 using their letters and numbers to correspond with the explanation above. Note that this is an estimation based on the used information in chapter 2.

The table gives an overview of the different vessels in terms of hull design, installation device and process. State-of-the-art solutions use very different hull designs in combination with component wise installation or fully assembled wind turbine installation. Most of the proposed solutions for future usage use single-lift installation or single-move installation. Concepts for future wind turbine installations do not always focus on cranes; a significant part of the concepts propose special lifting/installation devices. An important reason for this choice is the level of difficulty of installing fully assembled offshore wind turbines due to the size and CoG of a fully assembled wind turbine. A few vessels make use of the location of the CoG of a fully assembled wind turbine, such as the Rambiz, wind turbine shuttle and Windlifter.

		A					B						C				
		Jack-up	Monohull	Semi-submersible	Multi-body		Single rotatable	Double rotatable	A-frame (not rotatable)	Specialized lifting	Horizontal movement		Foundation and transportation	Foundation and feeding	Onshore and transportation	Onshore and feeding	Vessel assembly reduction number lifts
Vessel name		1	2	3	4		1	2	3	4	5		1	2	3	4	5
Goliath		green					green						green				
Aeolus		green					green						green				
Bokalift			green				green						green		orange		
Rambiz			green						green							green	
Saipem 7000				green				green								green	
Shun Yi 1600				green			green						green			orange	
Svanen wind					green					green						green	
Thialf				green				green									green
Balder				green				green									green
Voltaire		green					green						green				
OWTIS			green				green								green		
Windlifter			green								green				green		
SWIV				green			green								green		
Shuttle (WTS)					green					green					green		
Future Concept 1		green					green								green		
Future Concept 2		green								green					green		
Future Concept 3			green							green					green		
Future Concept 4			green					green							green		
Future Concept 5			green							green					green		

Table 11 Categorization of different wind turbine installation vessels

Installation vessels for later comparison

Typical vessels that show different wind turbine installation trends need to be identified to compare them later on with new developed principles in chapter 7. Since the Voltaire has properties to install 20 MW wind turbines, this vessel is taken as one of the future typical installation vessels. Another concept is the wind turbine shuttle which installs wind turbines in a different way without the need for a slewing crane. The hull design also shows different installation properties which is a good example of a typical different installation concept. The sheerleg is a common heavy lift crane vessel that has been used occasionally for wind turbine installation. The Rambiz and Saipem 7000 did perform wind turbine lifts in a same way and they are both covered by including a sheerleg installation type. The Windlifter is another example of wind turbine installation without the requirement to lift the wind turbines. The monohull has interesting properties for sailing which enables the vessel to have short transits between the marshalling ports and wind turbine parks. The final included concept is the OWTIS vessel which is representative for floating wind turbine installation using a single crane. This is a flexible solution due to the location of the crane on the vessel.

Schematic overview of proposed concepts

To illustrate the different concepts, schematic drawings have been made. These drawings make it possible to compare the in literature proposed concepts with the newly developed ones without going into the details. The drawings show schematically the essential parts of a vessel. If the transport capacity on the vessel can be varied, four wind turbines is taken as standard transport capacity. This is a normal number for the transportation capacity of a jack-up vessel and twice the capacity of the Wind Turbine Shuttle. Wind turbine components are shown in dark grey with yellow foundation. The lifting equipment (a-frame, slewing crane and skid bridge) is shown in blue and the vessels (barge and monohull) in black. Furthermore, the jack-up vessel is the only concept using parts of wind turbines and jack-up legs indicated in red. A white arrow is used to indicate the direction of installation, this means for example that the jack-up vessel is installing the wind turbine components by slewing its crane and the Windlifter is moving the wind turbines over the stern of the vessel. All these components are shown below in Table 12.

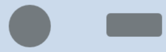
Components	Schematic drawings
Tower and Nacelle	
Blades	
Assembled wind turbine	
Foundation	
Lifting equipment	
Jack-up leg	
Vessel	
Direction of installation	

Table 12 Schematic drawings - component explanation

The discussed vessels that have been identified as typical for the proposed installation processes out of all the analyzed vessels are also drawn in a schematic way. Figure 39 below shows the typical installation vessels in top view which are jack-up vessel (A), wind turbine shuttle (B), sheerleg (C), Windlifter (D) and OWTIS (E).

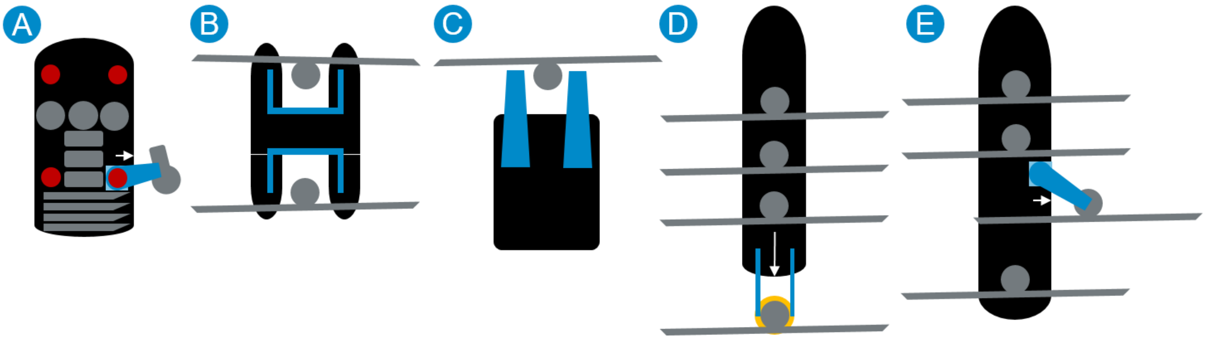


Figure 39 Schematic drawings of concepts proposed by literature

Criteria

Wind turbine installation can be very complex. Different properties of an installation vessel are important for wind turbine installation applications. One of the initial design decisions is the usage of fully assembled wind turbine installation due to favorable installation times and it reduces offshore lifting heights. The other initial design decision is the usage of cranes to install wind turbines since cranes on a vessel have proven themselves flexible in the offshore industry. No other (main) lifting devices were taken into account during further concept development which is discussed in the following chapters. The following criteria are formulated based on a general perception on the challenges of wind turbine installation:

1. **Size of vessel**
   The size of the vessel is important for wind turbine installation. The size has influence on transport capacity and accessibility of ports. The size should be proportional with the application. If transport capacity can be used, it should be designed from a wind turbine perspective and later adjusted for other applications (such as foundation or offshore substation installation). The size of the vessel must comply with the size of the installation device.

2. **Operational window**
   Waves and wind are factors that influence the operational window. The operational window limits the usage of a vessel. Both the size and type of installation influence the operational window. External factors could play a role (such as volatile wind which hinders wind turbine installation). The design of the hull can be adapted on these two factors. The operational window is not only influenced by the installation process but also by the transit process during which the vessel has to sail from marshalling port to the wind park and vice versa.

3. **Stability (sideway, backway)**
   The location of the installation equipment influences the stability of the vessel. A location of installation equipment far from the center of the vessel is more influenced by motions of the vessel. The stability of the vessel itself and during installation can be compensated using different systems. One example is ballasting the vessel with water which could stabilize the vessel. Another example is a motion compensation systems to limit motions of the wind turbine during operation. This is an usable system but can be complex for large wind turbine sizes.

4. **Scalable**
   Scalable should be interpreted as the ability to grow along with a maturing/fast developing market. Today we have a 12 MW onshore wind turbine which is designed for future offshore usage. The 15 MW reference wind turbine is published recently and the 20 MW wind turbine has been published in different projects. Which wind turbine is most interesting in future is unknown and growth of wind turbines is uncertain. For this reason, the concept should be

scalable up to the current or foreseen wind turbine size known at that time. The concept should grow with increasing wind turbine sizes such as the jack-up vessel has done. A wind turbine installation vessel can be built for a specific size of wind turbine but this limits the usage of the vessel. The vessel is more scalable once it is designed for a range of wind turbine types to be used for many project. The most scalable vessels will be able to be used up to a maximum size of wind turbines without the dependency of a lower range. In this way, the wind turbine installation vessel can also be used for (smaller) wind turbine decommissioning after years of service.

5. **Flexible**

The concept should be designed for wind turbine installation. With minor adjustments, the concept should be able to perform other wind park related installations. The following installations are identified in wind industry and other industries:

a. Wind turbine
b. Jacket
c. Monopile
d. Offshore substation
e. Decommissioning (topside and jacket)
f. Other (such as cable laying)

6. **Logistical challenges**

Part of a wind turbine installation vessel is the onshore and offshore logistics. In the marshalling ports the wind turbines need to be prepared and collected from manufacturers for installation. Some wind turbine installation vessels demand pre-assembly of components before loaded on the vessel. Onshore facilities need to be ready to assemble these components. Onshore logistics are important to reduce the time in the marshalling port which influences the wind turbine installation rate. If the logistics are challenging, the foreseen wind turbine installation vessel can have limited installation rates.

7. **Acceptance**

An important criteria for designing a wind turbine installation vessel is acceptance. In many industries products have been proposed which faced acceptance difficulties. Products need to fulfill the right requirements to achieve the designed goal. In this project, the goal is wind turbine installation. A design principle that summarizes the acceptance is the MAYA principle. Raymond Loewy called it the MAYA principle – Most Advanced, Yet Acceptable. The idea behind is familiarity and novelty need to be in balance for acceptance of a product. Novelty is unknown while familiarity is known. The right balance can result in an acceptance of a product.

Vessel properties

Wind turbine installation vessels could be restricted to certain areas. Such an example is the Baltic Sea and the North Sea which are separated and only accessible via the Danish Straits for large vessels. One of the strait is the Great Belt which is limited by 65 meters height and depth of approximately 15 meters (DanPilot, n.d.). Baltimax, B-max and Maersk Triple E-class vessels can pass the passages. The other large strait is the Øresund which has a bridge with more limited height, but when the vessel draft is limited (less than 8 meters), height could not be problem when passing the Øresund over the Drogden Tunnel (Swedish Maritime Administration, 2015). The passage options are shown below in Figure 40 (4C Offshore, n.d.a). The Øresund is located near the capital Copenhagen while The Great Belt passage is located within Danish territorial waters. Øresund and The Great Belt passage do have a relatively large open area for a large vessel to maneuver through both large passages.

Figure 40 Passage locations North Sea and Baltic Sea (4C Offshore, n.d.a)

Due to the absence of a jacking system, a floating installation vessel could perform more quick wind turbine installations. A jack-up vessel at heights limited the influences of the sea while a floating vessel still has to control the vessel. Only if the conditions of the sea do almost not influence the workability of the floating vessel by including several systems, it is competitive with a jack-up vessel. Systems that can help the floating installation vessel are (Krishnakanth, 2014):

1. Dual draft, fast transport while having stable installation position
2. Dynamic Positioning (DP) such as used for vessels near oil rigs
3. Properties of fast sailing ships if wind turbines are only loaded in harbors
4. Fast unloading of wind turbines with the use of a deck transportation system

Future vessels will use motion compensation for wind turbine or foundation installation (such as the Windlifter and Wind Turbine Shuttle). These systems can become important with the growing size of wind turbines. Without it, the wind turbine can only be installed at very calm water, no waves. The discussed systems aid a floating installation vessel to be more favorable than a jack-up vessel, if the systems eventually lead to a workability of the floating installation vessel comparable with the jack-up vessel. In other words, if the floating installation vessel has the same workability as the jack-up vessel but with missing the jack-up process, it is already more favorable due to a reduced installation time.

Summary

Different processes are involved during the development of a wind park. Besides wind turbine installation, heavy lifts occur for offshore substations that convert the generated power of the wind turbines to shore. At the moment, wind turbines are generally installed component wise, which takes a long time before a wind turbine is ready. The dimensions of the foundation are problematic since monopiles are at the limit of allowed installation noise due to hammering. Other foundations such as jackets and tripods are installed in a different way than monopiles.

The focus is fully assembled wind turbine installation and since this is only done a few times before, the CoG of the discussed wind turbines is estimated in order to be able to have some specific requirements for the turbine installation vessel. The estimated CoG can be used in a later stage of this research when detailed properties are needed for lifting. Larger assemblies used for installation means a lower CoG of the assembled components but with larger weights. State-of-the-art installation requires lifting up to nacelle heights while fully assembled wind turbine installation requires around 75% of the nacelle height. Furthermore, maintenance of wind turbines is briefly discussed in terms of maintenance, repair and decommissioning which require larger installation properties respectively.

An overview is made of the state-of-the-art vessels, adapted vessels and concepts in terms of three groups. The groups are hull design, installation device and installation process which determine the installation process of the wind turbines. State-of-the-art vessels often use jack-up systems with single crane installation of wind turbine components/sub-assemblies. Noticeable is the installation process of the future concepts which often is fully assembled wind turbine installation.

For later comparison, vessels with typical installation methods are identified. This identification is based on the overview in hull design, installation device and installation process. The vessels are a variety of existing vessels and proposed vessels. The following vessels are identified:

1. Jack-up vessel
2. Wind turbine shuttle
3. Rambiz
4. Windlifter
5. OWTIS

First is the jack-up vessel installing wind turbines component wise (tower, nacelle, hub and blades) such as the Aeolus and Voltaire. The second typical vessel and process is the Shuttle (WTS) (transporting two wind turbines with specific lay-out). The third concept taken in account is the installation using a sheerleg or semi-submersible crane such as the Rambiz or the Saipem 7000 with separate fully assembled wind turbine feeding. The Windlifter is chosen of the proposed or future vessels. This vessel has a special horizontal movement system that connects with the foundation for fully assembled wind turbine installation. Another chosen vessel is the floating OWTIS vessel equipped with one crane installing wind turbines fully assembled while transporting multiple on its deck.

Based on the analysis of the state-of-the-art wind turbine installation market and found concepts, criteria have been introduced for concept development. The criteria are:

1. size of vessel
2. operational window
3. stability
4. scalable
5. flexible
6. logistical challenges
7. acceptance

The dimensions of the vessel determine the usability of the vessel. Some areas have restricted access due to vessel passage limitations. In chapter 2, the opportunities of the North Sea and Baltic Sea are indicated which directly link to the passage of Denmark. If a vessel has limited draught, it can pass over the Drogden tunnel no matter the height, otherwise it needs to sail under the Storebælt bridge.

4. Conservative solutions

Different floating crane vessels exist which could install wind turbines. This chapter proposes some wind turbine installation vessels closely related to state-of-the-art vessels. The following sub question is partly answered in this chapter:

4. *In which way can large wind turbines (up to or over 20 MW) be installed with the usage of cranes on a floating installation vessel with transport capacity?*

Chapter outline

Different new principles will be proposed in this chapter, closely related to the state-of-the-art vessels used for foundation installation of wind turbines and installation and decommissioning of oil platforms or topsides. Since the principles are closely related to state-of-the-art solutions, they can be categorized as conservative solutions. The main input for these solutions is the starting point of the 'new normal'. Most of the jack-up vessels currently used for wind turbine installation are small compared to 20 MW wind turbine components. A typical blade for a 20 MW wind turbine has the same length as a typical jack-up vessel. As the size of wind turbines and thereby the length of a blade is expected to grow, installations vessels are required to grow along with. Typical for the proposed concepts below is the new base for wind turbine installation vessels in terms of size. 20 MW is the maximum capacity for which all the concepts are designed or thought out. Another size can be chosen, but since 20 MW seems to be possible and is yet unexplored in terms of vessel size (relating to the state-of-the-art solutions) 20 MW is a challenge to install.

Minor change

From the discussed concepts in chapter 3, only the jack-up vessel is widely used for wind turbine installation. The stable platform used for wind turbine installation is one of the main advantages of this concept. However, at this moment the Jan de Nul Voltaire jack-up vessel is probably capable to install future wind turbine sizes.

Many of the discussed concepts were developed over 10 years ago and have not been put into operation. These concepts were based on different sizes and future prospects of wind turbines and are not suitable for upscaling for 20 MW wind turbine applications. Still, these concepts have interesting properties which can be applied on the wind turbine installation

Relative size

A 20 MW wind turbine installation on a jacket foundation requires hook heights above 150 meters with crane capacities of up to 4,000 tons in total. Large wind turbines require cranes with large bearing diameters for slewing. A vessel with cranes at the stern is very wide when the cranes are located in the same way as in Figure 36. The length of a blade of the 20 MW wind turbine is 120 meters which is the same as the diameter of the London Eye. To indicate the size of the London Eye, Heerema (n.d.) has made a figure with the Sleipnir which is currently the largest crane vessel with two 10,000 tons tub mounted cranes of Huisman, shown in Figure 41.

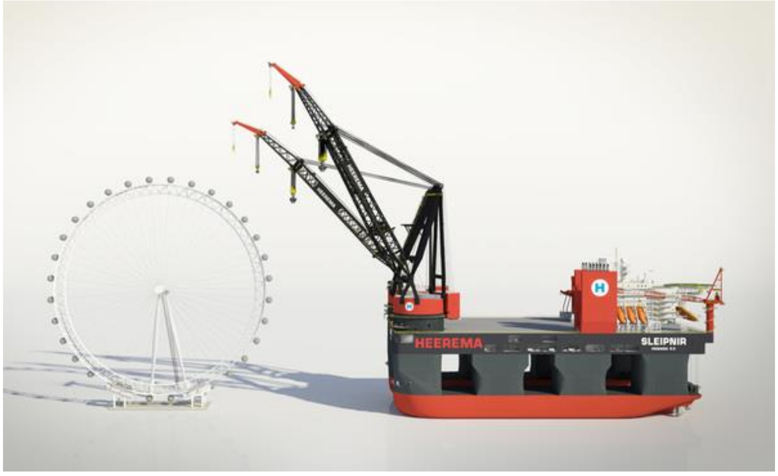


Figure 41 Sleipnir and London Eye size (Heerema, n.d.)

State-of-the-art crane vessels often are dimensioned with possibilities to travel through locks and under bridges. Common vessel sizes are ranging from 30 up to 60 meters beam and lengths up to 400 meters. The size of the vessel is related to the ports and the requirement for accessing these ports. Wind turbine installation vessels do not immediately require heavy transport capabilities due to voluminous cargo (wind turbines or foundations).

On the contrary, a large vessel means different reactions upon motions during installation of wind turbines. Different waves will influence the usability of the vessel and the bigger the better is not always the case. The area where the vessel will be used also influences the size of the vessel. Each area has its own typical waves and depths.

Side or stern lifting

One of the concepts for wind turbine installation and other installation types is side lifting or lifting over starboard/port side. Lifting over the side is favorable due to accessibility of the deck with a crane, less motions due to closer to CoG/motion point, smaller beam of the vessel relative to the overall length. Side lifting also means easy (un)loading of cargo at a port due to normal docking of the vessel.

However generally speaking, heavy lift crane vessels often lift over the stern of the vessel and smaller crane vessels can lift over the side of the vessel. This is probably due to the stability of the vessel. Side lifting is limited by the width of the vessel. Heavy lift over the stern also limits the transport capabilities of the crane vessel due to the fact that the boom rests on the vessel. Furthermore, the clearance between two cranes located on the stern is often relatively small. This results in not having the ability to easily pick up cargo from its deck (if located in middle of the vessel).

There are solutions proposed and build to combine the heavy lift with side lifting, such as the OOS international vessels. The boom rest is an important feature for crane vessels since not all cranes can be positioned in boom up position during sailing. A crane with a hook height of over 150 meters can require deck space. This deck space is not necessarily a problem for wind turbine transportation but can be for foundation installation and other applications.

The different lifting locations are indicated in Figure 42 below. Lifting from the center of the vessel is most favorable to reduce motions while lifting over the stern and side is unfavorable due to the large distance from the center of the vessel. This location is influenced by many vessel motions such as roll and pitch.

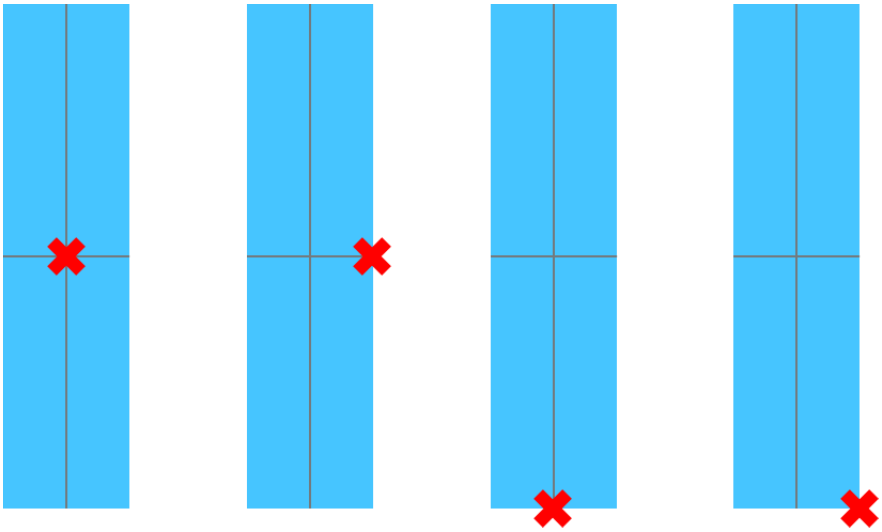


Figure 42 Location of lifting on vessel

Principle 1 – rotating sheerleg

The first principle is the rotating sheerleg. This design was proposed at the start of the project during the first brainstorm session about wind turbine installation vessels. The vessel consists of two cranes located at the stern of the vessel with wide space between the cranes to move the wind turbines through. The vessel is shown in Figure 43 in top view, side view and back view.

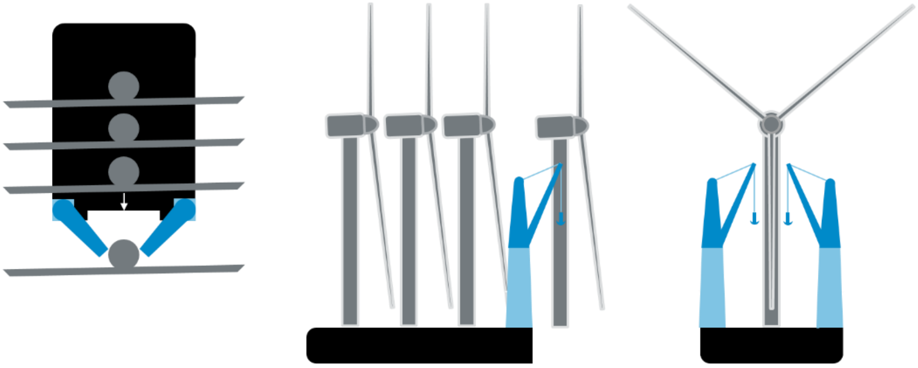


Figure 43 Schematic drawing of Principle 1 (rotating sheerleg)

The size of the vessel of Principle 1 is related to a barge design such as a sheerleg. Principle 1 is a wide body to make space for the cranes to rotate while lifting the wind turbine. This makes it a stable vessel for lifting, but slow vessel during sailing. Furthermore, the cranes located at the stern of the vessel require a harbor with enough space to lift the wind turbines over the stern of the vessel. If a 20 MW wind turbine is taken as the maximum size of wind turbine, the vessel becomes very wide since each crane requires a certain working area to slew. The width of the vessel will easily be above 80 meters in case of a 20 MW reference wind turbine. However, the wind turbines must always be lifted over the cranes themselves, which limits the usable size of wind turbines to be installed. The space that can be used when the wind turbines are moved on the vessel is indicated in Figure 44. This vessel is still very versatile since using the crane at the stern enables it to be used in the same way as a sheerleg while having the possibility to transport its own loads more easily. Principle 1 is even more versatile if there is an option to have a larger lifting capacity once the cranes lift parallel over the stern of the vessel (in the same way as a sheerleg). This Principle is thus closely related to a sheerleg with rotatable cranes for wind turbine installation. The stern lifting has also disadvantages since now the vessel is unable to dock to a quay via the side. The large wind turbines cannot be loaded in the harbor over the side.

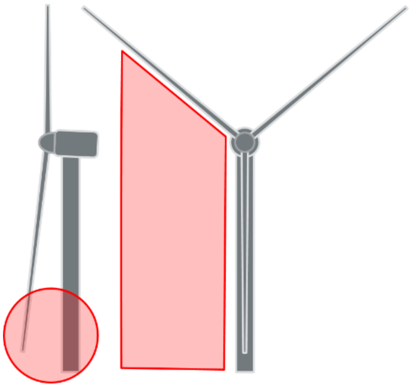


Figure 44 Space around a wind turbine in 3D

Principle 2 – double side lift

The second Principle is closely related to the OWTIS vessel. Both vessels are equipped with a crane on the side of the vessel. Principle 2 has a second crane which makes it possible to install the wind turbines over the side of the vessel without rotating the wind turbine blades during lifting. The Principle named double side lift is shown in Figure 45.

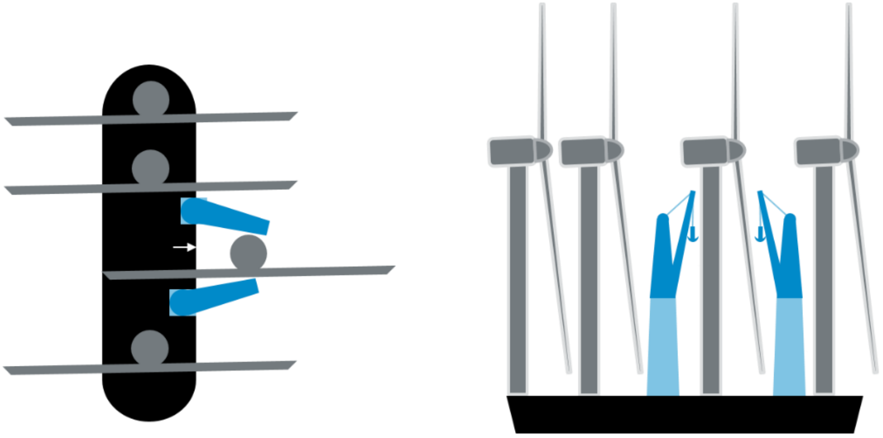


Figure 45 Schematic drawing of Principle 2 (double side lift)

This Principle has two cranes arranged at the side of the vessel. This makes it easier in harbors to load itself. One of the cranes is located outwards of the vessels beam. This makes it possible to install the wind turbines using a spreader between the cranes. The challenge with this Principle is the blade pointing downward takes a lot of space and can get in the way of the crane while lifting. The blade pointing downward is indicated in Figure 44. A special spreader can be used to solve this problem. Installing a complex skidding system which moves the wind turbines in the direction from bow to stern and near the cranes from the middle to the side can be used in this Principle. The wind turbine blades need only to be moved over the cranes when the cranes themselves are not used. If the base of the crane is relatively low and the boom is arranged outside the vessel, the blades have more free space as Principle 1. The vessel is relatively small and can be used for many applications. Lifting over the side of the vessel has a positive influence on the hull design, it makes the Principle compact. Still in this Principle, the wind turbines should be moved over the cranes, limiting the range of wind turbines that can be installed.

Principle 3 – combined side stern lifting

The third Principle is a mixture of Principle 1 and 2. If the second crane on the side of the vessel is located near the stern, the crane has a large operational area to be used for lifting. The Principle is shown in Figure 46. Principle 3 is named combined side stern lifting. Principle 3 can perform liftings over the side with two cranes and stern liftings with one crane.

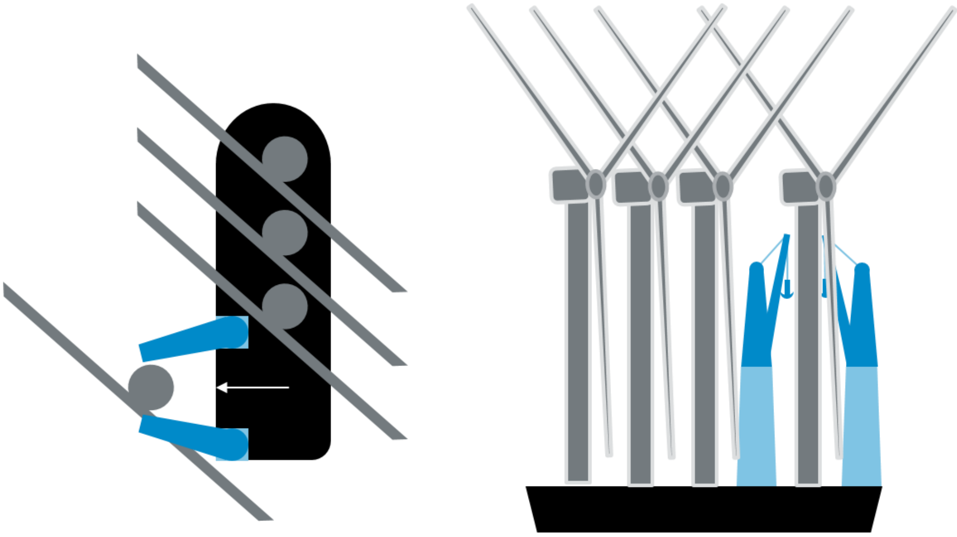


Figure 46 Schematic drawing of Principle 3 (combined side stern lifting)

The wind turbines are rotated in a 45° direction to be able to pick them up on the vessel more easily. The vessel is smaller as Principle 1 but still wider as Principle 2. Loading the wind turbines from the side in the harbor is an advantage of this Principle. The movement of the wind turbines in 45° direction is more complex but space saving. It saves space since the downward pointing blades do not interfere with the tower of the neighboring wind turbine. Also for this Principle, the wind turbines should be moved over the cranes to be able to install them. Another benefit of this Principle is the ability to install smaller wind turbines over the stern of the vessel, using only one of its cranes. The motions during wind turbine installation relative to the center of the vessel are less favorable over Principle 1 and 2 due to the combination of side and stern lifting.

Conclusion

Principle 1 was the initial idea behind this project, stern lifting of wind turbines. However, this demands a relatively large and wide vessel and wind turbine lifting over the cranes themselves which limits the variety of wind turbine sizes. Principle 2 is closely related to state-of-the-art vessels and uses side lifting which is the most favorable of the three Principles. Wind turbine installation can be performed in different ways while the 3D setup of a Principle needs to be kept in mind. The wind turbine has a favorable free space beneath the two blades pointing upward while the downward pointing blade requires space during transportation and lifting. The size of the wind turbines can vary and is based on the positioning of the cranes on the vessel and the rotated direction of the wind turbines. The benefit of diagonal positioning of the wind turbines is interesting as shown in Principle 3 which saves space on the vessel. Stern lifting is for more heavy applications due to the counteracting vessel length and weight for stability. On the contrary, side lifting is the most favorable due to the close location to the center of the vessel. The three conservative solutions are shown below in Figure 47.

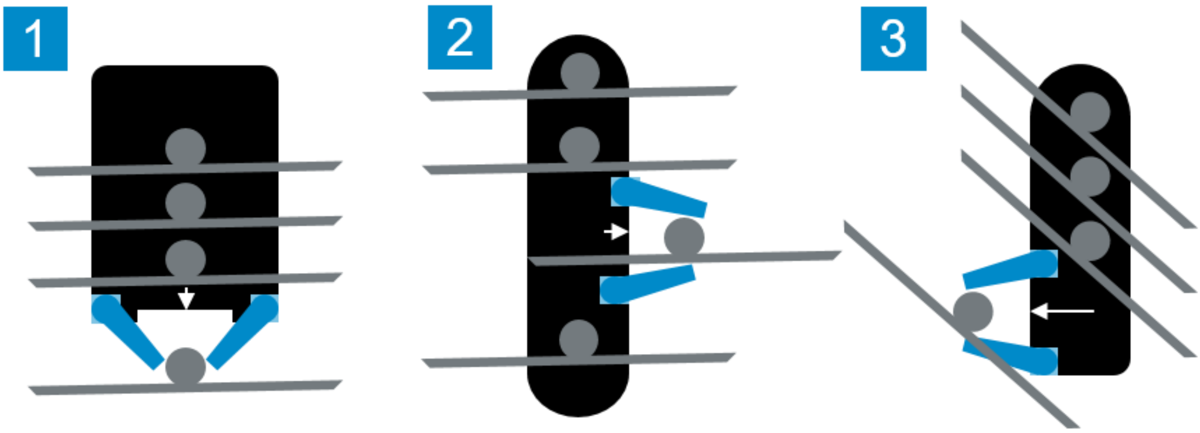


Figure 47 Overview vessels conservative solutions

5. Barge exchange solutions

Since loading wind turbines can take time in the harbor, another group of Principles is thought out. Some trucks can easily (un)load using swap bodies. The swap body makes it possible to separate travelling and loading of a truck. The truck can transport one swap body to a terminal while a new one is already loaded. This possibility reduces the time the truck is at the terminal. It does not have to wait for loading, it only has to swap the bodies. The swap body on a truck is translated in a similar system on a vessel (for wind turbine transportation). The following sub question is partly answered in this chapter:

4. *In which way can large wind turbines (up to or over 20 MW) be installed with the usage of cranes on a floating installation vessel with transport capacity?*

Chapter outline

A semi-submersible vessel can unload itself. In combination with barges, it can change barges without an assisting crane. The idea is using a barge loaded with wind turbines that can be exchanged with an empty barge in sheltered waters. This enables a relatively short loading time without dependency on the weather influencing the loading time of wind turbines. The number of barges can be expanded in future. The barge exchange idea is based on a semi-submersible vessel that can let the barges float on its submersible deck. State-of-of-the-art vessels can be used to transport the barges from one location to another if marshalling ports are too far away from the wind turbine parks and there is a possibility to exchange the barges in nearby calm waters.

Semi-submersible

Semi-submersible (transport) vessels are widely used for transportation of offshore platforms, vessels and other cargos. These vessels can be used to transport barges or vessels to their destination due to less ideal sailing properties of the barges or vessels. The ability to float the deck enables the vessels to transport a heavy load without making use of a lifting device such as a crane. The semi-submersible vessels are often loaded from the side since loads can exceed the maximum width of the vessel. However, Principles exist for transporting longer cargo lengthwise, as show in Figure 48. Typical for these vessels is the sea fastening needed to secure the large cargo on deck (the yellow pillars in Figure 48 (Boskalis, 2018)). The towers on the side of the vessel are needed during the sinking process to stabilize the vessel during floatation of the deck. These towers are sometimes movable on the deck to adapt on the size of the cargo.

The semi-submersible property can also be used for a crane vessel to reduce the motions of the vessel by having a different waterline during lifting as for sailing. This is used for the Saipem 7000 or Sleipnir introduced in chapter 2. There are other vessels using the semi-submersible transport property for crane stabilization such as the Alfa Lift of OHT. These have not been included in this study before since these are not applicable on fully assembled wind turbine installations.

Figure 48 Semi-submersible transport vessel Boskalis Vanguard (Boskalis, 2018)

Beam of vessel

The Principles discussed previously have shown that the width or beam of the vessel is an important property. The width of the vessel is in general observed as more critical than the length of the vessel. Reducing the width of the vessel could be beneficial for the usability of the vessel. In general, it can be observed that a crane vessel equipped with two cranes has a relatively high lifting capacity when the cranes are located relatively close to each other but this reduces the possibility to lift cargo between the cranes on deck. Principle 1 showed that an installation procedure with stern located cranes requires a relatively wide vessel, while side lifting could reduce the lifting capacity.

The width of the vessel can be important during transfer of the vessel from one location to another. The easiness of relocation of the vessel from North Sea to Baltic Sea and vice versa can be determined by the size of the vessel. A wide vessel is more difficult to move in congested areas while it also serves a purpose. The total area of the hull of a vessel determines the draft of the vessel which influences the passage of the Øresund if the height of the vessel exceeds the passage height of the Storebælt bridge. Since the wind turbines are relatively large, the width of the vessel is not very important during wind turbine transportation although the width influences the stability of the vessel.

Simplicity

Lifting can be very complex. Fully assembled wind turbine installation requires a good lifting technique for safe installation. Installation of wind turbines in sheltered water conditions is less complicated to installing wind turbines at sea. The wind turbines are built to catch wind which could negatively influence the lifting operation. Due to the fully assembled wind turbine installation, the wind turbine will probably react slower upon the wind blowing on the turbine due to the large weight of the assembly.

Wind is not the only force that generates motions at sea since the motions of the sea itself will also influence the installation vessel. The vessel will be subjected to waves for which the motions are shown in Figure 49 (Huisman, 2019b, p. 19). Due to the waves the vessel will surge, heave and sway which can be compensated for surge and sway motions using dynamic positioning systems. The heave motion (up and down motion) can be influenced by using the semi-submersible properties and ballasting techniques. However, the vessel will also tilt (pitch, yaw and roll) of which the yaw motion will be influenced by the dynamic positioning systems. This means that the heave motion and pitch and roll tilting will mostly influence the wind turbine installation.

The location of installation relative to the center of the vessel influences installation motions. Every degree of freedom of an installation device can result in more correcting motions and/or complex operations. The degrees of freedom during installation are slewing, luffing and lifting motions which can be used to control the wind turbine.

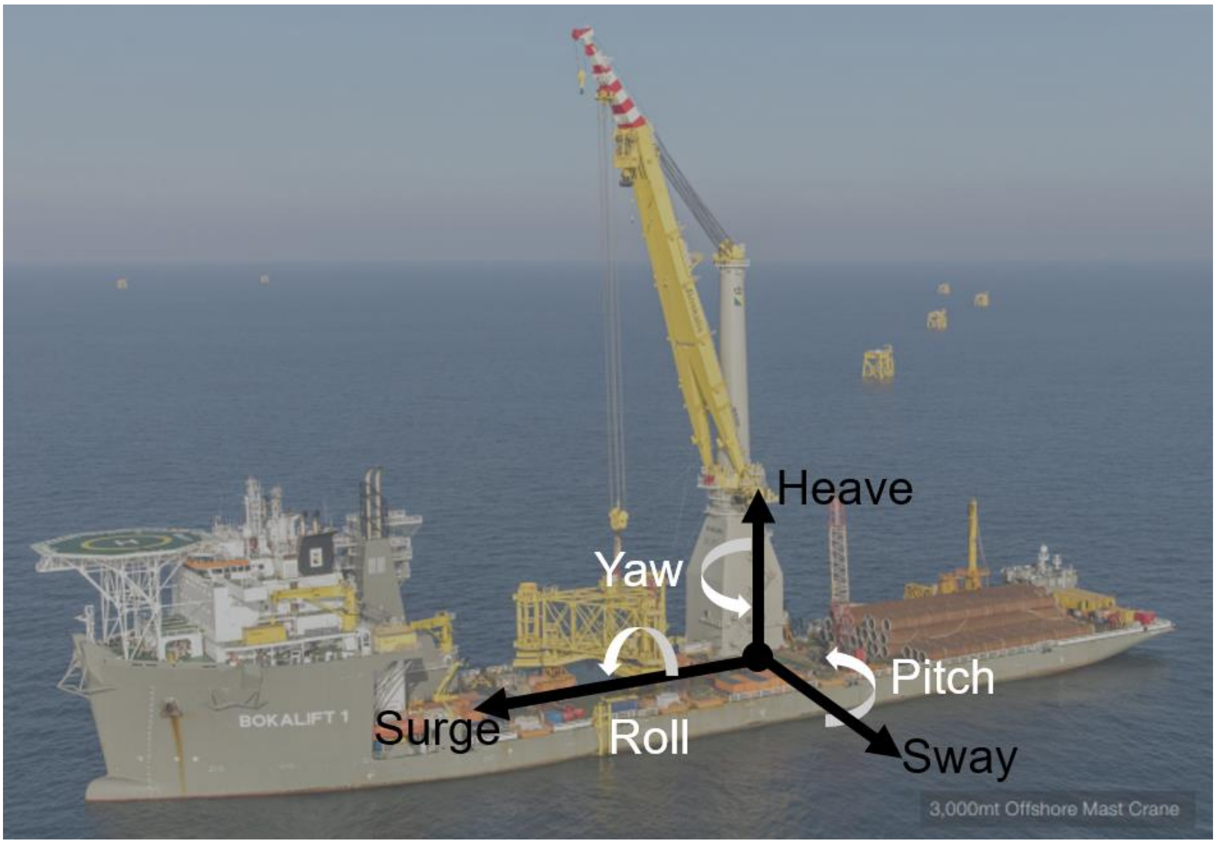


Figure 49 Bokalift 1 with ship motions (Huisman, 2019b, p. 19)

Principle 4 – diagonal barge crane

The first Principle of the barge exchange solutions is a semi-submersible vessel with a monohull and two cranes located near the stern of the vessel. The cranes must lift the wind turbines from the barge onto the foundation while lifting the turbine between the masts of the cranes. The Principle (diagonal barge crane) is shown in Figure 50.

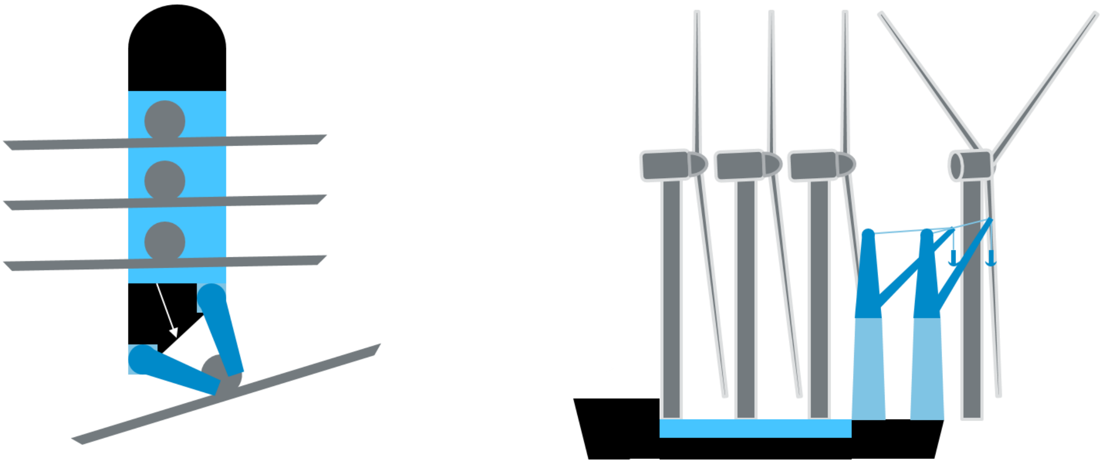


Figure 50 Schematic drawing of Principle 4

The diagonal position of the cranes limits the width of the vessel. Furthermore, it creates a relatively large area between the cranes to move the wind turbines through. Also, the capacity of the cranes can be used in an efficient way, since the cranes still have a large open space at the stern of the vessel. This makes it possible to easily install the offshore substation, transported on the barge of the vessel. The difficulty of this Principle is the lifting process, since the wind turbine needs to be lifted between the cranes. The blade pointing downward is a challenge. The wind turbine needs to be rotated in a specific order to enable the cranes to lift it from one side to the other. Still, the vessel can be used for many applications since it can transport its own loads and has semi-submersible properties. Due these properties, the combined side stern lifting is a smaller problem in this Principle. As the case for Principle 2 and 3, the wind turbines need to be moved over the cranes during the lifting process which limits the range of sizes of wind turbines which can be installed. If possible, the cranes do not need a boom rest during travelling which enables this Principle to be used on other applications. The transport capacity of the vessel is not limited by the capacity of the cranes due to the barge exchange mechanism.

The width of the vessel also needs to be taken into consideration for the stable transfer of a barge with wind turbines to prevent tipping of the barge. The relatively high CoG of the wind turbines of 20 MW on the barge (estimated at least 120 meters) demands a reasonably sized barge for stable loading and sailing of the barge in calm waters. The width of the barge can also be related to the jackets since these are approximately 40 meters wide at the base of the jacket (Pontow, Kaufer, Shirzahdeh, & Kühn, 2017). The barge exchange process is foreseen to be used in sheltered waters since offshore exchange seems challenging.

Principle 5 – barge crane

The barge exchange Principle can also be applied on a sheerleg crane. Some sheerleg cranes have enough space between the booms to move loads from one side of the vessel to the other. Figure 51 shows Principle 5 which is a sheerleg with barge exchange in length direction. This Principle is named barge crane, the combination of a barge and crane on one vessel.

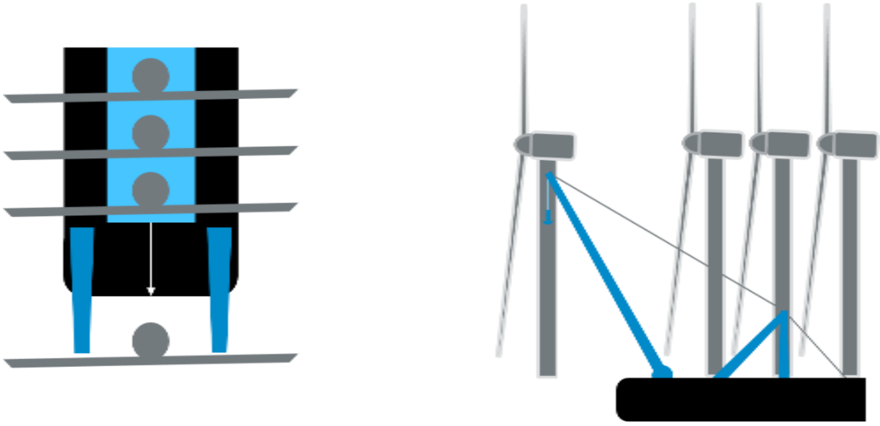


Figure 51 Schematic drawing of Principle 5

The A-frame of the sheerleg (booms of the cranes on each side of the vessel) can be used to adapt on wind turbine sizes. Moving the pivot point on the vessel forward or backwards creates the possibility to adapt on wind turbine sizes but limits the lifting capacity (Figure 52). This makes the a-frame of a sheerleg interesting above the usage of slewing crane, it is possible to have a broader range of wind turbines that can be installed. The sheerleg is furthermore a very strong vessel with a relatively simple system. The capacity of a sheerleg is enough for installation of offshore substations, which could be transported on their own barge. Transporting the wind turbines is relatively slow compared to Principle 4, due to the vessel size of a sheerleg. Transportation using a sheerleg is comparable with the offshore substation transportation on the Gulliver shown in Figure 53 (Scaldis, 2020). The cranes of Principle 5 do have similarities with the Gulliver (and Rambiz) shown in the figure although the size of the vessel is larger to be able to transport the wind turbines.

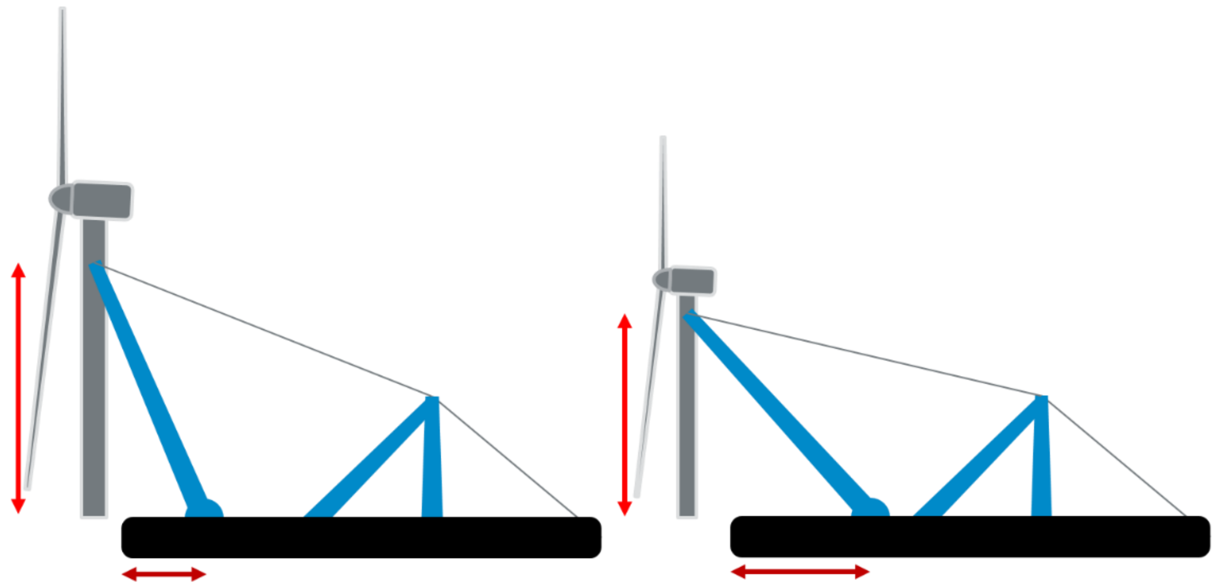


Figure 52 Sheerleg with pivot point adjustment

Figure 53 Gulliver transporting offshore substation (Scaldis, 2020)

The barge is transported within the hull and is (un)loaded over the stern of the barge crane. It is unknown which vessel width needs to be considered for this type of barge transportation. Possibly, the narrow barge on the vessel could negatively influence the stability of the barge once floated. The size of the vessel needs to be adapted on the barge size, which could result in a vessel that is relatively wide and thus has less ideal sailing properties. This means that the barge crane Principle could result in a wider hull, compared with the sheerleg (vessel C from literature). On the contrary, the combination of sheerleg and barge exchange makes the vessel very flexible.

Principle 6 – barge shiploader crane

A floating wind turbine installation is moving continuously offshore due to waves and wind. Another Principle is proposed to be used for wind turbine installation in relation to the continuous vessel motions. It has the same components of Principle 5 except for the a-frame. The Principle is shown in Figure 54. The cranes used for this Principle are shiploader cranes (derrick cranes) as used during the past decade on the first heavy lift vessels. Principle 6 is named barge shiploader crane.

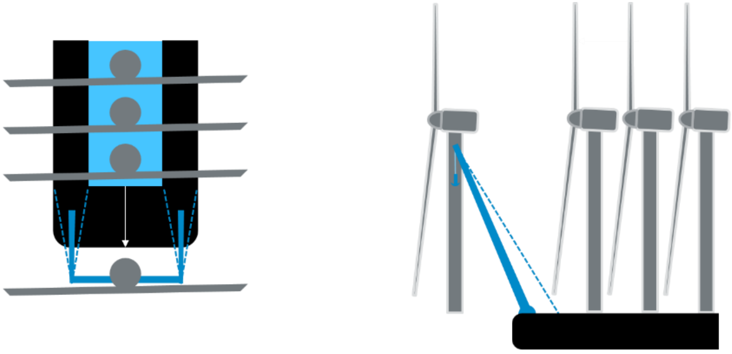


Figure 54 Schematic drawing of Principle 6

The shiploader cranes were also used on the Liberty ships during WOII. Some heavy lift vessels were equipped with these cranes up to a few years ago, capable of lifting a couple 100 tons. The interesting part of these cranes is the freedom in rotation of the boom. The boom is hinged on the vessel in this Principle and controlled by the two wires (indicated with blue dashed lines). The spreader connected to the wind turbine is part of the crane and can rotate around the top part of the boom. This means that the double shiploader crane can move in different directions, which could be beneficial for motion compensated systems required for installation of wind turbines. The wind turbine can be kept stable in a different way as for regular cranes with the shiploader cranes. Since each shiploader crane needs to lift at least 2,000 tons, they could grow relatively large. Motion compensation could become complex due to the size of the cranes and the required power for motion compensation.

Conclusion

Exchanging a barge of wind turbines could be time saving. The barge should stabilize itself once the wind turbines are loaded on it. Principle 4 shows that with cranes positioned diagonally, the width of the vessel could be reduced which is beneficial for relocation. However, the cranes need to install the wind turbine in a very complex way due to the 3D problem with the downward pointing blade. Principle 5 and 6 are very stable crane vessels that do not need to slew the crane booms during wind turbine installation. The downside of stable lifting is the large size of the hulls and its effect on the sailing properties. Principle 6 shows that adding an extra pivot point (the shiploader crane property) could be beneficial for motion compensation and stable installation of wind turbines. On the contrary, the cranes are subjected to relatively large loads and thus relatively large power requirements need to be met for motion compensation. The three solutions with barge exchange are shown below in Figure 55.

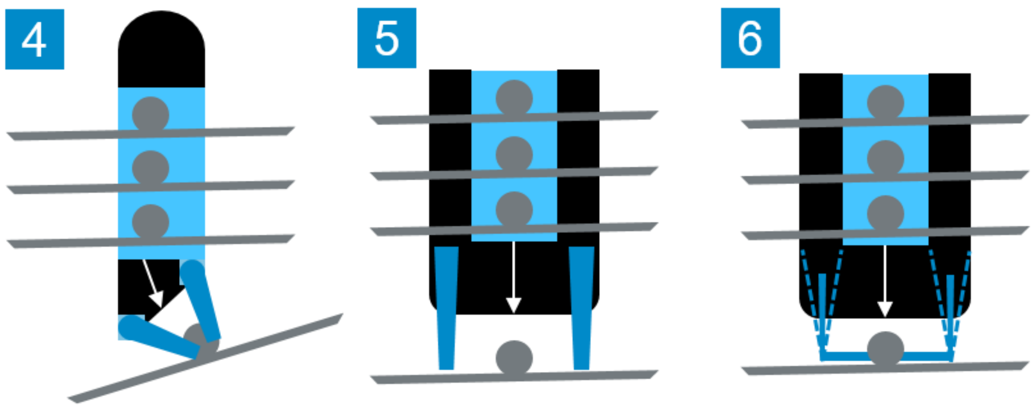


Figure 55 Overview vessels barge exchange solutions

6. PWT installation solutions

The third and final group is identified by the special arrangement of the cranes. Wind turbines need to be moved over the cranes in all previous discussed Principles. This limits the crane design since it must fit with the wind turbine sizes. The following sub question is partly answered in this chapter:

4. *In which way can large wind turbines (up to or over 20 MW) be installed with the usage of cranes on a floating installation vessel with transport capacity?*

Chapter outline

Movement of wind turbines during installation limits the crane design and some Principles show that relatively large deck space cannot always be used due to crane arrangement and vessels size. Wind turbines do not have to be installed in between the space of the cranes specifically, other ways are also possible. When combining the 45^{o} arrangement of Principle 4 and controlled movement of twin-lift cranes while not lifting between the cranes, a new Principle was created. The base of the Principle uses a parallelogram structure (four-bar linkage system) for wind turbine installation. This parallelogram structure is referred to with PWT installation (Parallelogram Wind Turbine installation) or cranes in PWT configuration.

Lifting property

Lifting wind turbines can be performed in many ways. In general it is observed that most of the lifting Principles for single lift installation require a fixed orientation of the wind turbine during lifting (Figure 56). This fixed orientation is relative to the boom (horizontal boom rotation) or vessel rotation. A fixed orientation relative to the boom is the easiest. The wind turbine rotates with the crane rotation. However, this can result in complex lifting since the blades of the wind turbines can easily bump into each other. A fixed orientation relative to the vessel seems to be more convenient since here the lifted wind turbine cannot easily bump in the wind turbines placed on the vessel (Figure 56).

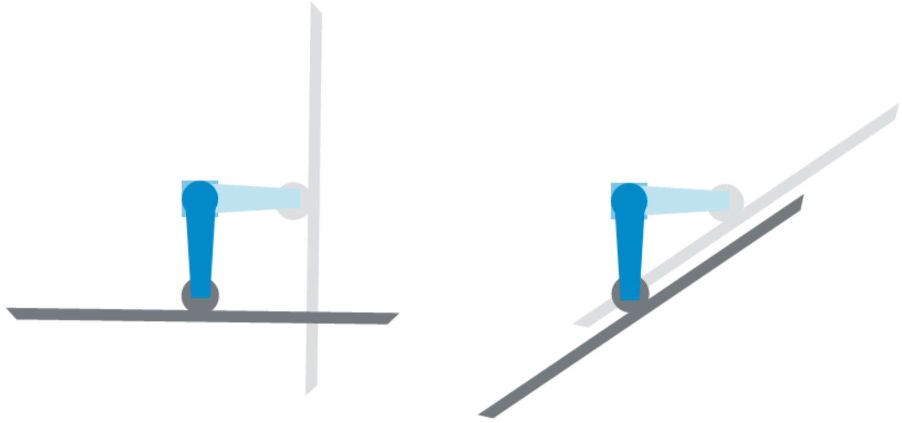


Figure 56 Single lift rotation wind turbine differences

The crane configurations proposed earlier in principle 1 till 4 require movement of the wind turbines over (parts of) the cranes. This can take place during lifting or during moving the wind turbine to the starting location of the lift. This limits the variety in sizes for lifting the wind turbines due to crane sizes. Therefore, for further Principle development, a cardboard sketch is made of a 20 MW wind turbine with two cranes of approximately the size that can lift the wind turbine. The radius is 50 meters and for size comparison the 20 MW jacket is included in Figure 57.

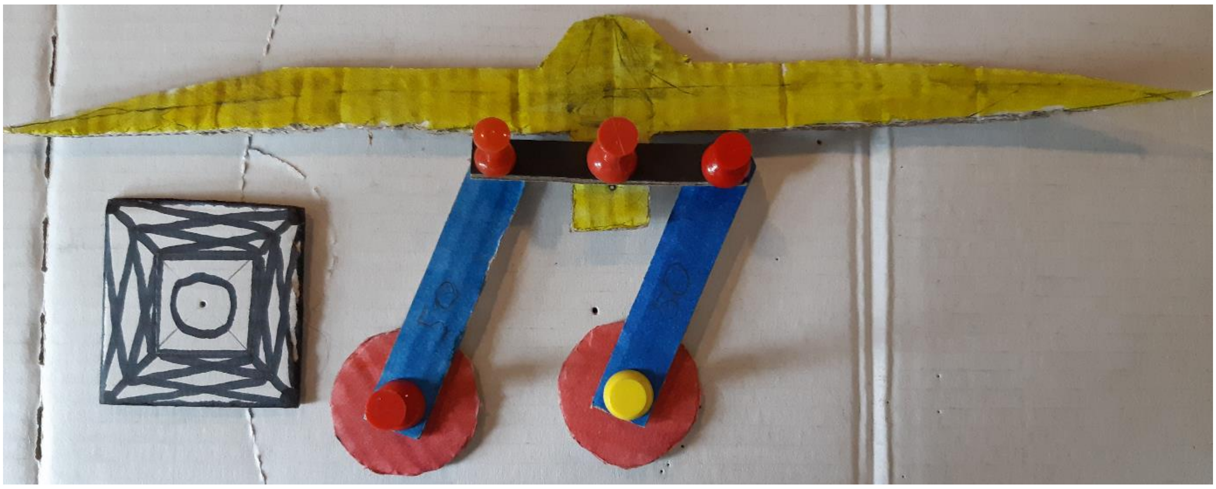


Figure 57 Cardboard representation of 20 MW wind turbine installation

It is observed that with this set-up the cranes can slew approximately 90 degrees without any trouble. This observation is schematically shown in Figure 58.

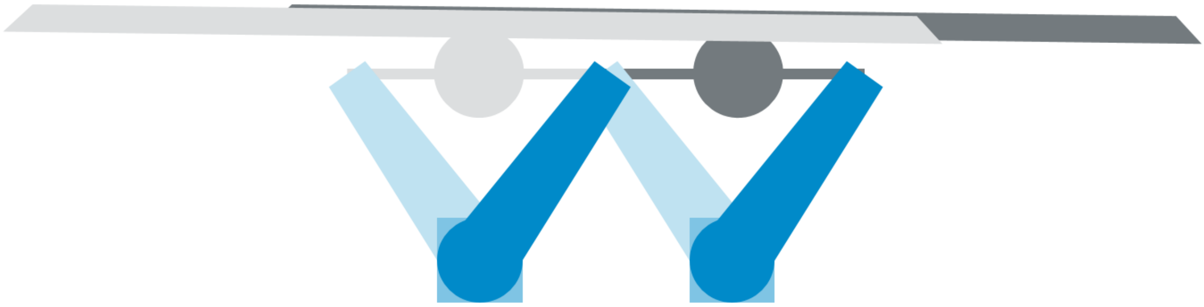


Figure 58 Lifting wind turbines sideways

Compact size

The before mentioned Principles indicate that a vessel has appropriate lifting properties or sailing properties due to the size of the vessel. A relatively small vessel is beneficial for sailing and a wide vessel for more stable lifting although larger vessels can negatively react on certain wave groups. A small vessel has more possibilities to enter a harbor if needed while larger vessels only have specific ports to enter. The wind turbines are voluminous but can be transported compactly such as Principle 3 suggests due to the diagonal position of the rotor blades. A good balance between lifting, transporting and accommodation is important for the vessel.

Main goal of installation vessel

The main goal of the vessel is wind turbine installation. If needed, some changes can be made for foundation installation or other applications. The Windlifter and Wind Turbine Shuttle are examples of vessels for which immediately becomes clear that wind turbine installation is their main form of application. If the Principle can install wind turbines using cranes, it has high potential to install easily foundations due to the usage of cranes combined with the relatively high lifting height.

Principle 7 – PWT 4

The combination of the lay-out of Principle 3 and 4 is able to install wind turbines in parallelogram configuration. Two cranes are mounted at the stern of the vessel diagonally while the wind turbines are located off centerline on the vessel. Principle 7 is shown in Figure 59. The name of Principle 7 is PWT 4 which is an abbreviation for the crane configuration with a transport capacity of four wind turbines.

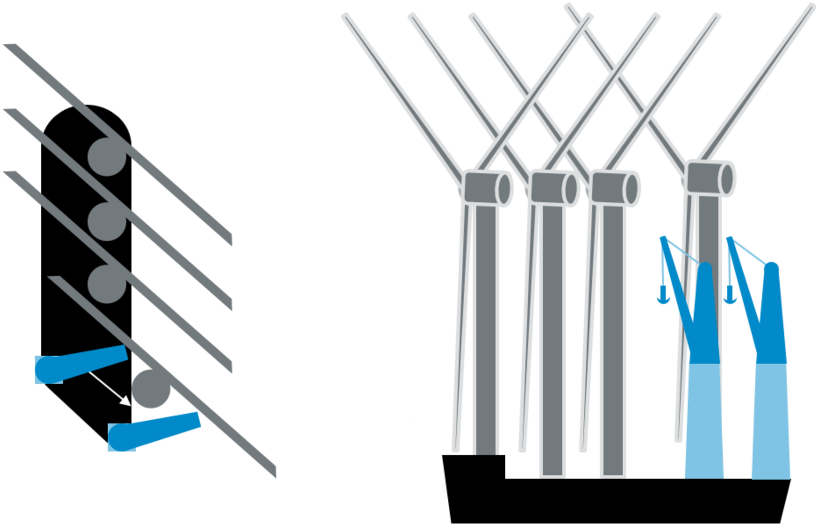


Figure 59 Schematic drawing of Principle 7

The wind turbines are picked-up in front of the crane at starboard side of the vessel. Then the cranes slew together the wind turbine to the location of the foundation. No wind turbines need to be moved over the cranes if the wind turbines are rotated 45° as shown in the figure. This means that the cranes need to match the largest wind turbine foreseen to be installed by the vessel and every smaller wind turbine can be installed with this configuration. This is different compared with other Principles, these vessels often have a smaller installation range. The vessel is relatively small, and the crane configuration is used optimally in this way. Furthermore, the cranes oriented over the stern of the vessel in diagonal direction make it possible to install larger structures, using the full crane capacity. The diagonal location of the cranes is novel about this Principle. For further investigation, the 45° orientation was varied (30° for example) to see whether it was feasible to position the cranes closer together. This was not convenient since it would be difficult to guarantee the same usability during wind turbine installation.

Principle 8 – PWT 8

Principle 7 can also be applied on a vessel which is capable to install wind turbines over the side of the vessel. This Principle 8 is double the size of Principle 7 with wind turbines located at bow and stern side of the vessel while the cranes are located in the middle of the vessel. Principle 8 (PWT 8) is shown in Figure 60.

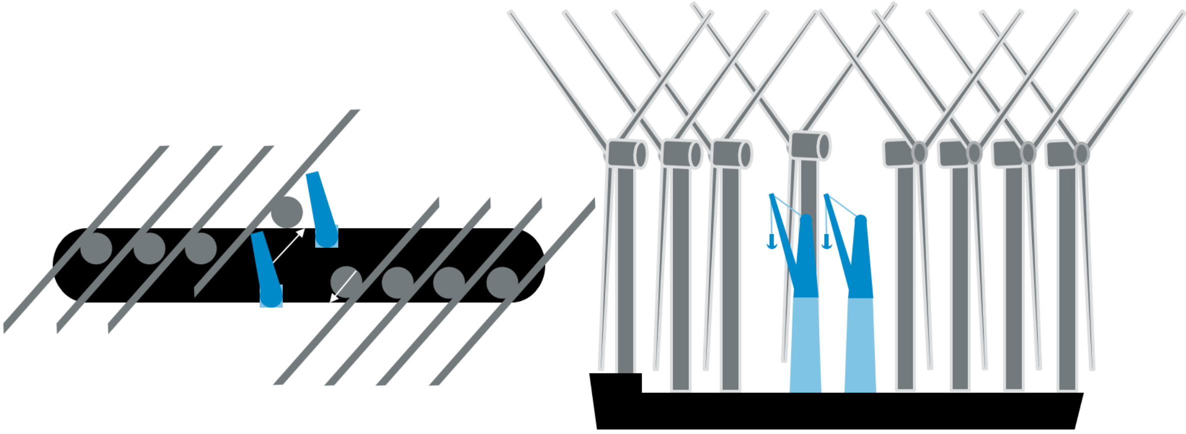


Figure 60 Schematic drawing of Principle 8

The wind turbines located at both sides of the vessel are mirrored over the cranes location. Installation of the wind turbines is achieved by turning the cranes 180°. A disadvantage of this Principle is the limited combined capacity of the cranes that can be used for other purposes. While all previous discussed Principles are also applicable in other markets, this vessels is more specialized for wind turbine or foundation installation. Something that applies for all the double crane configurations is the possibility to lift foundations with one crane while the other is assisting with equipment (such as a hammer). Increasing the capacity of one crane enables single side offshore substation installation. Still, one crane has to reach over the vessel. Interesting about this Principle is the small width of the vessel, making it more capable for sailing. However, if the wind turbines in Figure 60 have a capacity of 20 MW, the arrangement shown makes the vessel around 350 meters long. This length of the vessel is comparable with the length of the largest class of container vessels as used today. Special large marshalling ports are required for this vessel to load the wind turbines. The accommodation on this vessel can be made relatively small, such as the Boka Vanguard (Figure 48), which can reduce the length of the vessel. However, this immediately leads to less useful deck area for other applications such as foundation or offshore substation installation.

Principle 9 – PWT 11

Many more wind turbines can be transported on a vessel if the vessel is arranged compact. The diagonal direction of the wind turbines makes it possible to form two rows of wind turbines next to each other, while installing the wind turbines over the stern of the vessel. The Principle PWT 11 is shown in Figure 61.

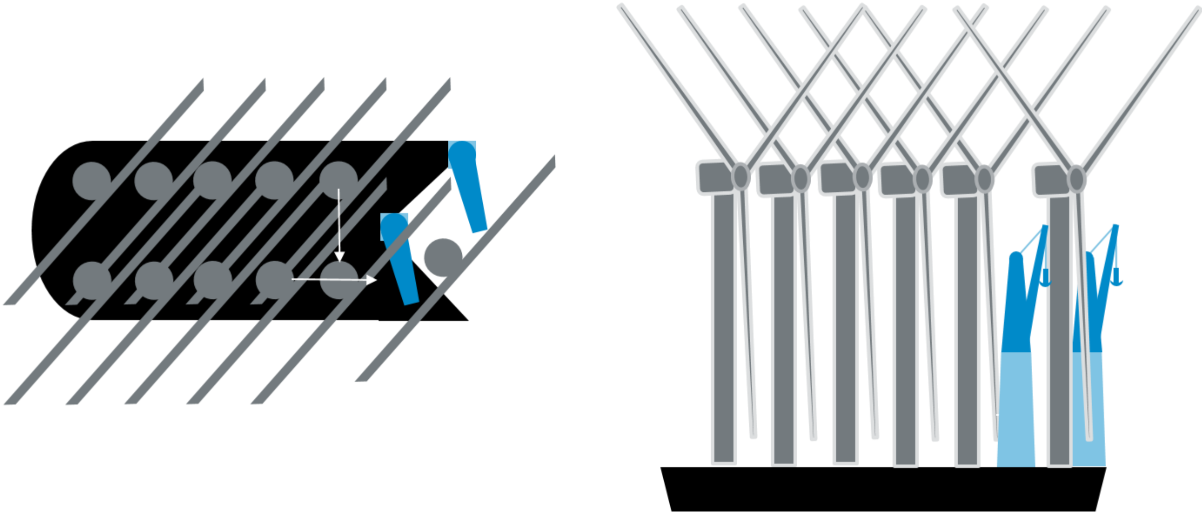


Figure 61 Schematic drawing of Principle 9

This Principle is shown to indicate the possibility of parallelogram lifting if the vessel can be built for specialized application. Still, the cranes can use their full capacity over the stern of the vessel and many wind turbines can be transported on the vessel. The benefit of Principle 7 and 8, no movement of wind turbines over the cranes, is not applicable on this Principle. A vessel size of over 30000 m^2 deck area (100 x 300 meters) is relatively large and in the range of the largest vessel by gross tonnage, the Pioneering Spirit. This Principle suggests that every time the vessel loads in the port, all the wind turbines need to be ready for loading which sets high requirements for onshore logistics.

Conclusion

The diagonal positioned cranes limits the width of the vessel and in combination with parallelogram lifting it can install a broad range of wind turbines. The cranes can be placed on different places on the vessel, depending on the specialism of the vessel. Principle 7 is the most versatile while Principle 8 and 9 are more specialized for wind turbine installation. Principle 8 has the best location for lifting, over the side of the vessel which negatively influences the available lifting capacity in twin lift configuration. Scaling up the capacity of the wind turbines installation vessels could be interesting for the vessels themselves but is depending on other logistical parts of the installation chain such as manufacturing. In Figure 62 below the three PWT installation solutions are shown.

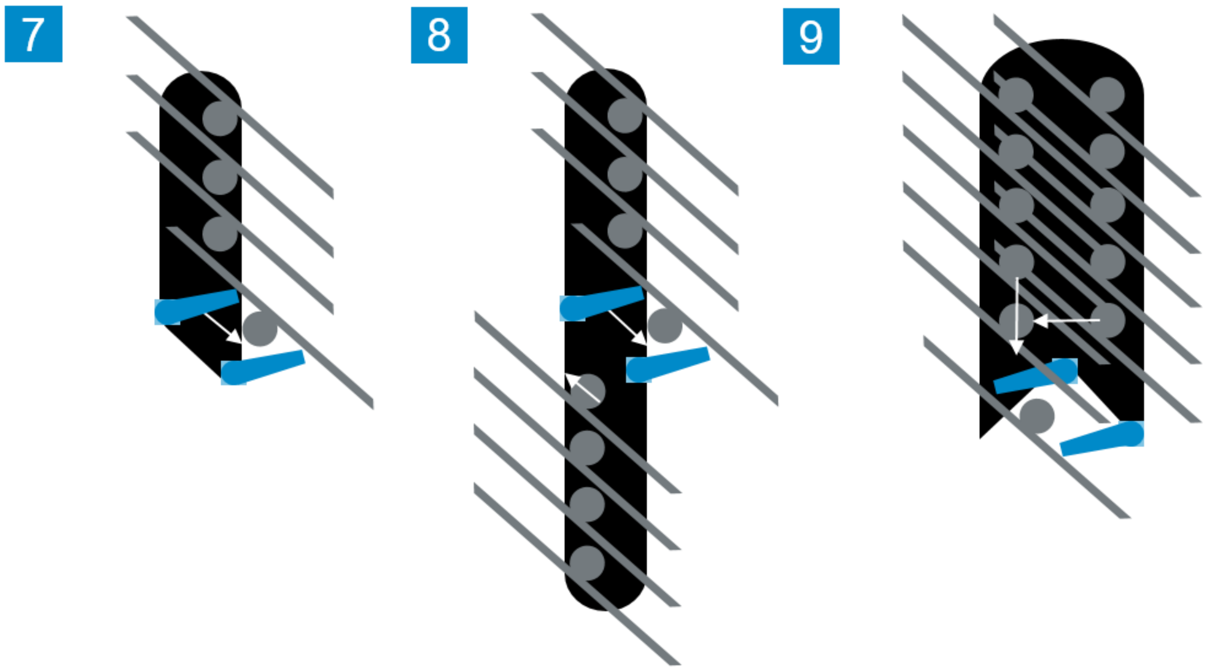


Figure 62 Overview vessels PWT installation solutions

7. Comparison

Several Principles have been proposed by industry and discussed in the previous chapters. In addition, nine different Principles are thought out for installation of large wind turbine. To identify which principles are most promising, a comparison is made based on the following aspects: solutions for loading, sailing and installation properties. The insights provided will answer sub questions 5 and 6:

5. *In which way do the proposed concepts relate to each other compared with earlier proposed concepts?*
6. *Which overall concept show potential to be used in future wind turbine installation industry in terms of flexibility and scalability and in which way does it fulfill the need for the wind turbine installation industry?*

Chapter outline

Different vessels and principles have been discussed in the previous chapters. An overview provided in Figure 63. The next step is to identify which solutions and/or principles are most promising. The identification is achieved by relating the solutions to different operations of wind turbine installation process in a morphological analysis. The morphological overview is the starting point for choosing a couple of solutions to cover different solutions for operation processes. These solutions form eight different concepts for which data is estimated for the wind turbine installation process. With this data two interesting solutions with relatively good installation rates were identified with the usage of a scenario comparison. The following step was finding the best solution, relating to the flexibility and scalability as defined in the research questions. This is discussed in the detailed comparison.

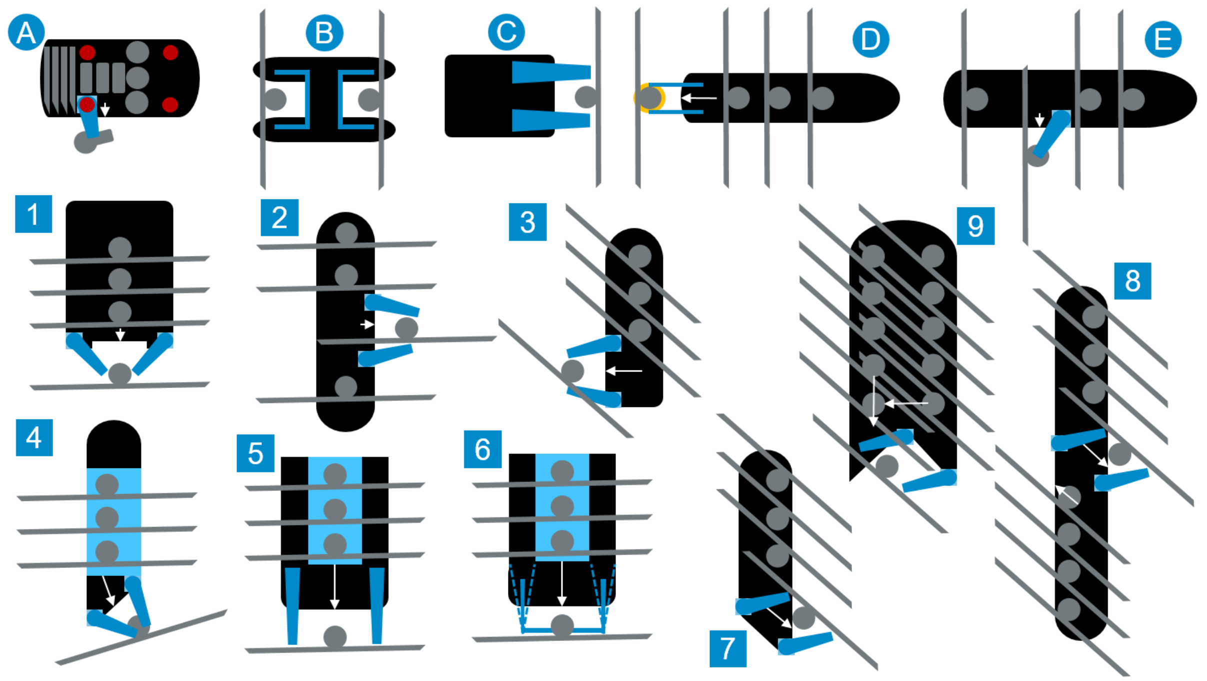


Figure 63 Schematic overview of concepts for wind turbine installation

A - Jack-up **B - Shuttle (WTS)** **C - Sheerleg** **D - Windlifter** **E - OWTIS**
1 - Rotating sheerleg **2 - Double side lift** **3 - Combined side stern lifting**
4 - Diagonal barge crane **5 - Barge crane** **6 - Barge shiploader crane**
7 - PWT 4 **8 - PWT 8** **9 - PWT 11**

Differences in principles

The introduced solutions in literature and chapter 4 till 6 beneficial for loading, transportation and installation processes of wind turbine installation. Different solutions have been proposed for each of these processes. A morphological analysis is introduced to narrow down the pool of possible solutions.

Loading, transportation and installation

The introduced concepts or principles do have common solutions which influence wind turbine installation. There are a couple of factors which in general influence the logistical performance of an installation vessel. An overall wind turbine installation process can be split in port activities, transportation and installation of wind turbines. The following factors are identified:

1. Port activities
    - Assembling wind turbines for fully assembled wind turbine installation
    - Loading of wind turbines in the port before transportation
2. Transportation
    - Sailing properties of vessel (related to hull design)
    - Transport capacity of vessel
3. Installation of wind turbines
    - Workability of vessel
    - Installation technique
    - Versatility of the concept

At first, the components of the wind turbines need to be collected at the port. The components need to be assembled in the port into a fully assembled wind turbine. This requires an assembling crane with enough lifting capacity to assemble the wind turbines. The following port activity is loading of wind turbines for transportation. The installation vessel needs to load the wind turbines by itself. This would be convenient for the onshore crane (smaller assembling crane onshore) due to the large properties of the wind turbines (height and overall weight). If the wind turbine installation vessel cannot load itself, the onshore crane needs to be able to lift fully assembled wind turbines on the vessel.

The following activity is the transportation of wind turbines. The efficiency of the transportation of fully assembled wind turbines is dependent on the transport capacity of the vessel and the sailing properties of the vessel (hull design). A large transport capacity means less port to wind park movements. Besides, the sailing properties of the vessel influence the speed of the transportation of wind turbines. A vessel with a narrow hull or SWATH (Small-waterplane-area twin hull) hull can easily sail between two locations and limits the transportation time.

The final activity is installation of wind turbines. The installation of wind turbines depends on many factors but is most influenced by the two factors: workability of the vessel and the installation technique. These two factors are dependent on the hull design of the vessel. The hull design determines the stability during lifting which is influenced by waves and wind. Specific technical solutions are not considered for the first logistical scenario comparison.

Morphological analysis

To identify the differences in solutions, the specific solutions of the vessels in Figure 63 (such as transport capacity and lay-out) are reorganized in a morphological analysis groups which are related to the logistical performance. This results in a better overview of how the concepts relate to each other once they are operational.

The following five operations (A till E) with different solutions (1 till 4) are identified for the investigation in logistics based on the factors identified in the previous section (Table 13):

	Operations				
Solutions	Assembling A	(Un)loading B	Transportation C	Sailing D	Installation E
1	X	Vessel equipment	2 Wind turbines	Barge	Vessel equipment
2	Onshore crane	Crane vessel	4 Wind turbines	Monohull	Crane vessel
3	Crane vessel	Barge exchange	8 Wind turbines	Multi-body	
4	Jack-up vessel		Supply vessel		

Table 13 Morphological overview of concepts

Jack-up	**Shuttle (WTS)**	**Sheerleg**	**Windlifter**
Barge crane	**PWT 4**	**PWT 8**	**Barge PWT**

A. Solutions for assembling operation

1. None

   The state-of-the-art installation vessel (jack-up) does not use an assembling crane due to the installation method.

2. Onshore crane

   A possibility for wind turbine assembly onshore is a large onshore crane. The crane is located on the quay and needs to provide enough lifting capacity for wind turbine assembly

3. Crane vessel

   It is possible to use a sheerleg for wind turbine assembly (and loading). This crane is movable over the water and thus makes no use of limited quay area. The vessel can relocate itself for other activities.

4. Jack-up vessel

Existing jack-up vessels could be used for future wind turbine assembly. Current vessels probably have enough lifting capacity for wind turbine assembly and can raise themselves high above the waters to reach the required lifting height. Furthermore, they can be relocated to another port after finalization of the wind turbine park project.

B. Solutions for (un)loading operation

1. Vessel equipment
   A self-loading vessel (such as the wind turbine shuttle or Windlifter) does not require other crane vessels for wind turbine loading
2. Crane vessel
   The sheerleg used for wind turbine assembly could also be used for wind turbine loading of transport vessels or barges.
3. Barge exchange
   Chapter 5 discussed the benefits of a barge exchange to limit loading times. The usage of this system does not require additional fully assembled wind turbine lifting or movements, due to the absence for the need of fully assembled wind turbine loading.

C. Solutions for transportation operation

1. 2 Wind turbines
   The smallest vessel from literature (wind turbine shuttle) is able to transport 2 wind turbines
2. 4 Wind turbines
   Most of the proposed concepts or principles use a transport capacity of 4 wind turbines (standard transport capacity), which is feasible for a jack-up vessel, Windlifter or other compact installation vessel
3. 8 Wind turbines
   Principle 8 is able to transport 8 wind turbines which is double the 'normal' capacity used in this research. This transport capacity is included for further investigation on whether transport capacity influences the wind turbine installation efficiency.
4. Supply vessel
   It is possible to use a crane vessel offshore which only installs wind turbines while being fed by supply vessels. Several already existing vessels are suitable for this activity.

D. Solutions for sailing operation

1. Barge
   Chapter 3 discussed categorization of vessel hulls. Those categories are related to the hull design during wind turbine installation only. The hull design for sailing is mentioned in this morphological. The barge means a relatively wide body (sheerleg, barge crane, PWT 11) which has worser sailing properties and a lower transit speed.
2. Monohull

Vessels with a relatively small but long hull design: slender vessels.

3. Multi-body

The wind turbine shuttle uses a special SWATH hull to increase sailing efficiency.

E. Solutions for installation operation

1. Vessel equipment

The installation is performed by on board equipment on the vessel

2. Crane vessel

The sheerleg can be used as a crane vessel at location for wind turbine installation. This solution is included in the overview.

Concepts for comparison

The different concepts based on the different operations and solutions in the morphological analysis are shown below in Figure 64. The overview is to idenfity of promising concepts which cover differently the wind turbine installation activities. Seven concepts are selected from the previously introduced principles and vessels shown in Figure 63. One new concept (a mixture between Principle 4 diagonal barge crane and Principle 7 PWT 4) is included in the promising concepts. Each of them will be discussed in this section in relation to their operations for wind turbine installation.

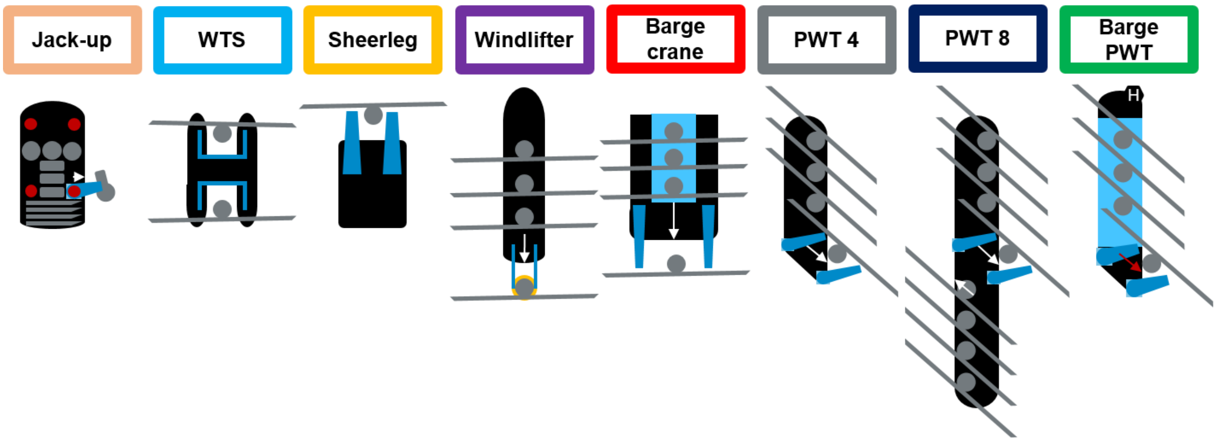


Figure 64 Overview concepts for comparison

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. The jack-up vessel does not require additional assembling cranes onshore but shifts this part of the process to the location of installation. This reduces the installation rate of the jack-up vessel. The overview of installation is shown in Figure 65.

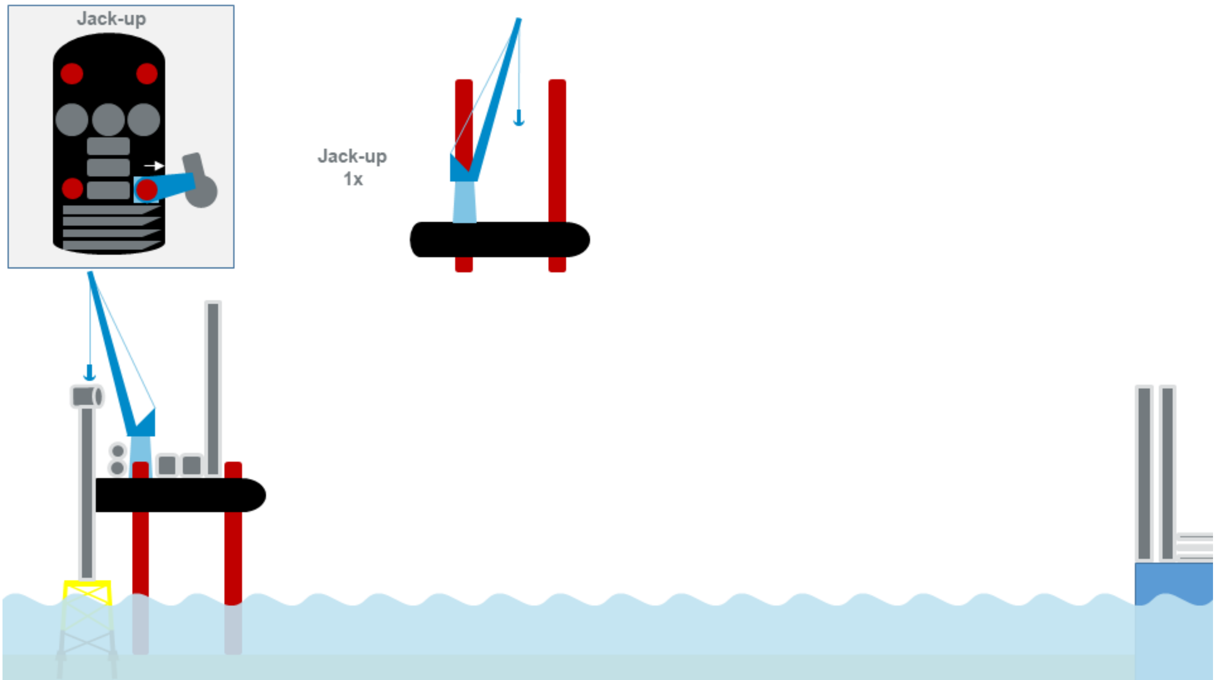


Figure 65 Jack-up vessel installation method – fleet overview

If the components for the jack-up vessel are delivered in smaller pieces, an additional crane is still needed, which is also required if the transportation vessels of wind turbine components (from factory to port) cannot unload themselves.

Shuttle (WTS)

The wind turbine shuttle can transport two fully assembled wind turbines and is specialized for this application. 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. The fleet overview is shown below in Figure 66. The lay-out of the wind turbine shuttle requires a special quay to load the wind turbines which is an extra requirement for onshore activities of the wind turbine shuttle.

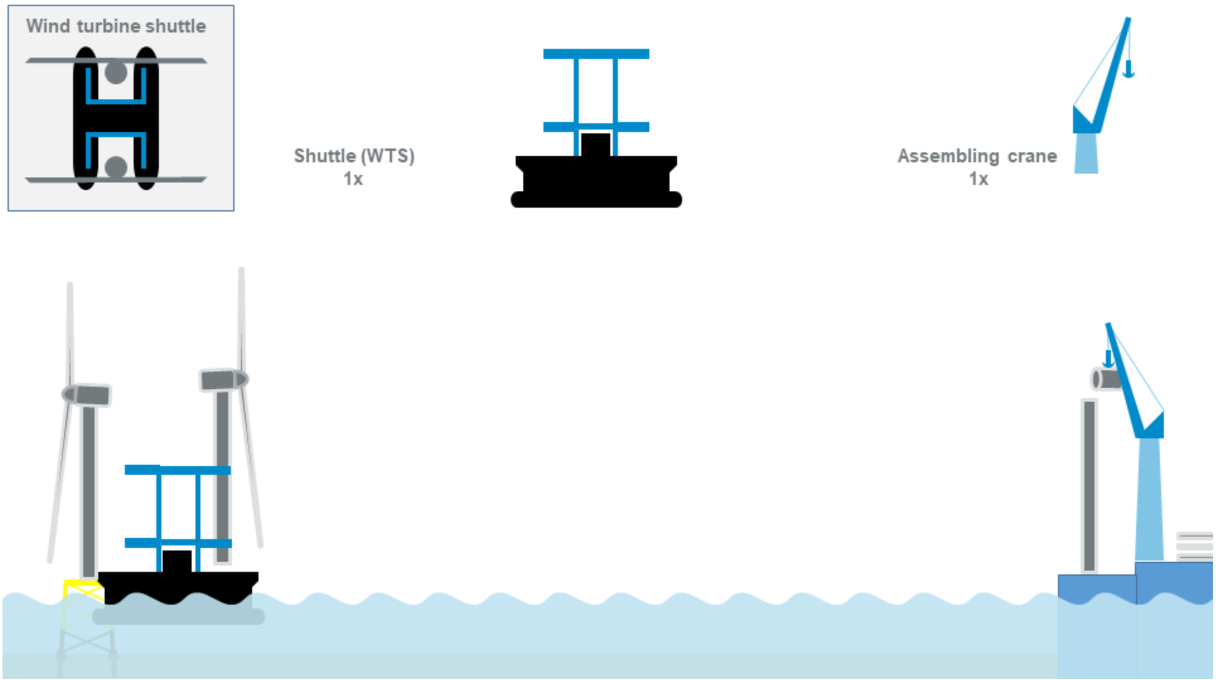


Figure 66 Shuttle (WTS) installation method – fleet overview

Sheerleg

The sheerleg cannot transport multiple wind turbines. For the 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. Sailing multiple supply vessels for the wind turbine installation requires multiple handling of the wind turbine before final installation (multiple lifts and risks) which is a complex solution. Besides, if it is financially possible to use two sheerlegs with supply vessels, it would be wise to invest in multiple wind turbine installation vessels (such as two WTS vessels). Multiple wind turbine installation vessels combined could be more efficient than using the sheerleg at location and another one in the harbor. The sheerleg installation method is shown below in Figure 67. Due to the usage of two sheerlegs, the installation rate and related numbers need to be doubled in the further comparison.

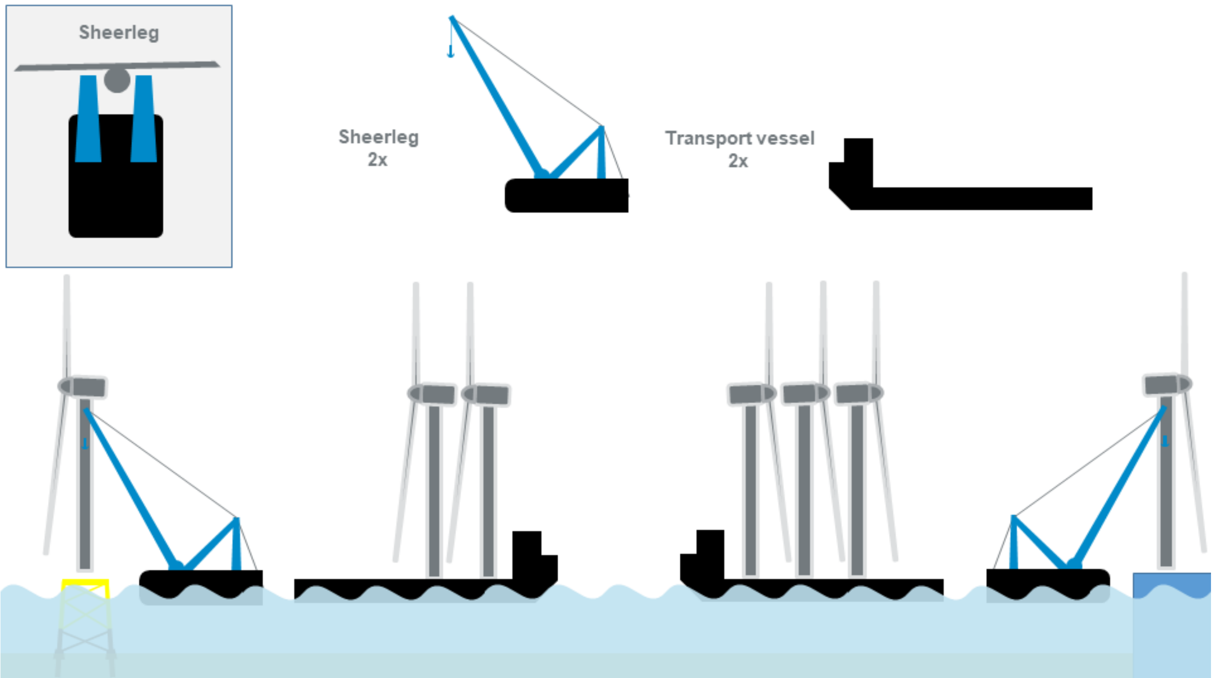


Figure 67 Sheerleg installation method with supply vessels – fleet overview

Windlifter

The Windlifter and OWTIS vessel have in literature a common property with a couple of the proposed concepts. The common property is the transport capacity which is four wind turbines. The technical installation solutions are different. the Windlifter is favorable for the four wind turbine installation vessel since single-lift wind turbine installation would be inconvenient for 20 MW wind turbines (Figure 36). The fleet overview of the Windlifter is shown below in Figure 68.

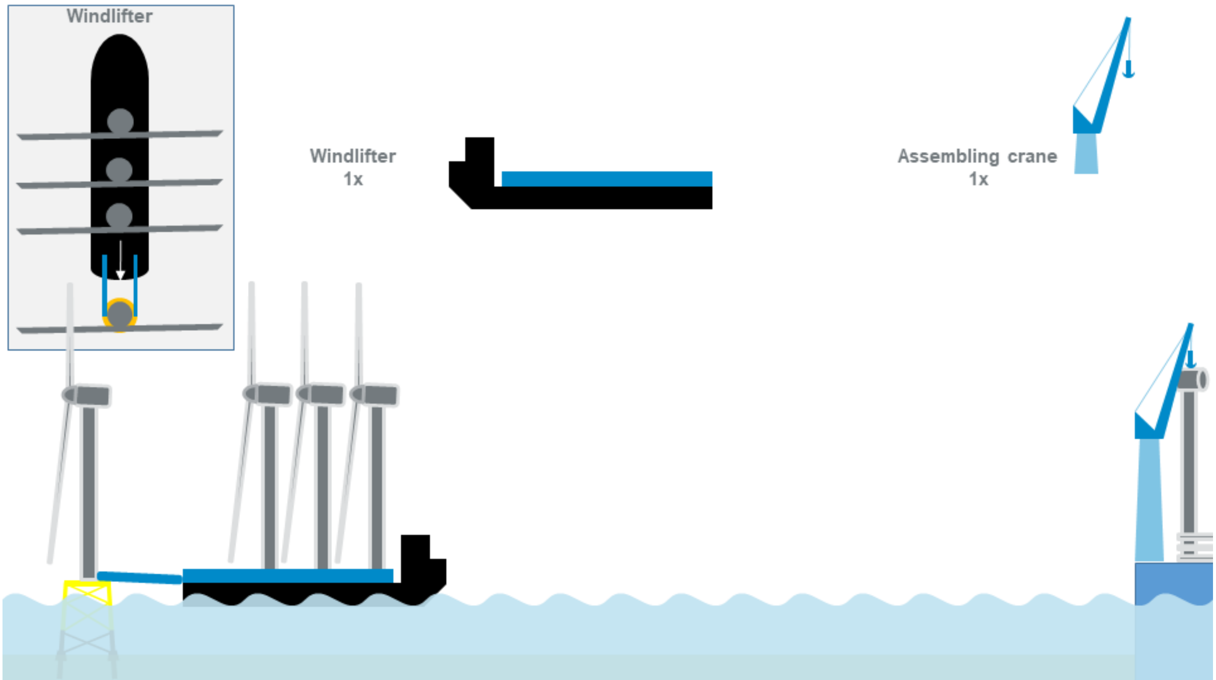


Figure 68 Windlifter installation method – fleet overview

Barge crane

Chapter 5 has introduced the concept for barge exchange. Principle 4, 5 and 6 are thought out to work with this mechanism. 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. Only the jack-up vessel does not directly require an additional crane for assembling components if all the components are delivered in the way the jack-up vessel transports them. The barge exchange loading process is shown in Figure 69.

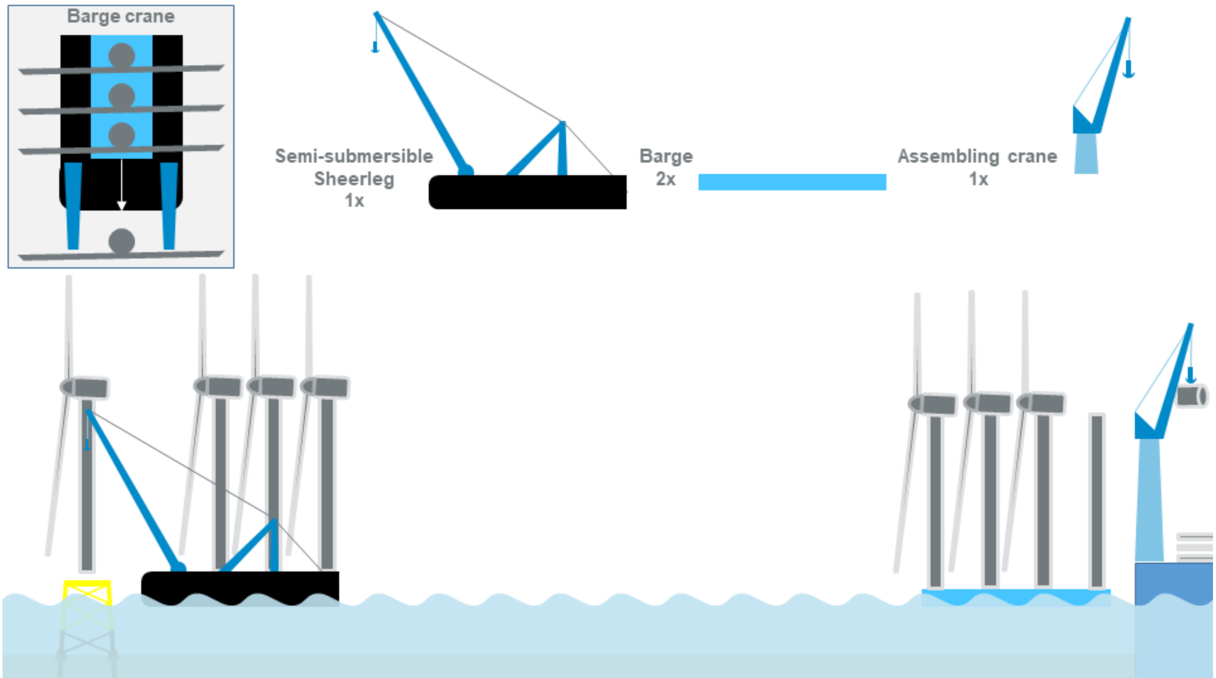


Figure 69 Barge crane installation method – fleet overview

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.

PWT 4 ■ and PWT 8 ■

PWT 4 and PWT 8 concepts are using the technical solution PWT crane configuration (Figure 70). The main difference between these two concepts is the transport capacity. A transport capacity of four wind turbines is assumed 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 due to the technical difference which is used in later analysis. Therefore, the PWT 4 is included in the total comparison. The comparison between these vessels will indicate whether there is a subsequent improvement when upscaling the transport capacity. These two vessels have a similar installation method compared with the Windlifter, no figure is included for these two vessels.

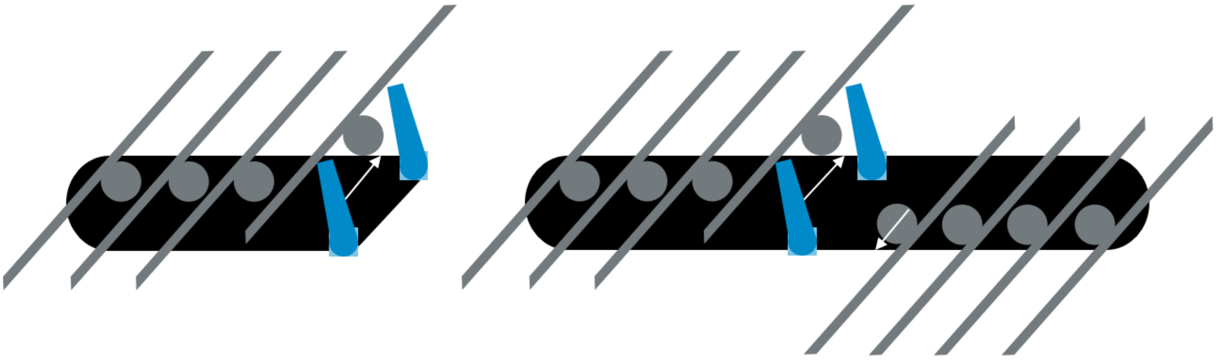


Figure 70 PWT 4 and PWT 8 installation vessels

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. Furthermore, the cranes can work independently with other applications. When slewed 180 degrees over the stern of the vessel they can be used at their maximum lifting capacity. No other crane arrangement is found for a vessel with a small hull without wind turbines moving over the cranes.

It could be possible to use existing jack-up vessels as a crane in the ports to load the barge with wind turbines. The jack-up vessels are used as a stable movable crane vessel which is not dependent on a specific port (which is the case for a quay crane). The PWT installation vessel with barge exchange and jack-up crane vessel is shown in Figure 71 below.

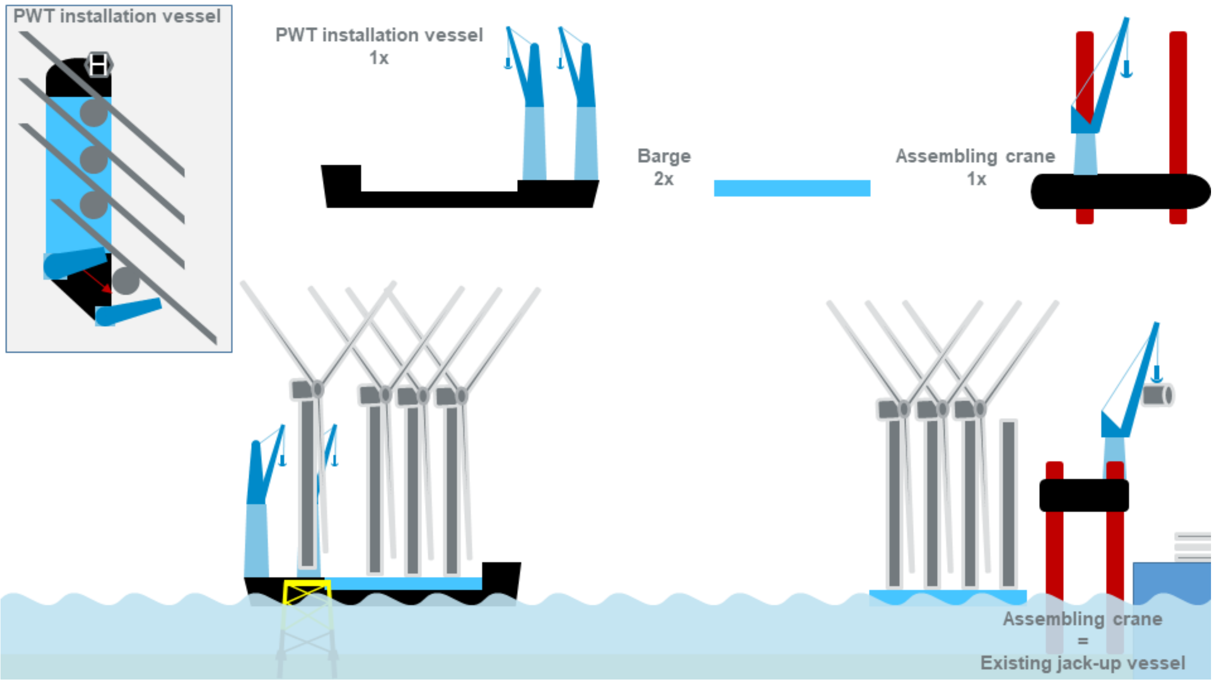


Figure 71 PWT installation vessel with jack-up crane vessel – fleet overview

Data of concepts

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 (Stamoulis, 2020) and a joint interdisciplinary project of Delft University of Technology (Guha, Thomas, Vega, & Zeijl, 2019) both in cooperation with Huisman Equipment Schiedam. Other data of the concepts is estimated based on the foreseen improvements of the different concepts relative to state-of-the-art installation vessels. An example is the (un)loading of the barge crane (Principle 5) in the harbor. A state-of-the-art semi-submersible vessel typically (un)loads within 24 hours. Such a vessel is the earlier discussed BOKA Vanguard (Figure 48 in chapter 5). The estimated data is verified by specialist of Huisman Equipment.

The data for the concepts is split in three activities, the loading, sailing and installation operations. Each activity has a weather factor which is a multiplier for the delay due to non-ideal conditions. This number is closely related to the workability as used in maritime engineering. These two numbers could be inversely proportional with each other, but this is not verified and used in the comparison. The assembling process is not considered in further comparison in relation to the installation rate of the different concepts. Additional processes are needed onshore to facilitate fully assembled wind turbine installation. The onshore assembly helps increasing the installation rate for wind turbine installation.

The data is an estimate and should be compared relatively and not absolutely. The comparison is a relative comparison, it is not important when a number slightly differs with another number in the comparison. More important is the conclusion whether a certain concept is twice as fast as another concept in overall installation time for example. The numbers are absolute with quantities such as time and speed and absolutely described.

	Number of wind turbines	Weather factor	Prepare harbor	Loading of one turbine	Prepare sail out	Weather factor	Vessel speed	Vessel speed	Weather factor	Prepare installation	Installation of one turbine	Prepare sail to other location
Unit	-	-	h	h	h	-	knots	km/h	-	h	h	h
Jack-up	4	1.5	0.5	6	0.5	1.6	11.5	21.3	1.4	2.5	24	2
WTS	2	1.2	0.5	5	0.5	1	14	25.9	2	1	4	1
Sheerleg	0	1.5	0	0	0	2	7	13.0	3	3	6	1
Windlifter	4	1.5	0.5	5	0.5	1.4	14	25.9	2	1	4	1
PWT 4	4	1.5	0.5	8	0.5	1.2	14	25.9	2	1	4	1
Barge crane	4	1.2	12	0	12	1.8	8.5	15.7	2.5	2	6	1
PWT 8	8	1.5	0.5	8	0.5	1.2	14	25.9	2	1	4	1
Barge PWT	4	1.2	12	0	12	1.2	14	25.9	2	1	4	1

Table 14 Logistical comparison data of concepts

The data as formulated for the comparison is shown above in Table 14. The first activity is preparation in the harbor. An example of such an activity is lowering legs for lifting or sinking in the harbor for barge exchange. The following number is the loading of one wind turbine which is an estimation. This number estimates the time for loading one turbine from the quay on the vessel considering (re)positioning of the vessel for the specific wind turbine (applicable on concepts such as WTS and Windlifter). Since the first harbor activity is preparation for loading, also preparation for sailing needs to be considered (such as lifting the legs and raising the hull after barge exchange).

The following activity is sailing which has a weather factor. Besides the weather factor, the vessel speed is considered. The numbers are based on state-of-the-art vessels that show similarities with these concepts while taking into account some future developments in terms of technology.

The final activity is the offshore wind turbine installation. The numbers of the activities preparation for installation, installation of the wind turbine and prepare to sail to another location are all related to one turbine. The sheerleg is assumed to be at location and only picking up wind turbines from other vessels/barges and install them offshore. This type of installation is included to identify whether it is interesting to have a specific crane vessel at location that only installs wind turbines.

Scenario comparison

In this section realistic scenarios are used to make a logistic comparison. For the scenario comparison, three wind turbine parks are identified with each a different distance from marshalling port to their location which are around 100, 200 and 300 kilometers. 300 kilometers seems to be one of the largest distances that need to be travelled to the nearest port (in Europe) in future if certain wind parks are developed. The first wind park is near the shore of The Netherlands and is approximately 100 kilometers away from the nearest marshalling port. The second wind park is located near Denmark and Germany in the Baltic Sea. The distance to travel from the port indicated in Figure 72 (4C Offshore, n.d.a) is approximately 200 kilometers. The final scenario is from the United Kingdom to the Doggersbank, this is approximately 300 kilometers.

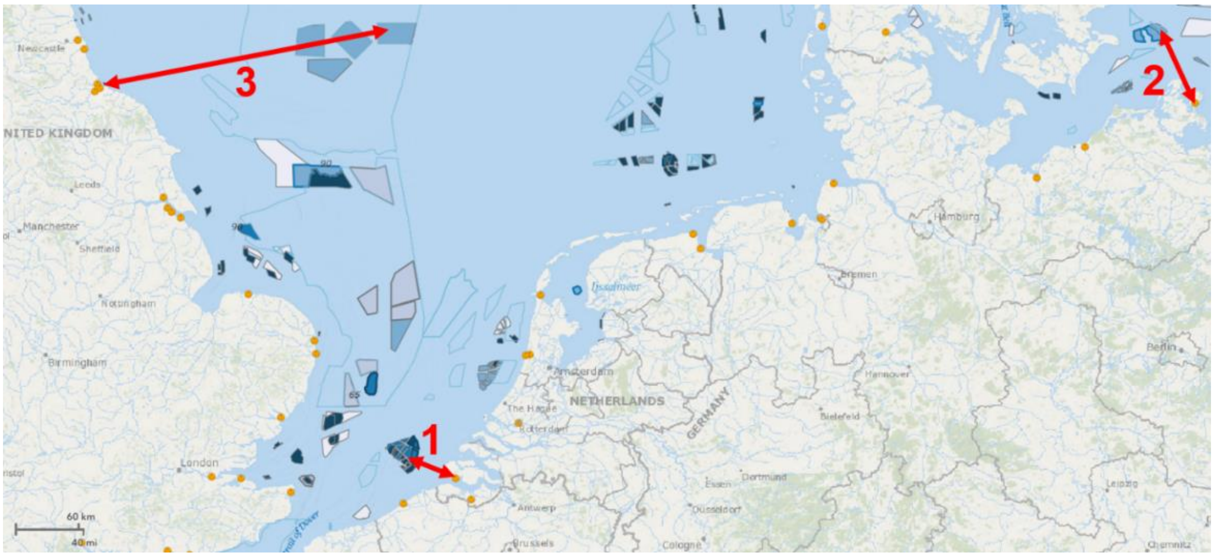


Figure 72 Map of three situations analyzed for logistical comparison (4C Offshore, n.d.a)

For the comparison, it is assumed that all three wind turbine parks have 100 wind turbines of a certain size (for all concepts the same). In the calculation, both distance and number of wind turbines can be changed. The number for comparison is 'day per turbine' which is the average installation time per wind turbine. Since the day per turbine is compared, the number of wind turbines of a wind turbine park would not affect the number of day per turbine except if the vessel is not fully loaded. This is the case once the maximum transport capacity of the vessel is not used during the last transportation of wind turbines.

Investigation

A comparison in logistics is needed to identify subsequent improvement in installation rates based on different solutions for the installation processes. The following factors are investigated for the logistical comparison:

1. Is it interesting to have a separate crane vessel (sheerleg) at the wind park, fed by supply vessels?
2. Which self-loading vessel has the best wind turbine installation efficiency?
3. Is it interesting to load wind turbines with barge exchange?
4. Is the transport capacity important for the installation efficiency?

First scenario

The first analysis is based on the first scenario of 100 wind turbines 100 kilometers from the nearest port. The effect of increasing distance is discussed later. Below, Table 15 shows the results of the analysis of scenario 1.

	Amount travelling	Loading time	Travel time	Retour time	Total time	**Day per turbine**
Unit	-	h	h	h	h	day
Jack-up	25	37.5	15.0	221.1	5528.5	**2.30**
Shuttle (WTS)	50	13.2	7.7	44.9	2245.7	**0.94**
Sheerleg	-	-	30.9	-	1812.0	**1.51**
Windlifter	25	31.5	10.8	94.6	2365.5	**0.99**
PWT 4	25	49.5	9.3	108.6	2715.2	**1.13**
Barge crane	25	28.8	22.9	160.0	3999.1	**1.67**
PWT 8	13	97.5	9.3	204.6	2659.9	**1.11**
Barge PWT	25	87	9.3	87.9	2197.7	**0.92**

Table 15 Logistical comparison Scenario 1 detailed

The amount travelling is calculated by dividing the number of wind turbines of the wind park by the maximum capacity of wind turbines of the vessel. The loading time is calculated by a summation of the time in the harbor multiplied with the weather factor. Travel time is calculated multiplying the weather factor with the vessels speed and distance to travel. The retour time is the summation of the loading and travel time including the time to install all wind turbines transported on the vessel considering the weather factor. The total time is the multiplication of amount of travelling of the vessel with the retour time. All these numbers highly depend on the lay-out of the vessel and a fair value to compare the different concepts is the amount of days it takes to install the wind turbines (day per turbine). This number is calculated by dividing the total time by the number of wind turbines of the park per concept.

A few conclusions can be drawn from this first analysis:

1. First is the fast installation time of the sheerleg although it has a high weather factor and relatively slower installation speed at the wind turbine park. The good installation rate relative to the jack-up vessel is attributable to separate feeding of wind turbines which excludes transport time by the crane vessel itself.
2. Next are the relatively low day per turbine numbers of the Wind Turbine Shuttle, Windlifter and barge PWT. This is related to their relatively short travel time. These vessels are designed for relatively fast travelling, which is positive for the installation rate.
3. Although the barge crane and barge PWT need to exchange its barge in the harbor, they show a loading time comparable with the Windlifter. The loading time of the barge is

independent of the number of wind turbines, the barge exchange idea works from four wind turbines on and is more efficient the more wind turbines can be loaded on the barge.

4. The PWT 8 vessel needs more than one day to install a wind turbine which is related to the relatively high loading time in the harbor. In the first analysis, the PWT 4 and PWT 8 vessels show comparable installation rates. This means that upscaling of the transport capacity is not interesting for scenario 1.

More conclusions can be drawn when the different scenarios are compared. The following section will discuss scenario 1, 2 and 3 in overall properties and not separately in loading, sailing and installation time.

Analysis of three scenarios

The three different scenarios are discussed in this section. The results of the three scenarios which increase distance port to wind park are shown in Table 16.

	Scenario 1		Scenario 2		Scenario 3	
Performance	Total time (h)	**Day per turbine**	Total time (h)	**Day per turbine**	Total time (h)	**Day per turbine**
Jack-up	5528.5	**2.30**	6129.5	**2.55**	6730.5	**2.80**
Shuttle (WTS)	2245.7	**0.94**	2631.4	**1.10**	3017.1	**1.26**
Sheerleg	1812.0	**1.51**	1812.0	**1.51**	1812.0	**1.51**
Windlifter	2365.5	**0.99**	2743.4	**1.14**	3121.4	**1.30**
PWT 4	2715.2	**1.13**	2992.9	**1.25**	3270.6	**1.36**
Barge crane	3999.1	**1.67**	5028.2	**2.10**	6057.3	**2.52**
PWT 8	2659.9	**1.11**	2804.3	**1.17**	2948.7	**1.23**
Barge PWT	2197.7	**0.92**	2475.4	**1.03**	2753.1	**1.15**

Table 16 Logistical comparison all three scenarios

Table 16 shows the data when repeating the calculations of scenario 1 but changing the distance (scenario 2 and 3). All of the discussed concepts in the comparison show improvement over the jack-up solution. The following important observations are identified:

1. The sheerleg is an interesting solution for wind turbine installation. It is independent of distance from port to wind park. The overal 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.
2. 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 these solutions are the installation method and usability of the vessels. This will be discussed in the following section.

3. 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 which is comparable with the Windlifter in Table 15. The loading time is quick compared with the PWT 4 solution. The barge exchange solution is beneficial for the installation performance.
4. The PWT 8 efficiency is increasing over distance and comparable with the barge PWT in case of scenario 3. 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 because every wind turbine needs to be loaded individually.

Relation distance and installation rate

The calculations for installation rates are repeated over distance for the different concepts. The calculations are made from 0 kilometers up to 500 kilometers. Figure 73 shows the results of the variety of distances. The barge PWT has the best installation rate between 60 and 450 kilometers. The WTS is has the best installation rate for short distances. The PWT 8 vessel with eight wind turbines is interesting with increasing distances of over 450 kilometers.

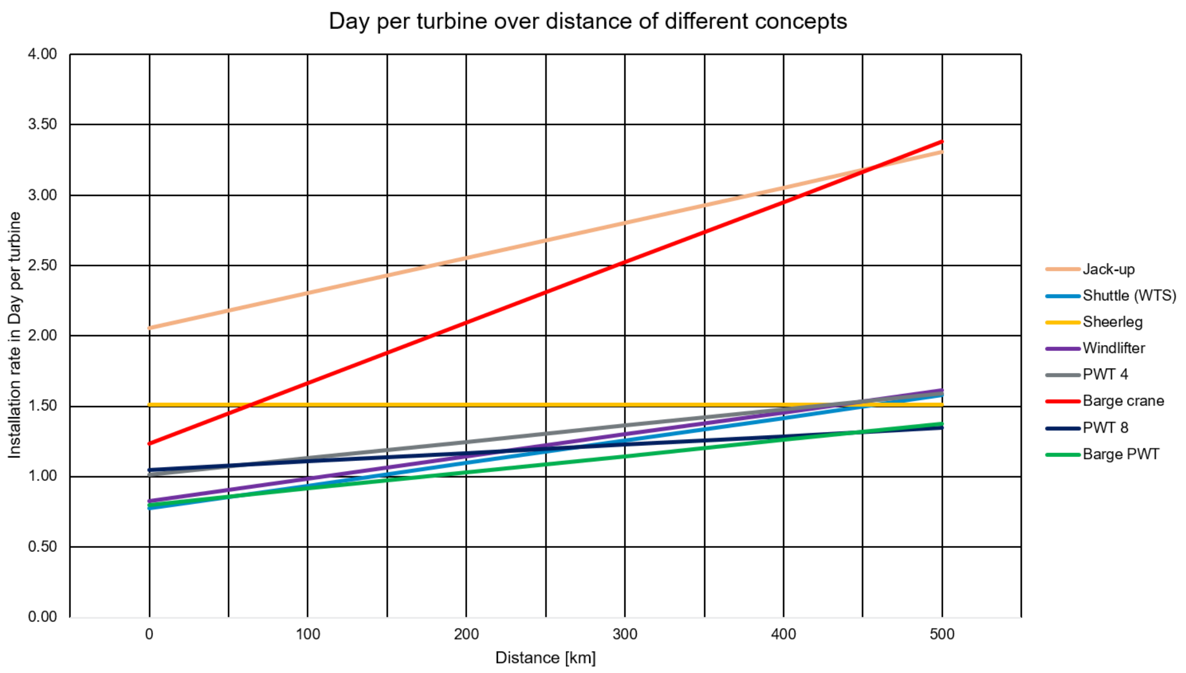


Figure 73 Installation rate (Day per turbine) over distance for all concepts

The concept Barge PWT modifications travel relatively fast and can compete with the WTS in scenario 1 and is the second-best solution for scenario 3. Comparing this relatively, the concept has probably the same installation rate as the WTS and is at logistic level a concept that comes close to the installation rate of the PWT 8 concept when the wind turbine parks are located far away from a marshalling port. However, this is not the case for the wind turbine park map of Europe (Figure 4) since scenario 3 (300 kilometers offshore) is one of the longest distances to travel from port to wind turbine park. Within the boundaries of this research, the PWT 8 concept is not feasible although other areas with large distances could be interesting for PWT 8 usage.

Figure 74 indicates that the results between the two best solutions over distance does not differ more than approximately 10% of a day which is between two and two and a half hours per wind turbine. However, the comparison is relative and the conclusion from Figure 73 is that installation rate/distance (slope) has a better ratio for the barge PWT than for the WTS.

Figure 74 Installation rate (Day per turbine) over distance for promising concepts

Detailed comparison

Two important factors are introduced for the detailed comparison of the promising solutions namely the scalability and flexibility. The concept Barge PWT is the most promising solutions using PWT crane configuration. No further comparison will be made with other PWT solutions. Therefore, Barge PWT is named PWT installation vessel or Parallelogram Wind Turbine installation vessel. The wind turbine shuttle is second best performing and included in the detailed comparison. The Windlifter has a comparable installation rate over distance relation with the wind turbine shuttle although a less efficient installation rate. Besides, the Windlifter has a limited application range (only wind turbines) over the wind turbine shuttle. This concept is not further discussed in this chapter, due to the limited application range and relatively lower installation performance of the vessel.

Scalability

There are a couple of differences between the wind turbine shuttle and PWT installation vessel. One of them is the scalability. The wind turbine shuttle has a given transport capacity, namely two wind turbines. This transport capacity is independent of the size of the wind turbines (Figure 75). Furthermore, the installation construction is probably made for a certain size of wind turbines (due to the overhang of the nacelle of the wind turbine). This construction can probably be adjusted to be able to install a wide variety of wind turbine sizes.

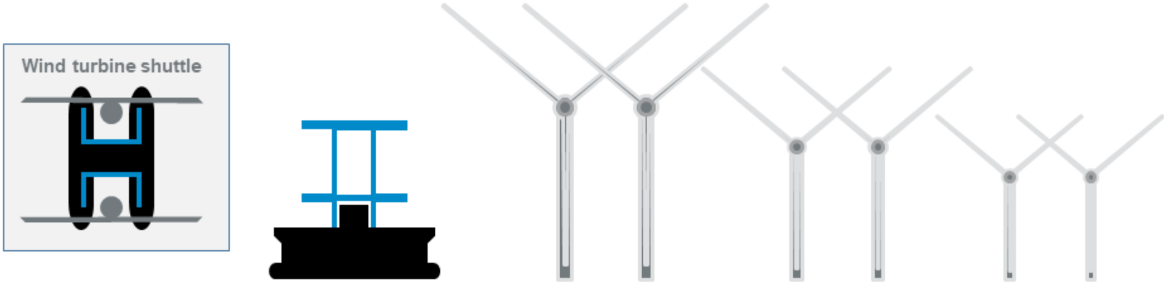


Figure 75 Wind turbine shuttle transport capacity in relation to wind turbine size

On the contrary, the transport capacity of the PWT installation vessel is dependent on the deck area of the barge. A transport capacity of four wind turbines has been taken for the largest wind turbines which the PWT installation vessel can install. If the wind turbines become smaller, more wind turbines can be transported due to a smaller deck area per wind turbine requirement (Figure 76). This results in a growing transport capacity for smaller wind turbines. The barge exchange in the harbor is independent of the amount of wind turbines which results in a better installation rate as the wind turbine become smaller. In the case of the PWT installation vessel and other barge exchange concepts, the installation rate is influenced directly by the size of wind turbines due to increase in transport capacity. Furthermore, the PWT crane configuration results in no lifting over the cranes of wind turbines. This makes it possible to install all wind turbine sizes up to the maximum installation capacity of the PWT installation vessel. In other words, a PWT installation vessel can install the smallest wind turbines up to the largest designed wind turbine size.

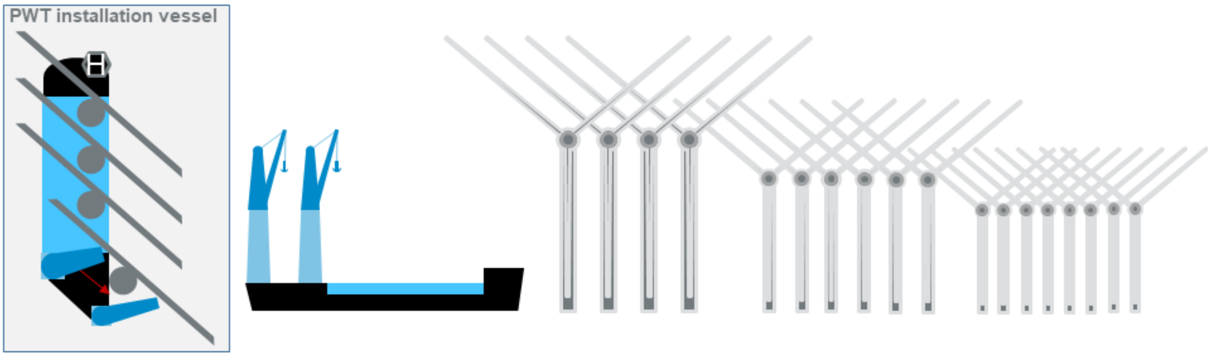


Figure 76 PWT installation vessel transport capacity in relation to wind turbine size

Above all, the PWT installation vessel can be used with one crane at the beginning of its usage. Once the wind turbine are too large for one crane, the second crane can be installed for twin-lift wind turbine installation. This is another definition of the scalability of the PWT installation vessel.

Flexibility

The wind turbine shuttle is only usable for constructions which have similarities with wind turbines. The wind turbine shuttle can probably also be used for monopile installation and jacket installation (Figure 77). However, the size of the jackets is dependent on the size of the U-shaped hull. The jacket needs to fit between the hull. The wind turbine shuttle is not usable for offshore substation installation and additional crane vessels are required to perform such activity.

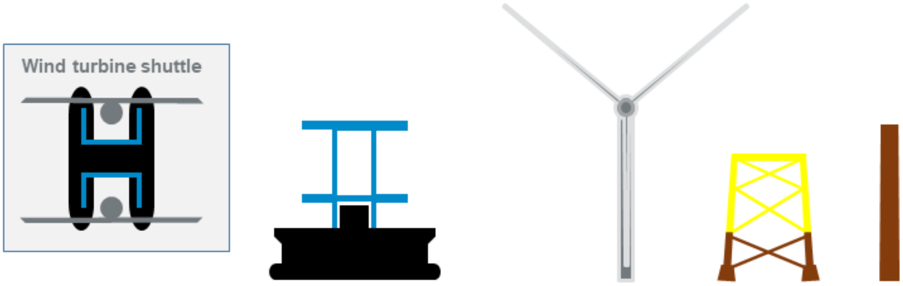


Figure 77 Applications Wind turbine park of wind turbine shuttle

The PWT installation vessel uses cranes for wind turbine installation due to the proven flexibility of cranes in general. The PWT installation vessel also uses the barge exchange for loading of wind turbines in the harbor. The combination of these two solutions results in a flexible vessel. The crane configuration makes it possible to install a variety of wind turbine sizes. The vessel can also be used for monopile and jacket installation. Smaller installation can be performed using only one crane. It is also possible to install the heavy offshore substations (OSS) with the PWT installation vessel (Figure 78). The OSS can be transported on the barge and once at location, the barge is unloaded from the vessel and located at the stern of the vessel. The two cranes on the PWT installation vessel can install the OSS in a similar way as a sheerleg (Figure 53), but in a more efficient way due to the slender hull design and large transport capacity. In conclusion, the PWT installation vessel can be used for all the lift installation processes in wind turbine park development: wind turbines, foundations and OSS.

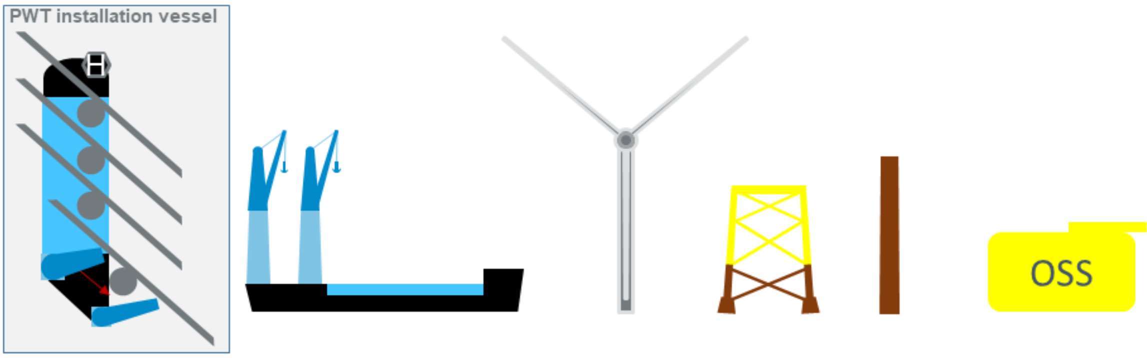


Figure 78 Applications Wind turbine park of PWT installation vessel

The barge and PWT crane configuration makes it also possible to use the PWT installation vessel for other markets. It is possible to decommision oil platforms with the PWT installation vessel to clear the sea for wind turbine instalaltion. The oil platforms show similarities with the OSS installation. Still, only one large vessel is needed for decommisioning due to the transport capabilities of the PWT installation vessel. Another application is cable laying, which could be applied for wind turbine park development. If this is possible, only one PWT installation vessel is needed to install the wind turbines, foundations, OSS and cables for the wind park.

Criteria

The PWT installation vessel with barge exchange is very compact and efficient for sailing. The configuration of the vessel makes it possible to enter many different ports. The operational window of sailing is good due to the slender hull design. However, the operational window and stability of the vessel depends on the motion compensation during wind turbine installation due to the location of the cranes. On the other hand, the location of the cranes for wind turbine installation is interesting for the scalability and flexibility of the vessel. The PWT installation vessel reduces the installation time of wind turbine parks due to the barge exchange mechanism. The barge exchange minimizes lifting of fully assembled wind turbines. Furthermore, the barge exchange mechanism is a flexible system which can be used as a temporary quay in ports which lowers port requirements. The state-of-the-art equipment are semi-submersible vessel, barges and cranes which are already in use in current offshore industry. The combination and configuration of these main components are novel which makes the vessel most advanced, yet acceptable.

Upscaling of PWT installation vessel usage

Larger wind turbine sizes require larger ports. It is possible for a PWT installation vessel to efficiently install wind turbine parks far away from the assembling port (Figure 79). If the harbor of Rotterdam is used for wind turbine assembly, the wind turbines on the barges could be transport by semi-submersible vessels hundreds of kilometers away. It is possible to use the barge exchange in a Norwegian fjord for example to unload the semi-submersible vessels with wind turbines without assistance of cranes or other large vessels. The PWT installation vessel is able to pick up the wind turbines in the fjord, which is located near the wind turbine park. In this way, the PWT installation vessel is used more efficiently when the distance from assembling port to the wind turbine parks is increasing. This is not possible with other concepts, due to the barge exchange mechanism.

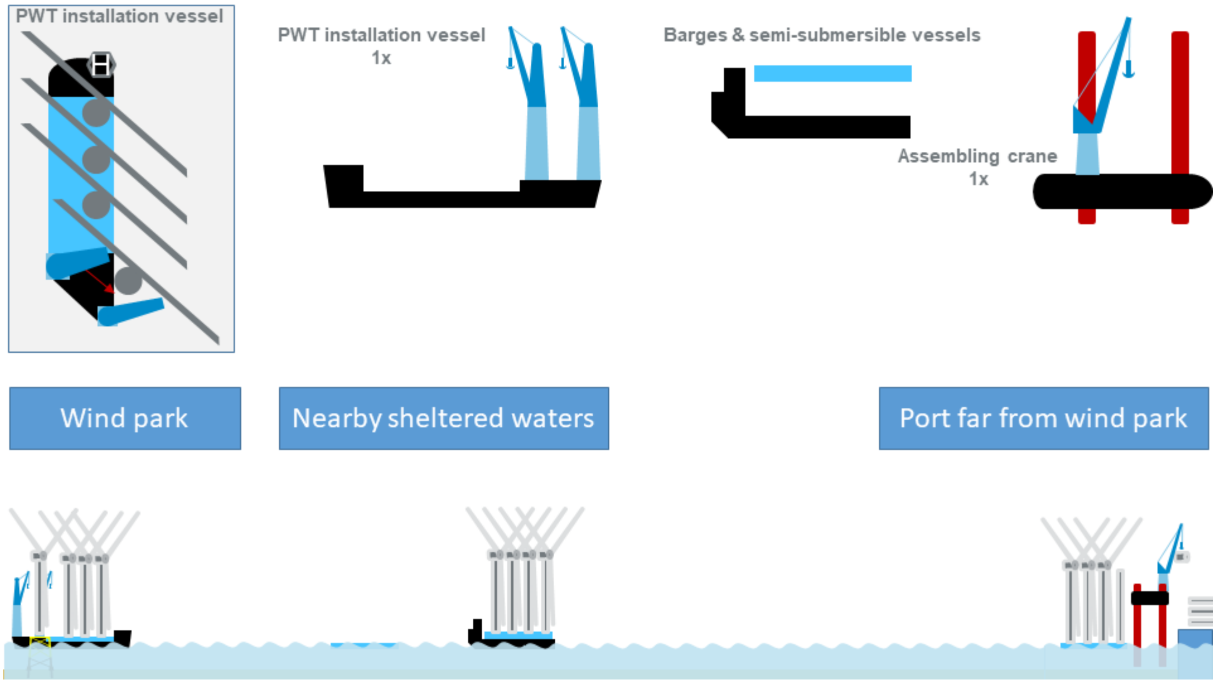


Figure 79 PWT installation vessel large distance installation – fleet overview

The feeding process can also benefits other markets. A construction can be manufactured in Asia and transported by another vessel with barge exchange. The manufacturing process can take place directly on the barge, no additional movements or liftings are needed to transport the construction. Once near the final location, the PWT installation vessel can exchange the barge with the supply vessel. In this way, the PWT installation vessel focusses on the task installation and not transportation. However, the vessel is still able to perform the task without additional vessels.

Conclusion

Different concepts have been discussed and proposed for wind turbine installation based on a couple of principles. The important operations are assembling, loading, transportation (capacity), sailing and installation. The assembling operation is for all concepts the same apart from the jack-up vessel. The installation technique is depending on the technical solution for wind turbine installation and is not considered for first analysis (scenario comparison).

Assembling, loading, transportation, sailing and installation solutions are used for the morphological analysis. Seven of the fourteen earlier discussed concepts/Principles are selected for further comparison based on the analysis. Furthermore, a new concept has been proposed, the Barge PWT, which is based on Principle 4 and 7. The barge exchange concepts make it possible to assemble wind turbine on the barge which can be seen as a temporary quay.

Since most of the concepts are not designed for 20 MW wind turbines and amount of public information is limited, it is chosen to estimate all the data for the concepts. The data for the jack-up vessel and WTS (wind turbine shuttle) are estimated on specific sources. These formed the base for the other concepts. 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.

Three different scenarios are proposed for wind turbine installation. These scenarios differ in distance from port to wind park (100 up to 300 kilometers) while the amount of wind turbines is kept the same. Scenario 1 (100 kilometers distance) shows that the sheerleg is an interesting solution for wind turbine installation. This solution represents a crane vessel on location fed by supply vessels. This is not a complete fair comparison, since another additional crane vessel (sheerleg) is needed in the port to load the supply vessels. The overall overview of the sheerleg fleet led to the introduction of a penalty of two for the installation rate for the sheerleg, since at least two sheerlegs are needed. Furthermore, a small hull is efficient for sailing and the barge exchange mechanism is interesting to reduce the loading time in the port. Transport capacity is not subsequent improving if the distance increases.

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. A more detailed analysis of the increasing distance revealed that the new concept has a good installation rate regarding to typical wind park distances. 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. An additional advantage of the barge exchange is the possibility to use existing jack-up vessels for wind turbine assembly on the barge in the harbor.

8. PWT installation vessel in detail

The base of the concept is using a barge with four wind turbines that can be exchanged in sheltered waters. Multiple details introduced in the previous chapters can be developed for the PWT installation vessel. This chapter completes answering sub question 6 by providing a detailed model of the PWT installation vessel.

6. *Which overall concept show potential to be used in future wind turbine installation industry in terms of flexibility and scalability and in which way does it fulfill the need for the wind turbine installation industry?*

Chapter outline

This chapter introduces a 3D model of the PWT installation vessel. First, the PWT installation vessel is explained in more detail including the special diagonal stern. Following is the evaluation of the crane type which needs to be used for the PWT installation vessel with barge exchange. Another important part of the 3D model is the explanation of the barge exchange in detail with a couple of design notations such as stability of the barge once in the port. After loading and sailing, installation needs to be considered in detail. A preliminary design of the spreader is proposed for efficient installation of large wind turbines. The detailed 3D model makes it possible to show the applications in wind industry and other markets. In this section, the foreseen applications and opportunities of the PWT installation vessel are explained. Finally, a conversion is proposed of an existing vessel into a PWT installation vessel of which a 3D model is made.

Base of model

The reference wind turbine size for the concept is 20 MW. Besides state-of-the-art concepts show potential for 15 MW but 20 MW seems further away. Due to the scalable property of the concept it can also be scaled down to a maximum of 15 MW or another type of wind turbine size. Furthermore the vessel should use the cranes diagonally positioned at the stern of the vessel enabling installation of wind turbines via the PWT configuration. Rotating the cranes 180 degrees enables the vessel to perform heavier lifts over the stern of the vessel. Preferably is the ability to sail from the North Sea to the Baltic Sea to change installation location. Therefore the vessel should have a relatively high floating area with low own weight to pass the Drogden tunnel. Another option is a limited overall height of the vessel to sail through the Storebælt. Finally, the vessel itself should not have a large beam, to be able to have a relatively high sailing speed and the main application should be wind turbine installation.

More detailed boundaries can be formulated based on the comparison made. The concept should be flexible and scalable and fulfill the criteria introduced in chapter 3. However for the design, a maximum size of wind turbines is assumed for further analysis in chapter 8 to be able to use real numbers instead of scaling properties. Wind turbines are growing in the coming years and no solutions was found yet specifically for 20 MW wind turbine installation in fully assembled configuration. Therefore it is chosen to propose a concept related to the maximum size wind turbines of 20 MW. When in the future wind turbine growth stops at a certain size of wind turbines, it will be still possible to scale the concept smaller or larger up to the specific wind turbine size.

Requirements

From chapter 7, the following main requirements for the concept can be concluded:

1. Main goal is installation of wind turbines up to 20 MW in size
2. Use a semi-submersible vessel as a platform for the installation vessel to transport at least 4 wind turbines of 20 MW on a barge which can be exchanged in sheltered water conditions
3. Reduce width of vessel to optimize sailing which is possible due to PWT crane configuration

An overview of applications are schematically drawn in Figure 80. The figure shows how the base of the vessel and the applications could look like. The base of the vessel 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 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.

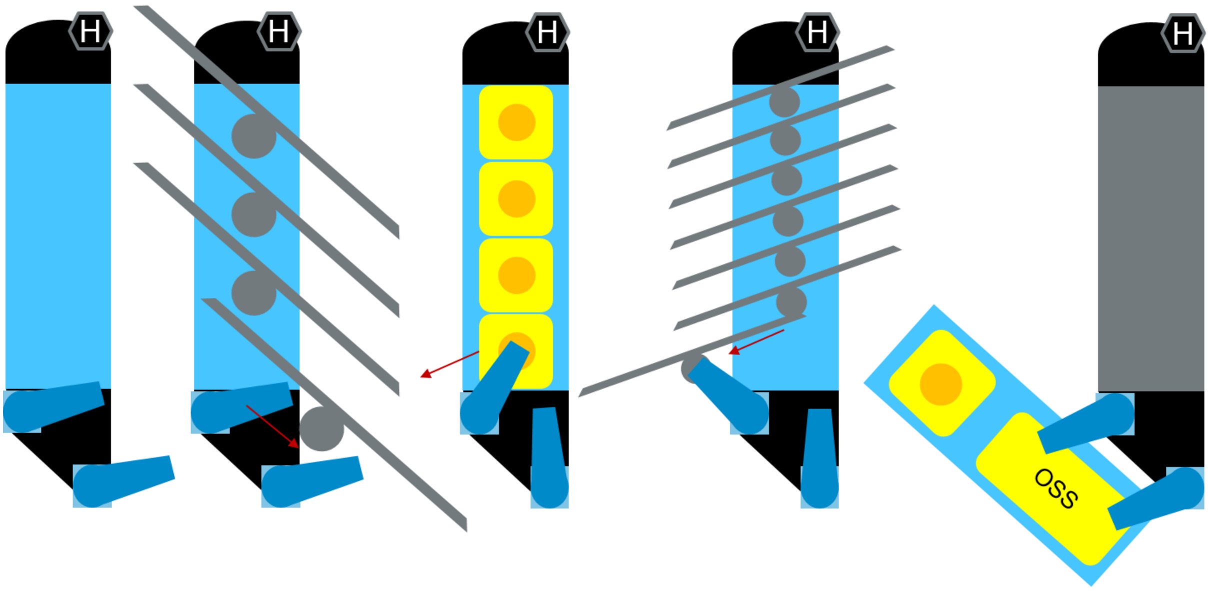


Figure 80 Schematic drawing of PWT installation vessel base and diverse applications

Diagonal stern

The diagonal stern for the cranes is part of the PWT installation vessel. As shown in Figure 80, the heavy lift application (such as offshore substation installation) is performed by side/stern lifting. The diagonal stern is part of this application. Since relatively fast sailing is part of the concept, the stern should not influence the vessels ability to sail quickly. The diagonal stern is ideally asymmetric above the waterline of the vessel during transit from one location to another. Other applications of such a stern are car carriers and the oblique icebreaker. The car carrier has an asymmetric stern for the loading ramp which is positioned under an angle to be able to dock the vessel sideways while the cars are (un)loaded via the stern. Another application is the oblique icebreaker. This vessel has an asymmetric stern (and hull) to make a wide channel through the ice by sailing backwards diagonally shown in Figure 81 (Schuler, 2016). The icebreaking application could also be applied on the concept if it is part of the applications of the vessel. The stern of the vessel could be used to access wind turbine foundations for wind turbine installation if applicable. This could be interesting since in Figure 4 is mentioned that in the northern part of the Baltic Sea, wind turbine installation need to be performed in the Gulf of Bothnia.

Figure 81 Oblique Icebreaker Baltika with asymmetric stern (Schuler, 2016)

Benefits of barge exchange

The benefits of using a barge for loading the wind turbines in the marshalling port is not limited to the exchange time in the port. Since the loading per turbine time is approximately one day, the vessel should exchange the barge every couple of days in the marshalling ports. Crew changes can be scheduled at the same time together with the barge exchange which means that crew changes do not necessarily need to be performed using a helicopter. Furthermore, fresh food supply can be performed at the same time, limiting the usage of long-life products. The fuel (such as LNG or electricity) for the vessel could be stored in the barge itself. This means that fueling activities do not have to be performed at the same time as the barge exchange process.

At least two barges are needed for the beneficial usage of the barge exchange mechanism. One barge is located on the vessel during the wind turbine installation activities while the second is loaded with wind turbines. The second barge does not have to be loaded necessarily by a new crane. If the operating company invests in multiple barges, sea fastening activities for coming projects (such as smaller wind turbine or foundation installations) can be prepared while the vessel is working on its current activity. When the vessel has completed its activity, it sails back to the port and exchanges the barge with the other one for the next projects. This investment of another barge results in better usage of the vessel. Normally sea fastening can take up a lot of time (weeks) since a regular vessel needs to be converted in the port while the weather conditions could be excellent offshore. The barge exchange makes it possible to perform such sea fastening activities parallel to the usage of the vessel itself.

3D model

For the formulation of the concept and to verify and explain diverse choices for equipment, the vessel is drawn in 3D. The model is made in Rhinoceros using publically available data to scale the size of the wind turbines with the cranes and other components. Different 3D models have been made such as a 20 MW wind turbine, a 20 MW jacket and a 10 MW wind turbine. Also different cranes are made in the model to choose the right ones. Note that the large wind turbines require the largest state-of-the-art offshore cranes or even bigger. The level of detail is sufficient to indicate main properties of a wind turbine, jacket or type of crane but are not usable for a one to one conversion into a detailed model which can be used for manufacturing of the components. The idea behind building the 3D model with the wind turbine, jacket and cranes is to identify and solve 3D problems. Furthermore it gives an overview of the final concept. Started is with building a base for the vessel consisting out of a semi-submersible hull with bridge and helideck and four 20 MW wind turbines placed on a barge. The base of the concept is shown in Figure 82. The width of the model is 50 meters which was found feasible during the cardboard ideation of PWT installation scaled with 20 MW wind turbines Figure 57.

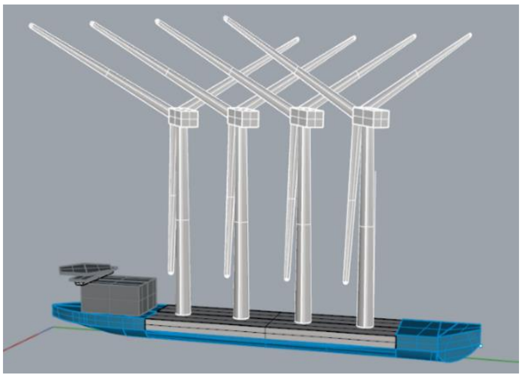


Figure 82 Lay-out of vessel with barge and four 20 MW wind turbines

Crane type

Installation of the wind turbines is performed by PWT installation (or in PWT configuration). As mentioned in chapter 2 in Table 10, the required lifting capacity for a 20 MW wind turbine is at least 3,510 tons. Including a spreader and other lifting equipment, it should be sufficient to assume a minimum twin-lift capacity of the cranes of up to 4,000 tons, which can still be scaled down if needed in the future due to lower weights. Table 5 and Table 9 indicate that if a jacket is used with a 20 MW wind turbine, the minimum lifting height above waterline is 20 meters of the jacket combined with 119 meters of the wind turbine. To make sure that there is sufficient height, 150 meters is assumed before for the required lifting height. Thus each crane should have a hook height of over 150 meters above waterline and lifting capacity of 2,000 ton at this height.

Different types of cranes for the offshore industry exist and have proven to be successful on different vessels. The PWT installation vessel needs a crane with a relatively large hook height and a minimum capacity of 2,000 tons each for the wind turbines. Larger capacity is probably needed for offshore substations. The required lifting capacity for the wind turbine installation can be used with the main hoist of the crane or via the auxiliary hoist. Both hoist arrangements are explained in the following subsections. Huisman offers different large cranes for offshore industry. Due to the large hook height, the largest offshore cranes are need for the PWT installation vessel. Since Huisman has provided different cranes in this segment, cranes from the portfolio of Huisman are discussed for the PWT installation vessel.

Offshore Mast Crane

The first type of crane that shows potential for the PWT installation vessel is an offshore mast crane (OMC) (Huisman, n.d.c). The Huisman OMC has enough lifting capacity and a relatively small footprint. This type of crane has the possibility to be equipped with a high pedestal, enabling the bearing for slewing of the crane to be placed relatively high to gain height for wind turbine installation. An example of such a crane is the crane for Jumbo's Stella Energy equipped with two Huisman cranes (Offshore Energy, 2018). The pedestal is the part of the crane that connects the slewing part with the vessel structure. The mast is the section that is put on top of the pedestal to upend the boom. The boom is connected to the pedestal and can rotate on the bearing on top of the pedestal. The largest crane of the Stellar Energy of Jumbo has a capacity of 2,200 tons, shown in Figure 83 (Ulstein, 2017).

Figure 83 Jumbo Stella Energy with offshore mast crane (Ulstein, 2017)

The benefits of using an offshore mast crane are shown in Figure 84. The cranes are relatively compact on the deck and do not require much space. Furthermore, the boom clearance is relatively large and this specific type of crane has the ability to upend the boom to the mast of the crane during sailing. However, the cranes do make the vessel relatively high. The height above waterline of the pedestal with mast is over 100 meters excluding the boom. The height limits bridge passing. Furthermore, a large pedestal needs to be made to support the crane itself. This pedestal is over 50 meters high to create sufficient lifting height.

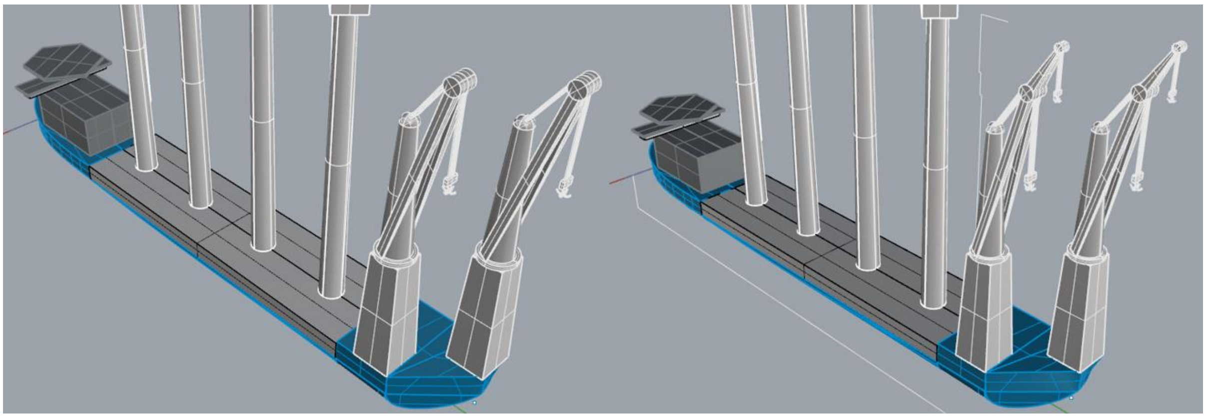


Figure 84 3D visualization of vessel with offshore mast crane main hoist and auxiliary hoist

Tub Mounted Crane

Another type of crane which can be used to create relatively large lifting heights with large capacity is the tub mounted crane. This crane is used on large vessels such as the Sleipnir of Heerema. The Sleipnir has a large lifting capacity of over 10,000 tons which is not necessarily needed for this concept (Heerema, n.d.). The requirement for this concept is lifting height with a minimum lifting capacity of 2,000 tons for wind turbine installation which is also feasible with this type of crane.

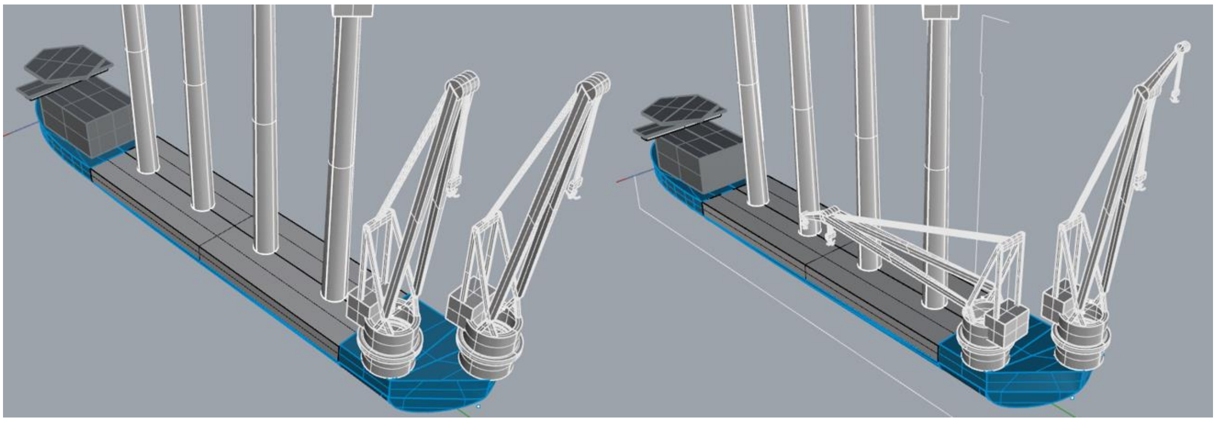


Figure 85 3D visualization of vessel with tub mounted crane main hoist and auxiliary hoist

The tub mounted crane is shown in Figure 85 with the same lifting heights as for the offshore mast crane. In other words, the crane structure is different in Figure 84 and Figure 85, but the hooks are kept at the same heights. The benefit of the tub mounted crane is the ability to lower the overall vessel height during sailing for bridge passing. The tub mounted crane is also suited for the heavy lifting for the offshore substations. As indicated in Figure 85, the tub mounted crane needs a boom rest during sailing. This boom rest combined with a larger required deck area for mounting the crane on the vessel means less flexibility for the vessel.

Crane choice

The requirement for the PWT installation vessel is a flexible and scalable solution. The versatility of the semi-submersible vessel is depending on the effective usage of the barge exchange concept. Wind turbine installation can be a seasonal activity due to weather conditions which means that the concept could benefit from other application of the vessel during other seasons. The relatively small deck area used by an OMC, larger boom clearance (shown in Figure 86) and boom rest in upright position are chosen to outweigh the benefit of the TMC for bridge passing due to limited transit height. The 20 MW wind turbines are relatively large and cannot pass bridges once fully assembled. The benefit of bridge passing is only beneficial when changing project location, enabling the vessel to have a larger working area. Since project change can be performed without loaded wind turbines, the draft of the vessel should be relatively small. The passing between the North Sea and Baltic Sea can also be performed with shallow draft which was discussed earlier. Furthermore, the TMC makes it difficult to exchange barges in the ports due to required boom rests. This can influence the barge exchange time which is the benefit of the PWT installation vessel.

The used 3D models are based on the OMC and TMC cranes already installed by Huisman in the past on the Seven Borealis and Pioneering Spirit respectively. The boom of the TMC crane was stretched to compare it with the OMC crane on the high pedestal. Existing cranes of these two types are relatively large compared with current standards, but still are probably too small for the 20 MW wind turbine installation. This is indicated by the CoG symbol in Figure 86. The main hoist of these cranes typically consist of many wires and sleeves while the auxiliary hoist has less of those due to the lower hoisting capacity. To make the vessel as compact as possible, it is proposed to hoist the wind turbines with the auxiliary hoist while the main hoist can be used for the offshore substation installations (or other heavy lifts). This means that the cranes need to lift a minimum of 2,000 tons above 150 meters of hook height relative to the waterline with still enough cable length to compensate for the motions due to waves and lifting.

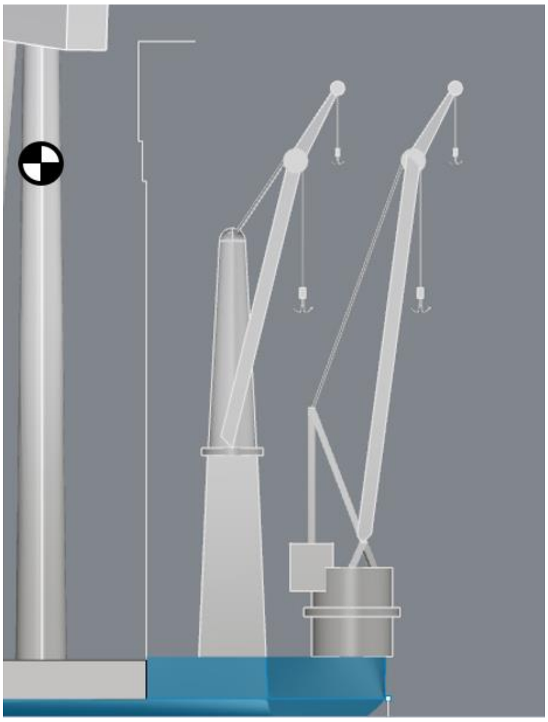


Figure 86 Boom clearance of HMC and TMC crane

Barge exchange

For the barge exchange mechanism, some details need to be worked out. First of all is the size of the barge related to the size of wind turbines. The barge should be initial stable when loaded with wind turbines in sheltered waters. Besides, the barge should be sea fastened on the vessel and the wind turbines should be sea fastened on the barge itself. The details about the barge are explained in this section.

Barge size

The jacket size for the 20 MW wind turbines are important for the length of the barge since they are approximately 40 meters in square (Chaviaropoulis, et al., 2017). If the length of the barge is appropriate with the 40 meters per jacket, less deck area is lost. An example is a barge of 150 meters long which cannot transport four jackets but three. The extra ten meters in length provide much more efficiency for the 20 MW jackets. Since the width at mudline of the jackets is approximately 40 meters without appurtenances taking into account, the barge size per jacket should be over 40 meters (Chaviaropoulis, et al., 2017).

The length of the barge is not only determined by the size of the jackets but the space the wind turbine fills three-dimensional since the rotor and nacelle do consume space apart from the slender tower. In the 3D model (Figure 87), four wind turbines of 20 MW or four jackets of 20 MW will fit in length and width on a barge of 200 meters long and at least 50 meters wide.

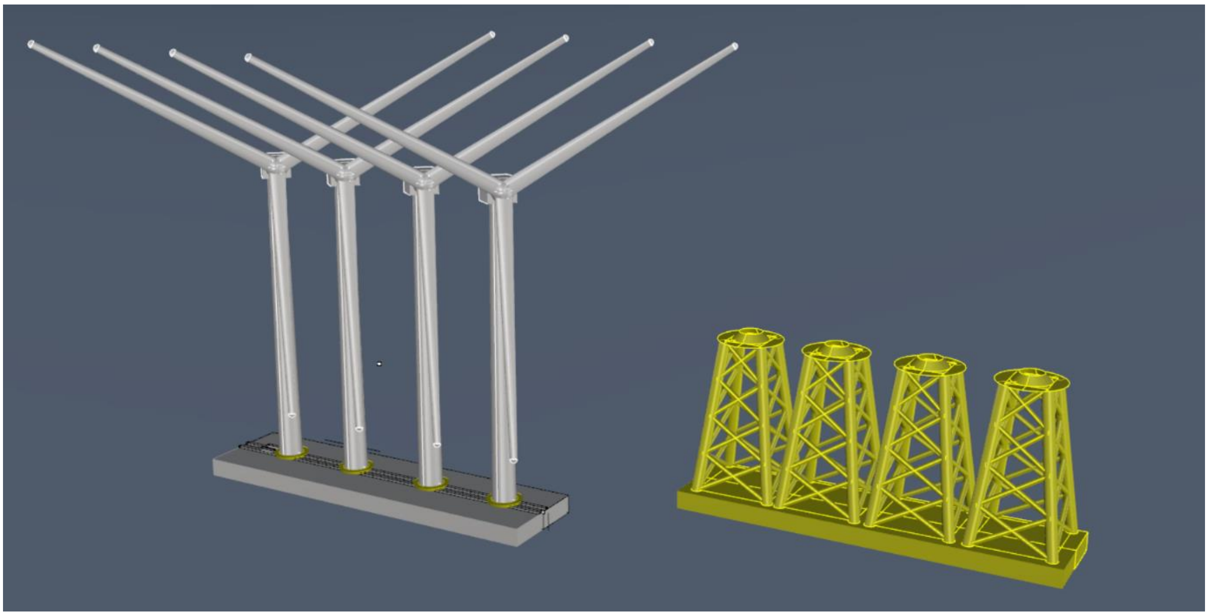


Figure 87 3D model of barge (200x50x10 meters) with four 20 MW wind turbines and four 20 MW jackets

Stability calculation

The width of the barge determines the stability of the barge once floated in sheltered waters such as an marshalling port. The relatively high CoG of the wind turbines create a relatively high total CoG of wind turbines combined with the barge.

A stabilization calculation is required to estimate the width of the barge. This width is important to let the barge float by itself in the harbor before loading on the PWT installation vessel. The assumed initial properties of the barge were 200x50x10 meters. A width of 50 meters proved to be insufficient for static stability of the barge. The width is adjusted to 60 meters which resulted in sufficient static stability. The weight of the barge was needed for this estimation and is estimated based on 200x60x10 meters initial size. The height of the CoG of 20 MW wind turbines was estimated on 119 meters discussed in Table 9. Since this CoG is an estimation, stabilization calculation are performed with 130 meters height. This is a conservative approach to make sure that the barge is stable. The assumed properties are summarized below in Table 17.

Properties		
Height	10	m
Width	60	m
Length	200	m
Structural weight including ballast	20,000	tons
Amount	4	-
Weight including sea fastening	4,000	tons
CoG relative to deck of barge	130	m
Water density (ρ)	1.025	t/m^3
Gravitational acceleration (g)	9.81	m/s^2

Table 17 Initial properties of barge for PWT installation vessel

Other properties are calculated and shown in Table 18 such as the total weight and draft of the barge. These properties need to be known to calculate the GM of the barge. The GM is the metacentric height of a floating body which can be related to static stability of a floating body.

Properties		
Total weight	36000	ton
Water area	12000	m^2
Initial draft	2.9	m
Volume under water ($V_{under\ water}$)	35122	m^3
$I_{surface}$	3600000	m^4

Table 18 Calculated properties of barge for PWT installation vessel

Different stability properties can be calculated based on the estimated properties in Table 17 and Table 18. These stability properties are named the initial stability properties. The initial stability properties can be calculated using the metacenter (M), center of gravity (G), center of buoyancy (B) and keel (K) which are shown in Figure 88. The GM is an important number for initial stability. The floating body is stable if the GM is above 0 without considering dynamics such as waves and wind.

$$KM = KB + BM$$

$$BM = \frac{I_{surface}}{V_{under\ water}} \quad with\ I_{surface} = \frac{1}{12} * b * h^3$$

$$GM = KM - KG$$

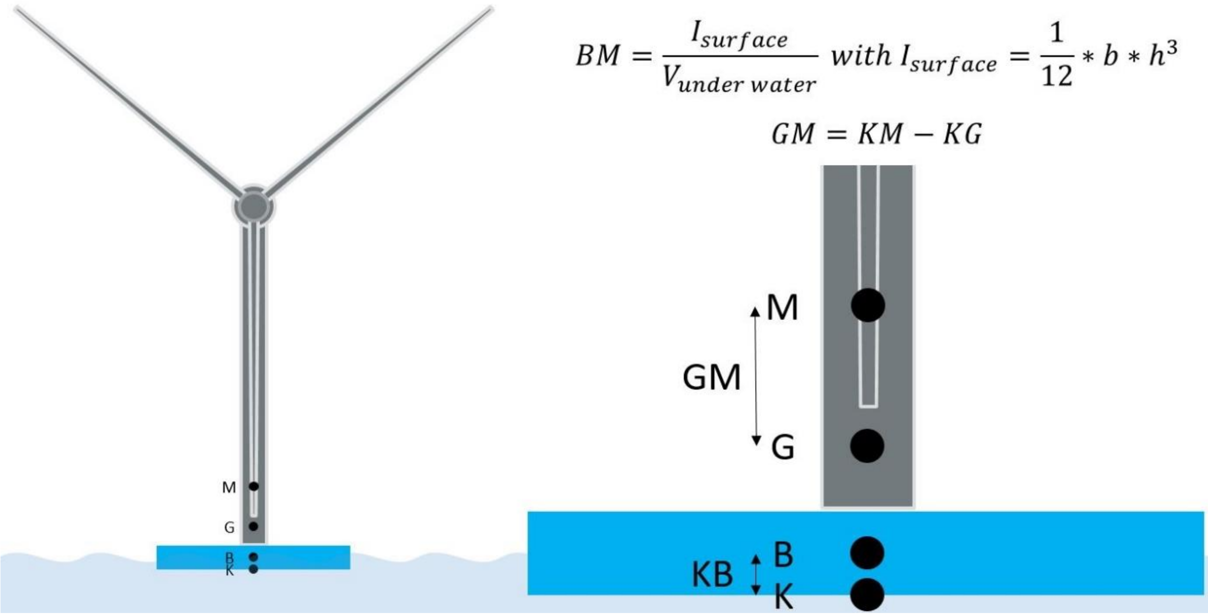


Figure 88 Stability properties of barge with wind turbines

The width of the barge is assumed to be at least 50 meters (vessel width). Calculations with the initial stability properties indicated that the width plays an important role in the initial stability of the barge loaded with the wind turbines. The GM can be varied under influence of changing the barge size in width, length and height. These variances are shown below in Table 19.

Width [m]	Length [m]	Height [m]	GM [m]
Varying width			
60	200	10	39.0
55	200	10	15.6
50	200	10	-3.9
Varying length			
60	200	10	39.0
60	195	10	36.4
60	190	10	33.9
60	185	10	31.4
Varying height			
60	200	10	39.0
60	200	12	37.5
60	200	8	40.4

Table 19 GM calculation with varying dimensions of barge

The width highly influences the initial stability of the barge. Changing the width with a couple of meters determines whether the GM is positive or negative. The initial stability does not guarantee the stable usage of the barge with wind turbines under operational circumstances such as waves or wind but gives insight in the influence of the barge size. For modelling purposes, the initial size of 200x60x10 meters is still assumed to be feasible. This size has a GM of 39.0 meters and is initial statically stable.

Sea fastening of barge

The barge needs to be moved between the stern and bow of the vessel. Rounded corners of the barge help maneuvering the barge on its location on the vessel. First the barge need to be aligned with the vessels direction after which it can be slowly moved above the submersed part of the vessel. The vessel can be equipped with bumpers to prevent damage to the hull of the vessel due to the barge movements. Assisting tugs are probably needed during the barge exchange to control the barge with wind turbines. In Figure 89 the barge exchange process is shown left and the bumpers schematically shown right.

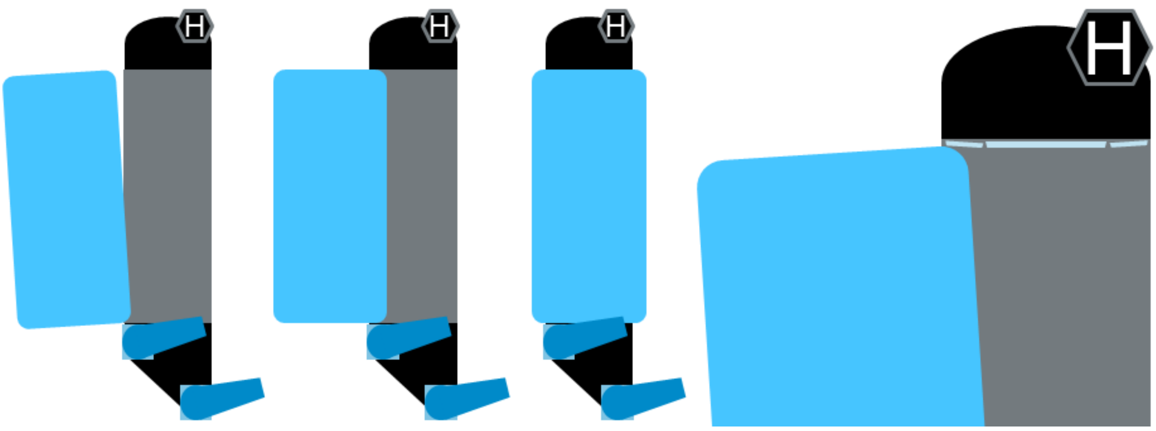


Figure 89 Barge exchange process and bumpers on vessel

The barge needs to be locked in place. Different pins on the vessel which lock the barge for horizontal movements and roll and pitch movements are suggested for this locking mechanism (Figure 90). Dominantly, the pins should control the roll movements of the barge and vessel. Besides they should prevent sliding of the barge from the submersible deck of the vessel. The size and location of the pins are very important since local structural loading of the hull should be prevented. The pins should match the design of the submersible hull and guide the forces through the whole structure. The proposed pins can endure loading in surge and sway direction but there is also a possibility to spit these direction of forces. Pins for sway forces can be introduced along the side of the vessel while at the bow and stern of the vessel surge force pins are applied. Smart usage of deck area and pins can prevent limit usage transport applications due to the pins on the deck.

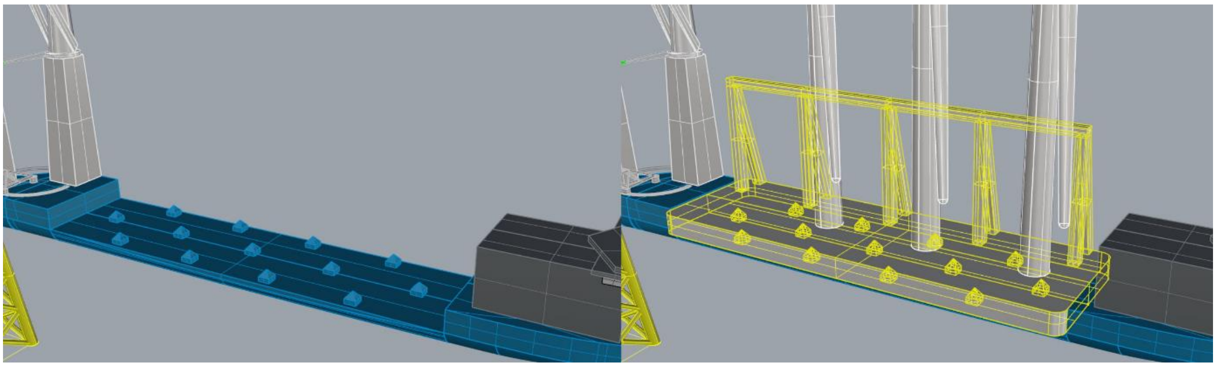


Figure 90 Pins for barge locking mechanism

Sea fastening of wind turbines

The wind turbines need to be transported on the barge in a save way. The operational window of wind turbine installation should be usable but are not comparable with for normal sailing conditions of a regular vessel. The wind turbines are relatively high and designed to capture wind. The wind turbines need to be sea fastened on the barge to be able to transport them from the marshalling port towards the (future) wind turbine park. A preliminary design is proposed for sea fastening of wind turbines which is integrated in the wind turbine installation process.

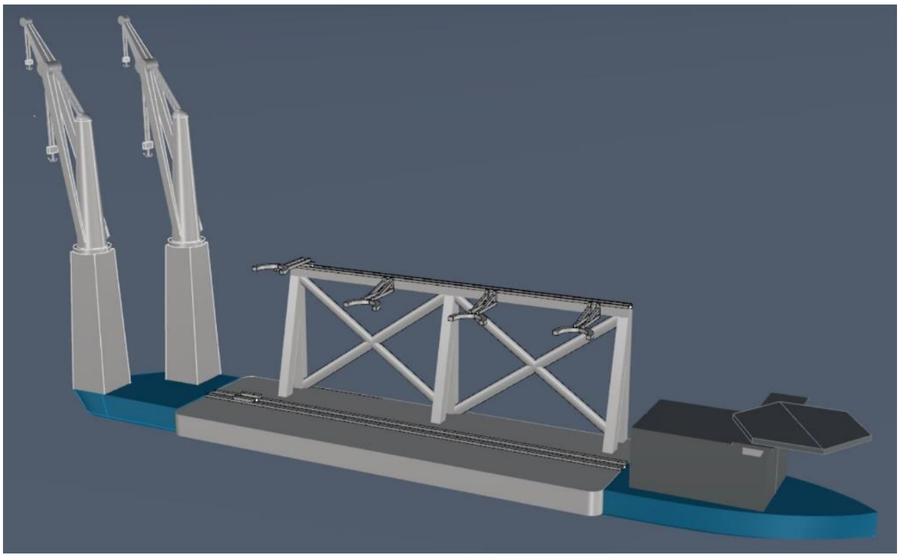


Figure 91 Barge with sea fastening grippers for transportation of wind turbines

A construction is shown in Figure 91 for fastening of wind turbines on the vessel. The sea fastening should be flexible to be used for multiple sizes of wind turbines. Therefore, the height of the sea fastening should be limited. The construction shown is approximately 50 meters high and is equipped with four grippers that grip around the tower of the wind turbine. The grippers have a fixed (bolted) location on the sea fastening construction. More grippers can be added when transporting smaller wind turbines. Only the gripper near the cranes is movable to be used during the installation process.

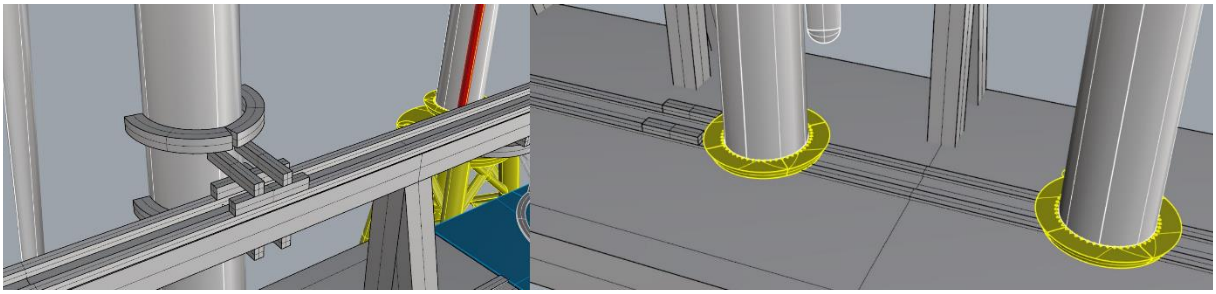


Figure 92 Skidding system on barge

The barge is equipped with a skidding system which moves the wind turbines towards the cranes together with the movable gripper. The skidding system should lock multiple wind turbines during travelling on fixed locations on the barge. For this, the wind turbines should have a special small platform located under the tower of the wind turbine. This platform is also used during the lifting process which is explained later in this chapter. Four 20 MW wind turbines are shown in Figure 93.

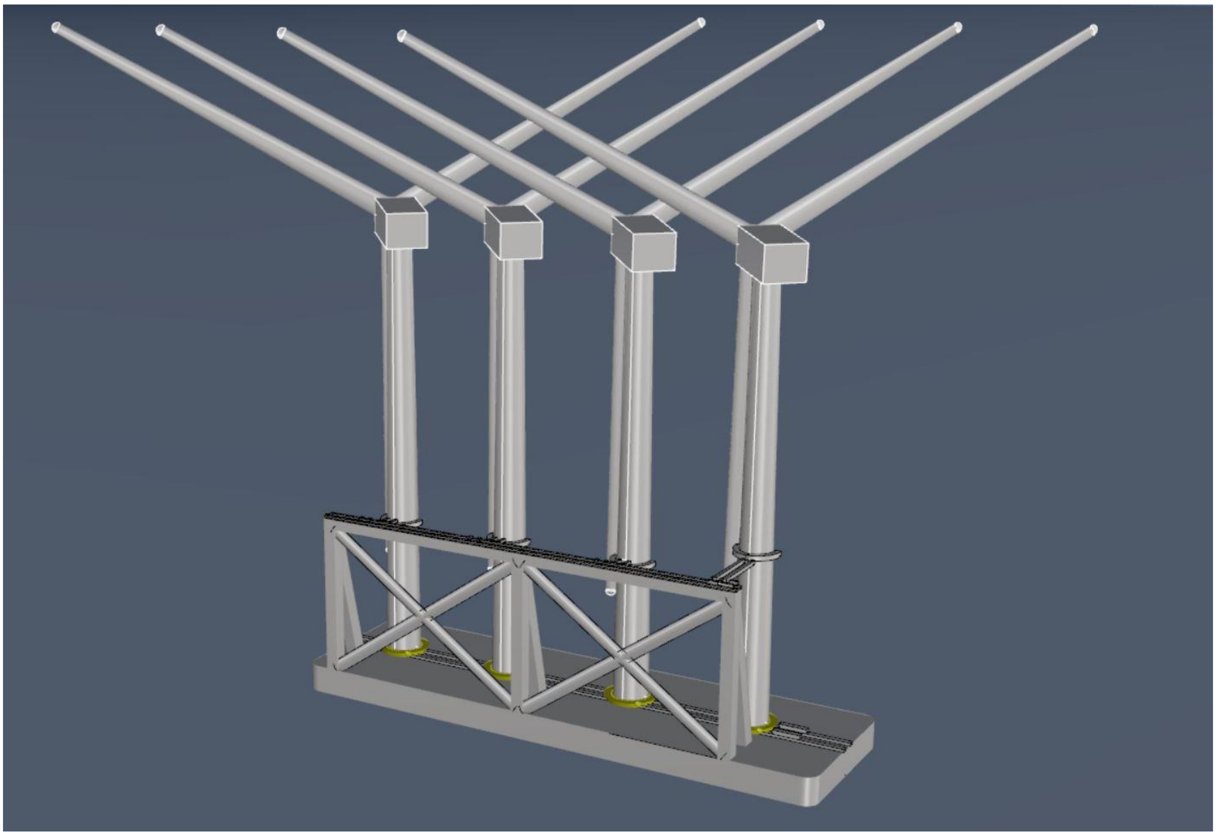


Figure 93 Barge with sea fastening and four 20 MW wind turbines

Spreader design

The spreader needs to lift the wind turbines stable above the CoG of the wind turbine. Since the CoG is relatively high, the connection between the spreader and the hook blocks need to be above the CoG for stable lifting. The spreader design is based on the wind turbine installation example using the sheerleg Rambiz which is shown earlier in Figure 12. A rigid connection is needed around the wind turbine tower connecting it with the hook blocks of the portside and starboard crane. This top part of the spreader is shown in Figure 94.

Figure 94 Spreader design top part

The idea is to re-use the spreader for the wind turbine lifting. The spreader should be opened to enclose the wind turbine during lifting and to be removed later. However, wind turbines are probably not relatively strong to be lifted along the tower. Therefore, a preference is there for using a construction under the tower of the wind turbine to lift the wind turbine on its foundation if there is no attachment for lifting available on the wind turbine. This construction should be designed mainly for vertical loading while th top part of the spreader needs to be designed for horizontal loading. The bottom part will be part of the foundation once the wind turbine is installed. Two different lower parts of the spreader are thought out. These different designs are explained below.

Lifting frame

A very efficient way of using the spreader is combining the lower part of the spreader with the sea fastening on the barge. If the sea fastening of the wind turbine is incorporated in the design of the spreader, it can be used for the multiple application. Another benefit of using the lifting frame is the temporary application of wind turbine fastening (Figure 95). Wind turbines typically need to be bolted in place once put on the foundation. Since motions due to waves and wind exist during operation, it could be difficult to hold the wind turbine in place during the bolting process. The lifting frame can be used as a temporary connection between the wind turbine and foundation. The lifting frame has to withstand at least the weather conditions which are workable for the vessel during wind turbine installation. The disadvantage of this concept is the request for a second lift to remove the lifting frame. Although it can be performed using a smaller crane vessel, it is a second movement that needs to be performed requiring time of an installation vessel. It can reduce the day per turbine number if the same installation vessel is used for removal of the lifting frame. The jacket should fit the lifting frame. The jacket could be equipped with catcher plates (yellow half round plates on jacket in right sketch in Figure 95). The (orange) pins of the lifting frame enables a locking mechanism while the lifting frame is in motion. First the right hand pin is locked in place. The pin located opposite with the smaller catcher plate is the following. The smaller flange under the wind turbine tower is the only part of the frame that cannot be removed. This part is needed to support the tower of the wind turbine.

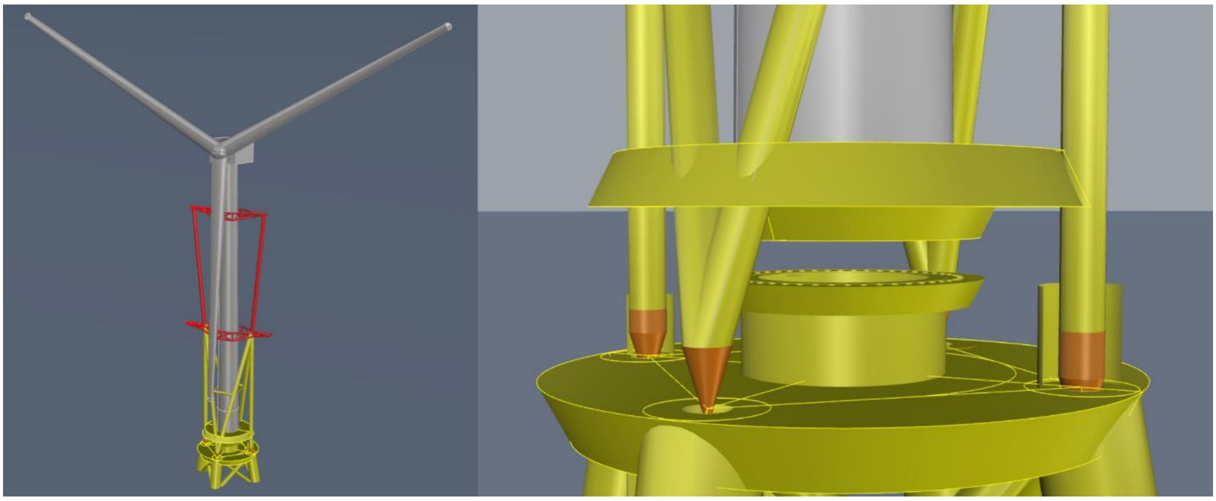


Figure 95 Preliminary design of lifting frame with catcher plate installation

Bottom support structure

Another structure to install wind turbines is the bottom support structure. This structure utilizes a flange that is bolted under the wind turbine tower. The spreader is connected to this structure. The bottom support structure is shown in Figure 96.

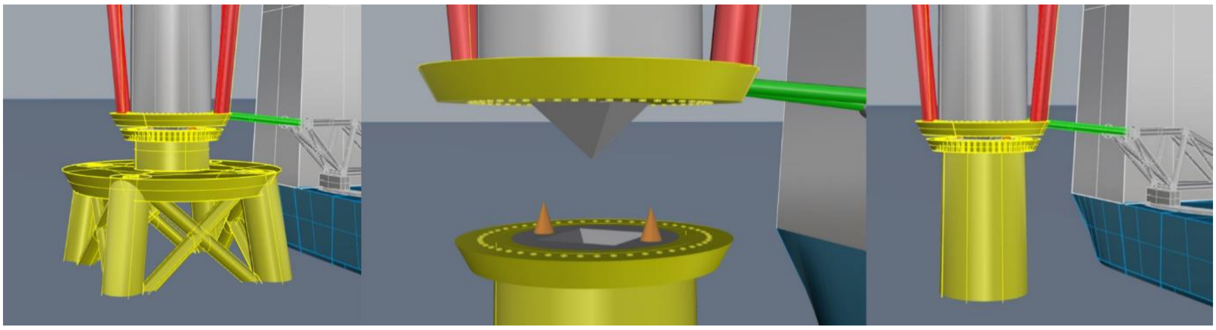


Figure 96 Preliminary design of bottom support structure

The structure is fitted with catchers both mounted below the bottom plate and on the flange on top of the foundation. Placing the wind turbine on top of the foundation is performed in two stages. First, the large catcher (in grey) is used to align the wind turbine with the foundation after which the pins (in orange) are used to place the wind turbine at its exact location. This solution is versatile since it can be used on jackets and monopiles. The bottom support structure together with the flange on the foundation is a relatively small extra part of the total wind turbine assembly including the foundation. No extra lifting is required afterwards as is the case with the lifting frame.

Control of the wind turbine

The bottom support structure is used in the further explanation of wind turbine installation mainly due to the small extra required components and the flexibility to be used on jackets and monopiles. To control the wind turbine during lifting, a second spreader (mid spreader) is proposed at the height of the bearings of the cranes. From these locations, a connection can be made with the pedestal of the cranes to exert horizontal forces on the wind turbine. The crane hooks at 150 meters are made for vertical forces, which cannot fully control the complex motions of the vessel. The mid spreader at approximately 50 meters height from the bottom support structure combined with a connection with the bottom support structure can control the wind turbine in different ways. Later, the motion compensation system will be explained.

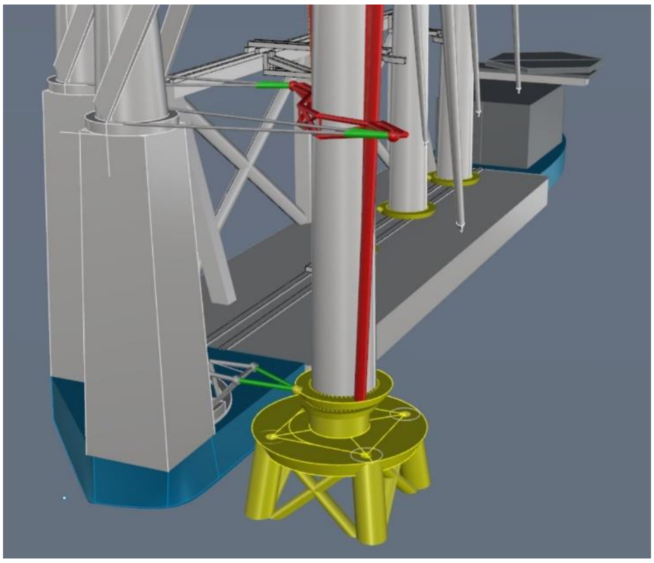


Figure 97 Overview of preliminary design of bottom support structure

The systems uses the hook blocks and three introduced control points on the spreader design. Note the critical interaction of the mid spreader with the sea fastening frame on the barge which is indicated in Figure 98. This is not taken into account in detail but should be considered during further detailed design research.

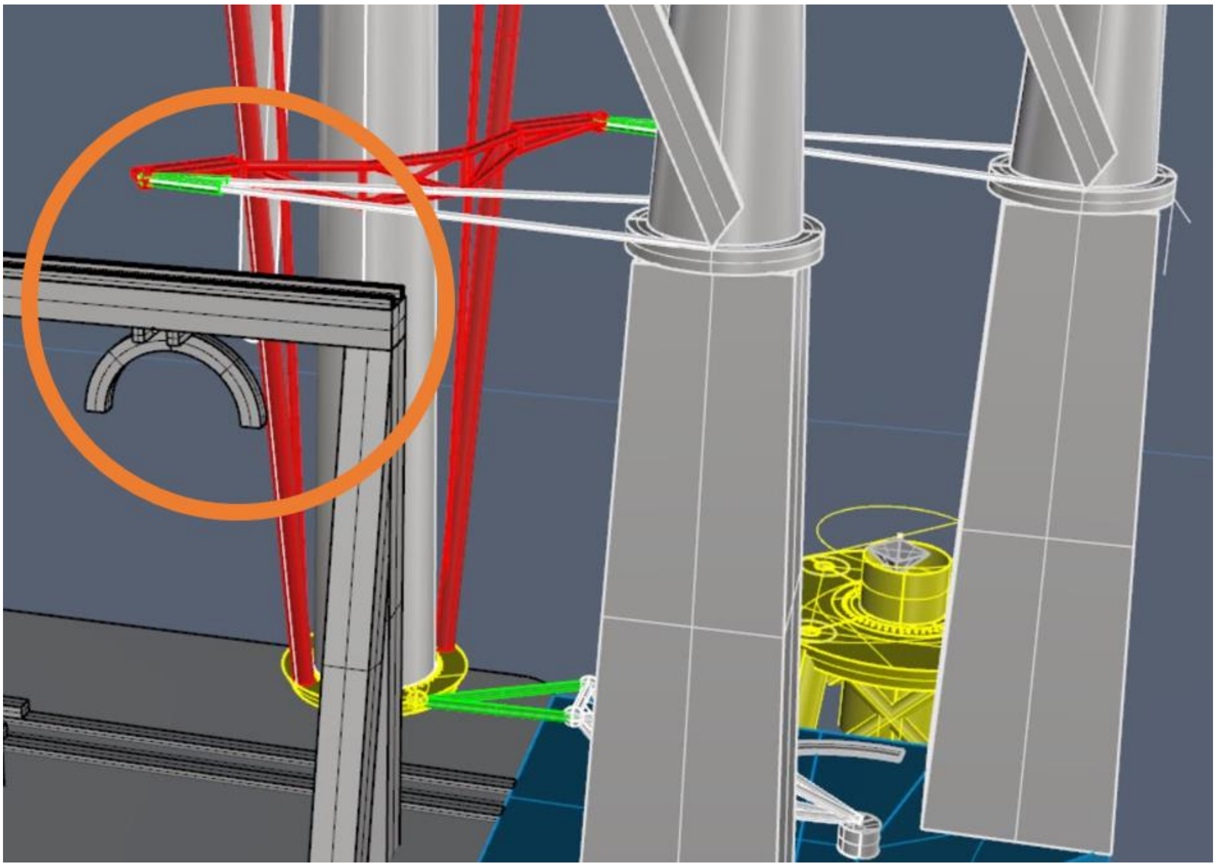


Figure 98 Point of attention - spreader design and sea fastening frame

Wind turbine installation

For wind turbine installation, additional systems are needed to safely install the wind turbine during movement of the vessel. The motion compensation system is explained in more detail and a quick connector is introduced to temporarily install the wind turbines on the foundations.

Motion compensation

A floating installation method lead to the motions of structures during installation due to waves and wind. The motions for the PWT installation vessel are estimated based on a response amplitude operator of a floating crane vessel. This estimation is performed and verified with expertise and knowledge within Huisman.

The motions of the wind turbine are dominantly sideways due to the roll movement of the vessel. This roll movement is directly related to the width of the vessel and the relatively high and heavy wind turbines which need to be installed. In sway direction this movement is approximately 10 meters at the height of the CoG of the wind turbine. This movement is during the lifting operation when the wind turbine is lifted above the foundation. In surge direction, this movement is estimated to be around 6 meters and in heave direction 3 meters. These quantities are relatively high but estimated to be feasible at the time this concept could be realized (Figure 99).

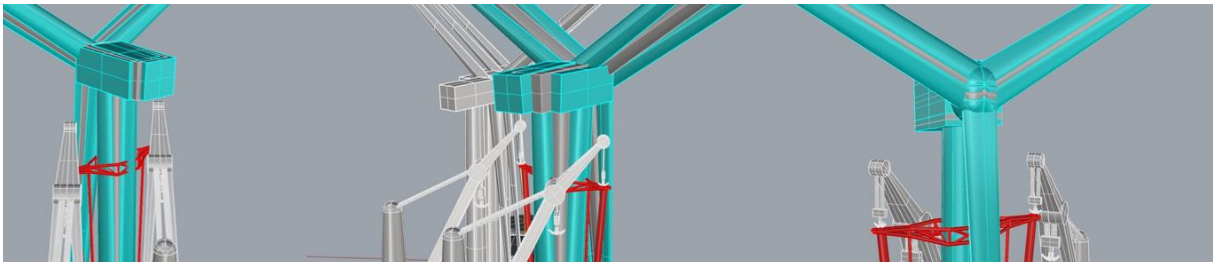


Figure 99 Visualization of wind turbine motions, left pitch motion, middle roll motion and right heave motion

The point of attention of the motion compensation system are the accelleration forces. These forces are relatively high due to an estimated high average roll velocity. The average roll velocity of the wind turbine at the CoG is over 1 m/s. Typical is a roll period of a vessel of 8 seconds. Further research is needed to known whether excitation takes place due to wind turbine installation and the roll period of the vessel. Furthermore, if excitation exists it need to be solved to install wind turbines over the side of the vessel. This is not only applicable on this concept but generally on floating wind turbine installation vessels that need to install large wind turbines.

Introduced earlier is the usage of heave motion compensation on the auxiliary hoist of the crane which can compensate the heave motion of the wind turbine. The other motions can be controlled using the previously proposed control points along the tower and at the bottom of the wind turbine tower. The control points connecting the mid spreader with the pedestal of the cranes are named mid control points and the control point connecting the bottom of the tower of the wind turbine with the vessel is named the bottom control point.

It is proposed to use the mid control points mainly for rotational control of the wind turbine. Tuggers (control cables) can be used for this control of the wind turbine. A better solution could be a more stiff system since cables are made for pulling forces and cannot exert pushing forces. The grey structure of the mid control points in Figure 101 are proposed to be a steel structure while the small green part should be a hydraulic/electric cylinder that can exert push and pull forces on the mid spreader.

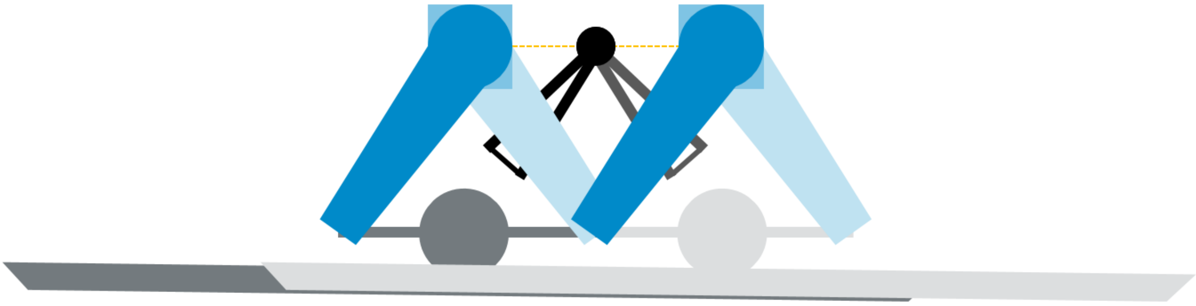


Figure 100 PWT configuration with bottom control structure

The bottom control point is attached to a rotating frame that rotates in the PWT configuration (Figure 100). The rotational point of this system is in line with the center of rotations of the cranes. This bottom support frame can rotate with the slewing motions of the cranes to control the wind turbine. The frame should be rigid to withstand the dynamic forces of the wind turbine exerted on the bottom control point. Compensating the roll and pitch movement of the wind turbine will be the main focus of the bottom control point. Motion compensation of the wind turbine will be performed using the auxiliary hoist for the heave motions or vertical motions and the other control points (mid and bottom) will be used to control the rotations of the wind turbine due to the movement of the vessel.

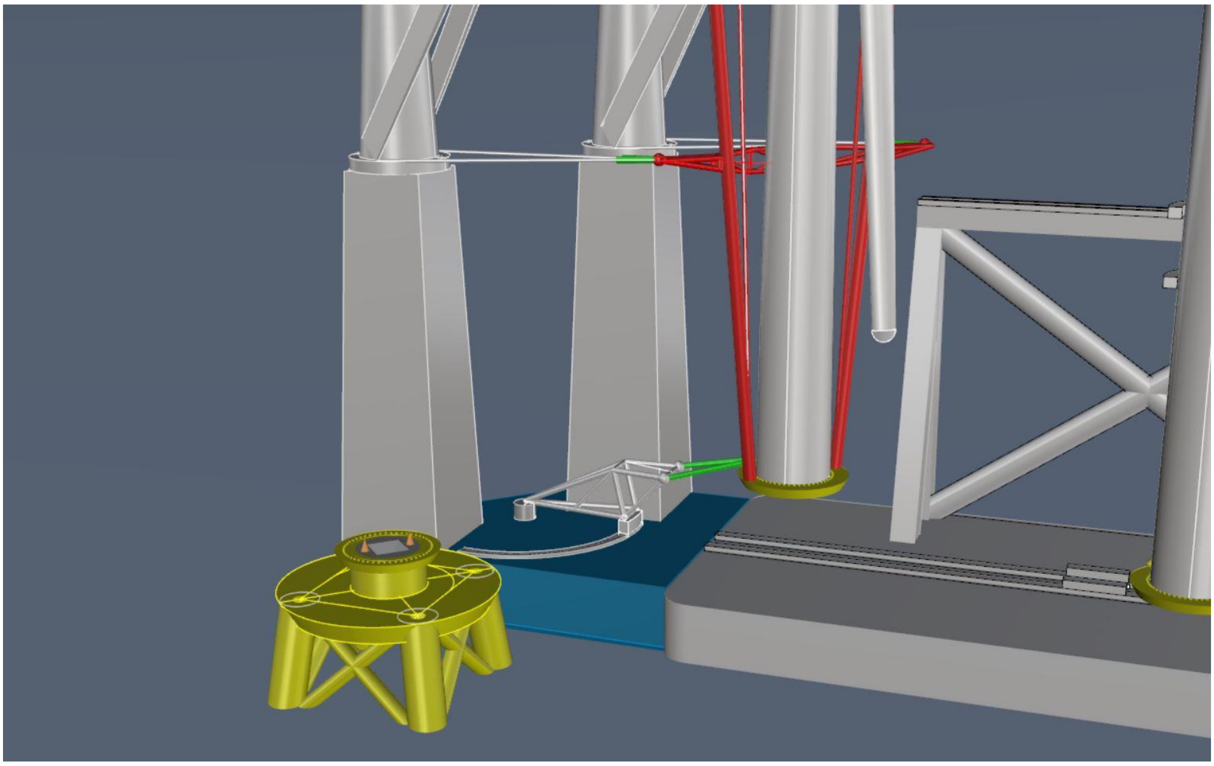


Figure 101 Overview of motion compensation system using heave motion compensation and three control points

Figure 101 shows the start of the installation of the wind turbine. After the wind turbine has been lifted from the barge, the cranes slew in parallelogram configuration together with the bottom control structure toward the foundation. Once above the foundation, first the bottom of the wind turbine should be aligned with the foundation (Figure 102).

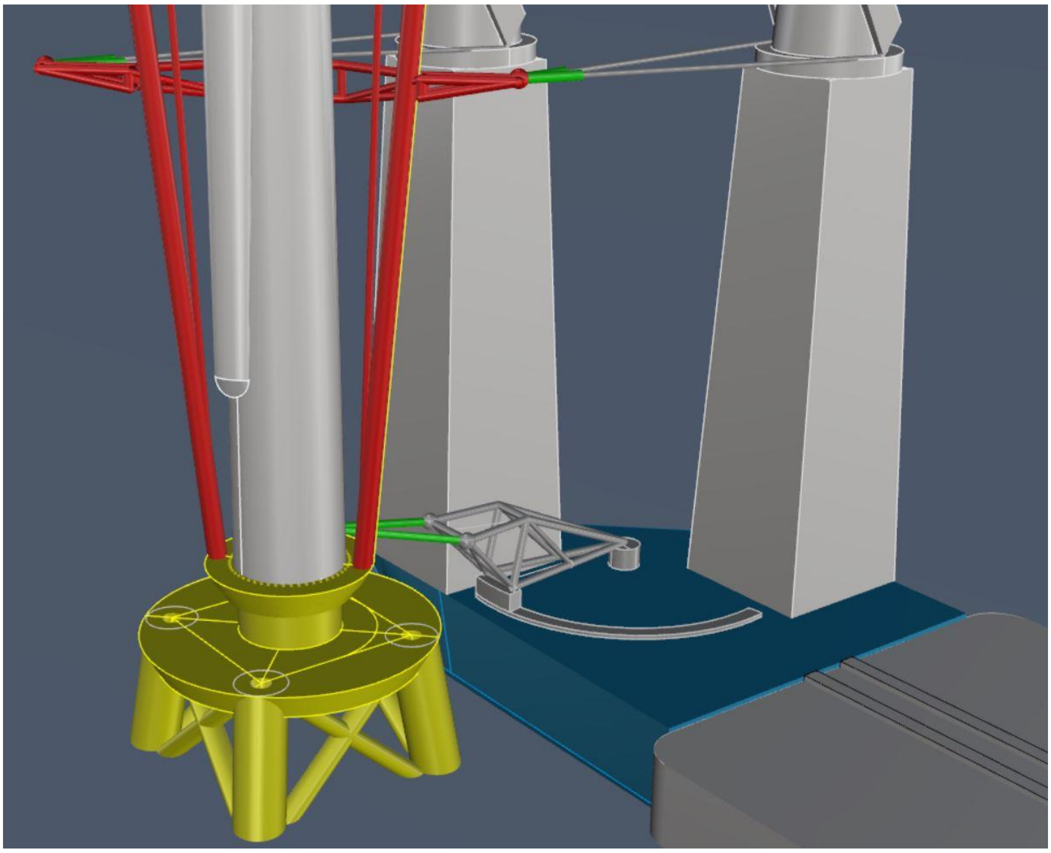


Figure 102 Overview of motion compensation system using motion compensation above foundation

Quick connector

Apart from the motion compensation system, the wind turbine needs to be held in place once placed on its foundation. The wind turbines are typically bolted on place. Without a quick connector, the installation vessel has to hold the wind turbine in place until the bolts are installed. This process does take time and therefore introduces a large risk since the floating installation vessel still has to prevent the wind turbine from disconnecting from its foundation. A quick connecter is introduced to temporarily connect the wind turbine with its foundation once the installation vessel has put the wind turbine on top of its foundation. Once this is performed, the vessel can be disconnected from the wind turbine and proceed installation of other wind turbines.

Due to the spreader design, a bottom support structure is introduced to lift the wind turbine from the vessel on the foundation. On this structure a removable connector can be installed that is able to connect the wind turbine with the foundation. If the quick connector is manageable, it can be removed later using a maintenance support vessel (which is significantly smaller as the installation vessel). The quick connector is shown below in Figure 103.

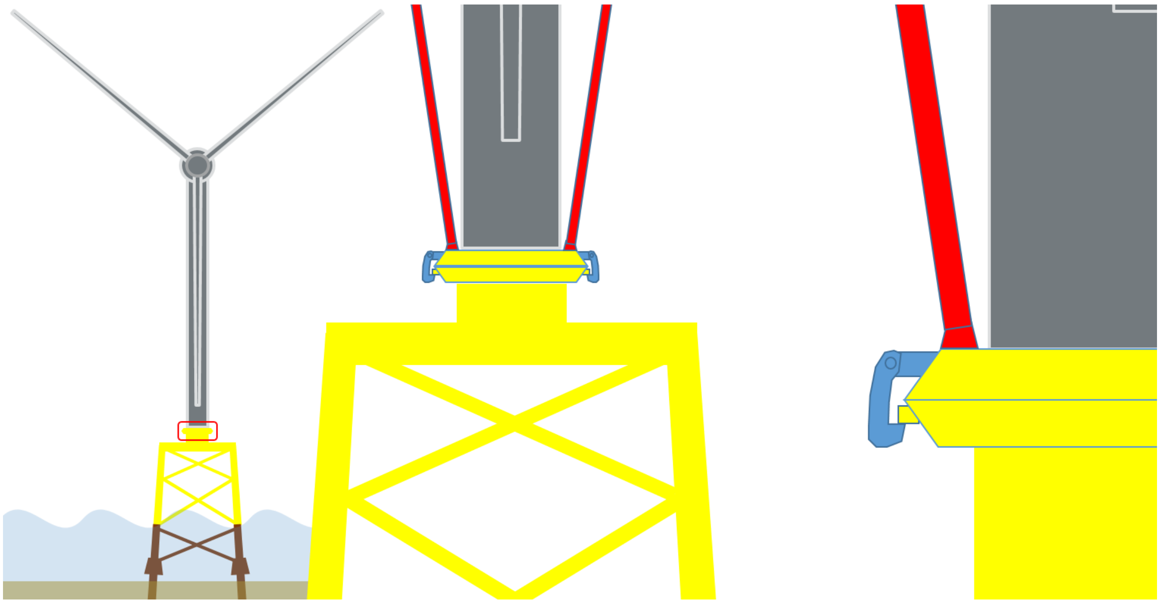


Figure 103 Preliminary design of quick connector for wind turbine installation

First the wind turbine needs to be aligned with the foundation (Figure 104). Once the alignment is correct, the wind turbine can be put on top of the foundation. The quick connector hooks are lowered to temporarily connect the wind turbine with the foundation. The installation vessel can proceed with the installation of the next wind turbine while a crew is installing the wind turbine inside (connect the wind turbine and foundation using nuts and bolts). The quick connector can be placed around the bottom support structure without interfering the (red) spreader connection and the bottom control point structure. The bottom support structure in combination with the quick connector is a solution comparable with the lifting frame.

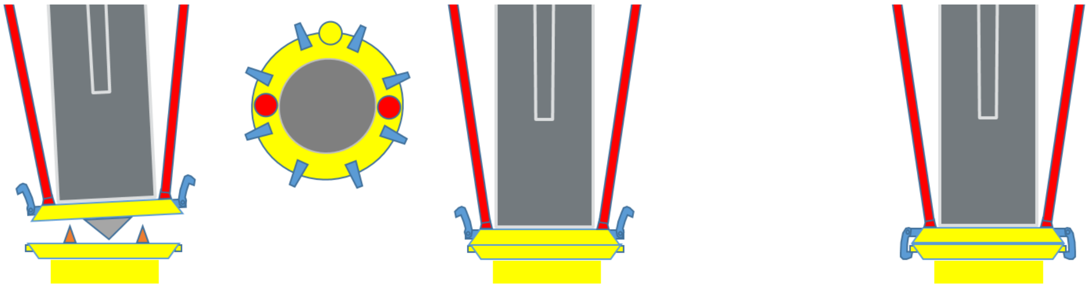


Figure 104 Process of installation using quick connector

It is possible to install the quick connector on the re-usable spreader with small adjustments on the spreader design. If performed, it is possible to re-use the quick connector without separate connection of the quick connectors. Note that if the quick connector is constructed on the re-usable spreader, the installation vessel has to wait until the spreader can be detached from the wind turbine. If multiple re-usable spreaders are fabricated, the installation vessel can pick up the re-usable spreaders later requiring extra installation time.

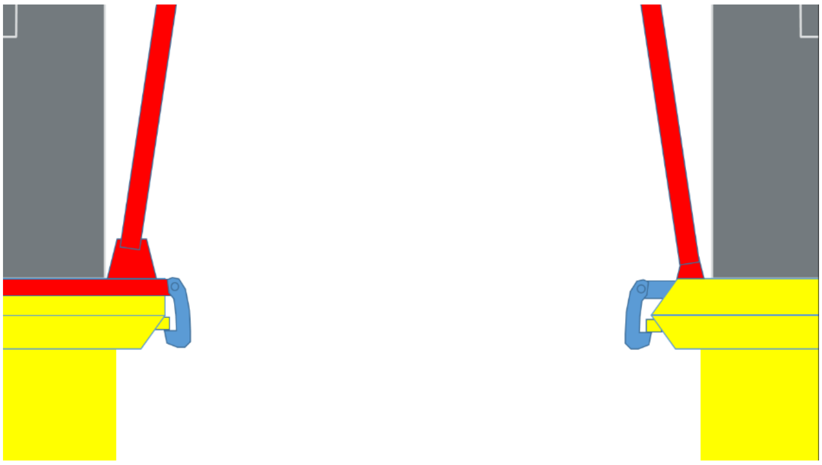


Figure 105 Different quick connector designs

Wind industry applications

The main installation purpose of the PWT installation vessel is fully assembled wind turbine installation. The properties of the vessel are scaled up to 20 MW wind turbine installation. Since the scope defined that the solution should be scalable and flexible, other applications are discussed in this section. Only for the large wind turbine additional tools are proposed. No tools will be discussed for e.g. smaller wind turbine installation or foundation installation. If the owner of the PWT installation vessel invests in many different barges for diverse applications, the PWT installation vessel is the only vessel needed for the large installation processes for realization of a wind turbine park. The PWT installation vessel could install wind turbines, foundations, offshore substations and even cables.

Wind turbine installation 20 MW

The main purpose of the installation vessel is wind turbine installation. Due to the compact arrangement of the cranes the vessel can install wind turbines without interference of the crane with the wind turbine blades. The typical parts for wind turbine installation are the barge with sea fastening, the crane arrangement and the spreader design combined with the motion compensation. All these typical parts are required to be able to install large wind turbines (Figure 106).

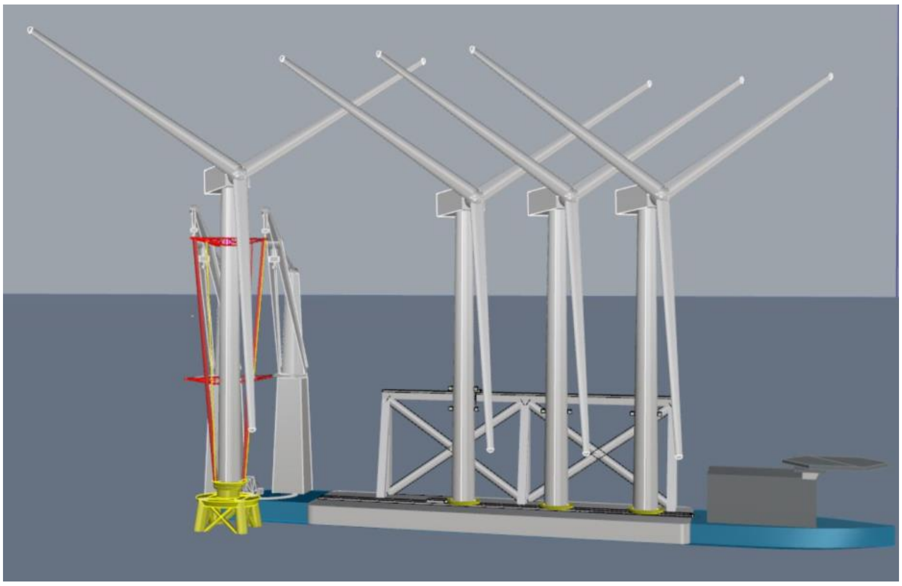


Figure 106 Application large wind turbine installation

Jacket installation 20 MW

A wind turbine needs to be put on a foundation. Within this research, fixed foundation was assumed to be applied on wind turbines. The jackets of a 20 MW wind turbine are less heavy when compared with the wind turbines. Since it is estimated that the jackets weigh less than 2,000 tons, just one crane can be used for jacket installation. The portside crane can be used for this application which can lift the jackets using the auxiliary hoist. The auxiliary hoist is fitted with a heave motion compensation for wind turbine installation which too can be used during jacket installation. The mid point control structure can be used for motion compensation of jacket installation. The bottom support frame could be used for jacket installation in combination with the usage of the starboard side crane. The jackets need still to be moved towards the cranes to lift them from the barge. The barge for the jacket installation could be the same barge as for wind turbine installation. Another option is a new barge which has the width of the vessel enough to fit up to four 20 MW jackets. The application of 20 MW jacket installation using the portside crane is shown in Figure 107. The starboard crane could be used for assisting application such as hammering the piles of the jacket.

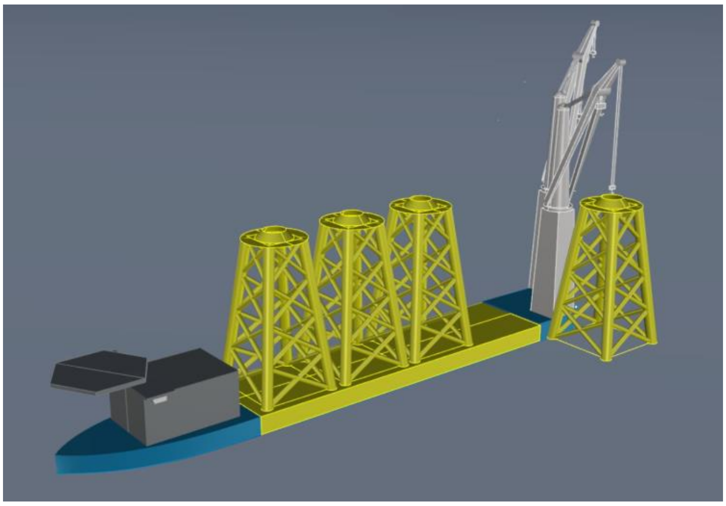


Figure 107 Application jacket installation of 20 MW wind turbine

Monopile installation

A flexible wind turbine installation vessel should be able to install other types of foundation too. Since the tripod has similar dimensions as a jacket, a quick view on monopile installation is included. Monopiles could be installed by the PWT installation vessel. The monopiles could be over 100 meters long and could weigh up to 2,000 tons using the auxiliary hoist. The monopiles can be laid down on the barge lengthwise. If the monopiles are less than 100 meters long, two rows of piles can be laid down on the barge. The bottom support frame can be used as an upending tool to rotate the monopiles in vertical direction and it can be used as a control mechanism during lowering the monopile in the ocean. An additional gripper on the bottom support frame is needed to control the monopile. The barge can be rotated in nearby sheltered waters to provide access to the second row of monopiles. If it is possible to transport wind turbines fully assembled as proposed for the PWT installation vessel, monopiles could also be transported this way which requires an additional system to move them towards the crane. The monopile application is shown below in Figure 108.

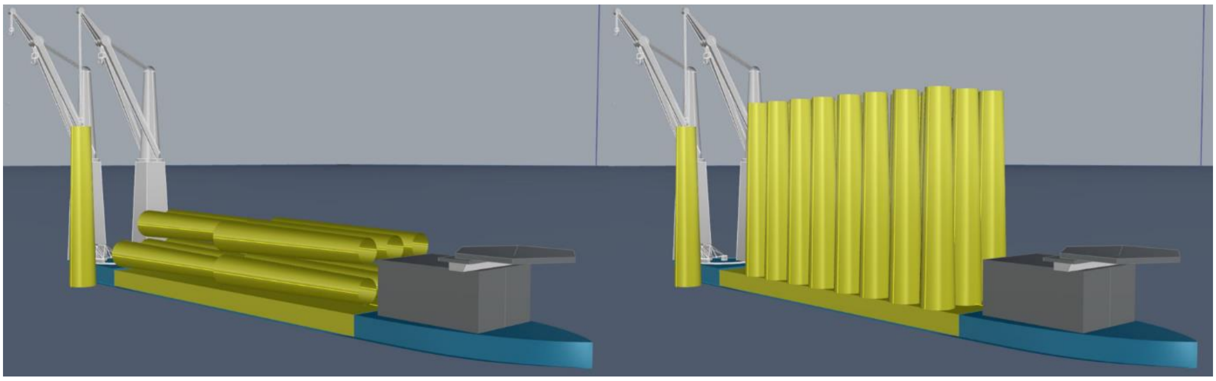


Figure 108 Application monopile installation

Offshore substation installation

Wind turbine parks demand offshore substations for the conversion of the voltage to be transported efficiently onshore. The PWT installation vessel can transport and install offshore substations without large assisting vessels. The offshore substation installation probably requires calm waters (similar conditions as sheltered waters). During calm water, the barge can be moved away and positioned at the stern of the PWT installation vessel. From here, the PWT installation vessel acts like a sheerleg to install both the jacket and offshore substation from its own barge. The diagonal stern combined with the relatively high pedestal of the cranes provide enough space for heavy lifting of offshore substation installation. The jacket of the offshore substation can be upended if needed since there are two cranes available. These calm water lifts can be executed using the main hoist of the two cranes which probably have a combined hoisting capacity of over 10,000 tons. The installation of an offshore substation with its jacket foundation is shown in Figure 109.

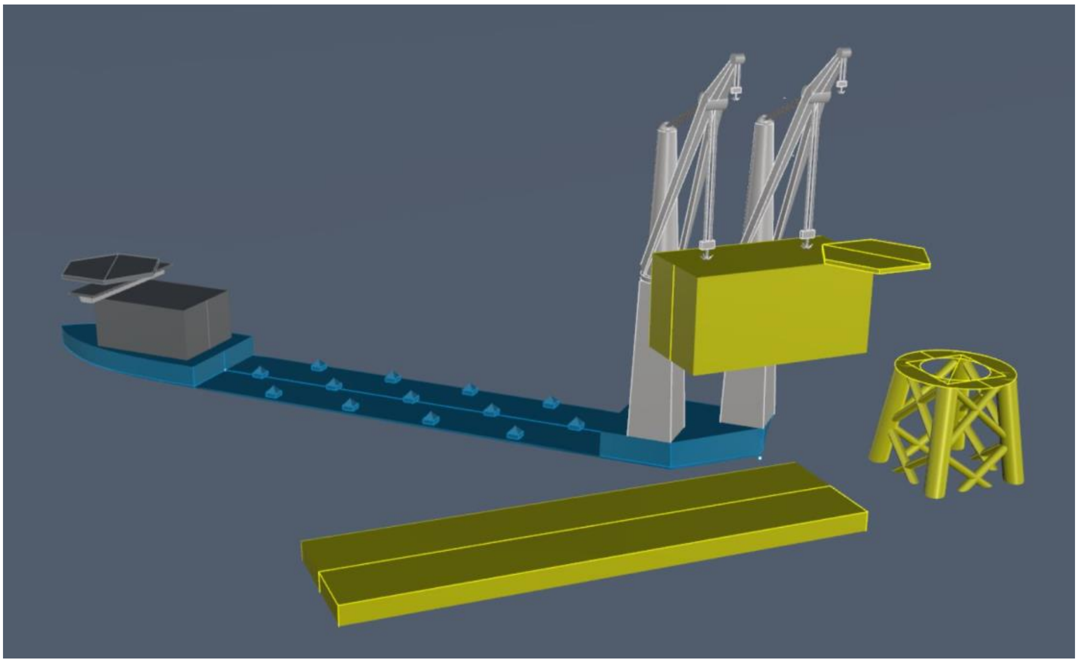


Figure 109 Application jacket and offshore substation installation

Smaller wind turbine installation

If wind turbines are relatively small, they can be installed with only one crane. The two important properties for single crane installation are nacelle height and total weight of the wind turbine. The single crane wind turbine installation can be performed with the auxiliary hoist equipped with heave motion compensation. Other motion compensating systems are not included in this application, but probably the mid control point structure can be used for this installation too. The wind turbines for single crane installation are rotated counterclockwise at an angle of approximately 20 degrees. This enables the portside crane to lift the wind turbines from the vessel onto the foundation without interference of blades. This requires the wind turbine to be rotated during lifting. The wind turbine cannot be rigidly connected to the crane during slewing motion and has to hold its original 20 degrees orientation.

Figure 110 Application small wind turbine installation with single crane

Additional applications

The PWT installation vessel can be used for other application in general or during the yearly window wind turbine installation cannot be performed due to wave height or wind strength.

Pipe or cable lay system

Apart from wind turbine installation, the vessel can also be used for pipe or cable laying activities. If a new barge is outfitted with a complete fabrication hall to connect and transport the pipes/cables, the PWT installation can easily pick up this barge in the harbor. At the stern of the vessel, a laying system can be installed between the cranes to sink the pipe or cable in the water. The two cranes can load the vessel with the heavy pipes or cable rolls. The cranes can be raised up to the mast of the crane during transport. If wanted, a boom rest can be designed on the barge to lower the crane booms. The cable laying activity can be part of the wind turbine installation since cables are needed to connect the wind turbines with the offshore substation and to connect the offshore substation with the power grid onshore.

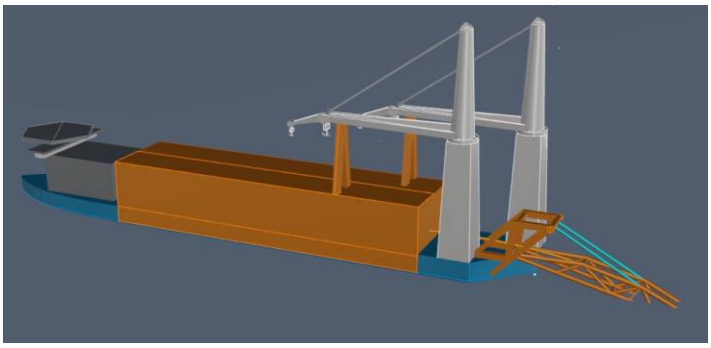


Figure 111 Application pipe or cable laying

Transport or heavy lift

The PWT installation vessel could also be used as a general heavy lift and transport vessel (Figure 112). The two cranes at the stern combined with the ability to transport a barge on deck enables the vessel to be used in varying heavy lift and transport applications. Decommissioning of oil rigs can be performed with this vessel. The PWT installation vessel can clear an area with oil rigs to later install a complete wind turbine park, all with one vessel. If the barge exchange mechanism is adjusted, the deck of the vessel itself can be used to transport large offshore structures such as a new drilling platform.

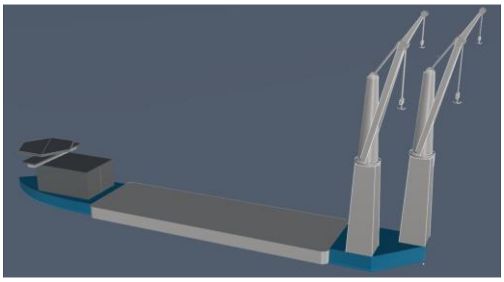


Figure 112 Application heavy lift and transport

Existing vessel conversion into PWT installation vessel

The PWT installation vessel concept uses a semi-submersible vessel equipped with a diagonal stern for crane applications and a separate barge for quick (un)loading of the submersible deck. The introduced properties for the application of 20 MW wind turbine installation are a future design. Some crane vessels in the offshore industry are made using another vessel as a base for the crane vessel. The PWT installation vessel requires a relatively small width of the vessel due to the crane arrangement. Small existing semi-submersible vessel can be used as a starting point for building a PWT installation vessel (with or without barge exchange mechanism).

An example of such a vessel is the Black Marlin of Boskalis. Due to the interesting width of the vessel, a PWT installation vessel conversion could be feasible. The main point of attention for conversion of such a vessel is the strength required of the submersible deck to support a heavy lifting stern with two cranes. A sketch of the Black Marling equipped with a new PWT installation vessel stern is shown in Figure 113. Note that these wind turbines are the small wind turbines of Figure 110.

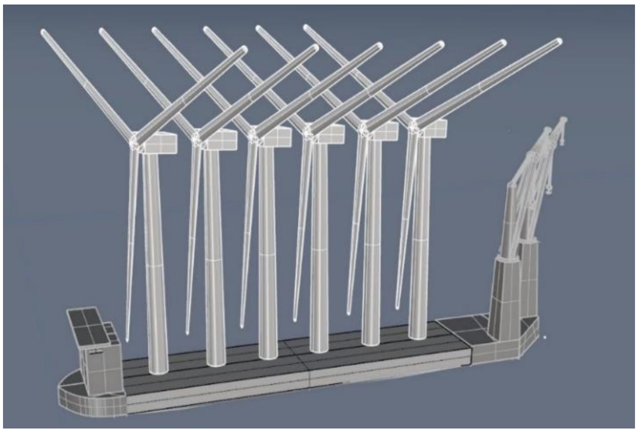


Figure 113 Conversion of existing semi-submersible vessel into PWT installation vessel

Summary

The PWT installation vessel consists of different elements. The concept is based on a semi-submersible hull with a barge that can be transport on the submersible deck. The stern of the vessel is diagonal to apply the PWT configuration. Mast cranes with a high pedestal are needed for this concept in combination with the barge exchange mechanism to provide deck space. Wind turbine installation is executed using the auxiliary hoist with heave motion compensation systems. The cranes needed for wind turbine installation need large hook heights while having enough capacity. Scaling the cranes up to the required installation dimensions indicate that the cranes need to be relatively large. Each crane could have over 5,000 tons maximum hoist capacity.

The barge exchange mechanism is a solution for quick (un)loading of wind turbines without the need for individual loading of wind turbines. The dimensions of the barge are mainly determined by the size of the wind turbines, size of the jackets and stability of the barge. Deck space is needed to transport efficiently multiple jackets. The wind turbines determine the stability of the barge once floated. The barge needs to be stable in sheltered water for (un)loading of the PWT installation vessel. The width of the barge determines mainly the initial stability of the barge without considering external factors such as waves and wind. The barge needs to be sea fastened on the submersible deck. It is suggested to use pins on the deck to lock the barge for horizontal movements. A sea fastening system is proposed to fasten the wind turbines on the barge using grippers and an one sided frame. The barge exchange show opportunity for regular crew changes and it can be used for fuel change.

A special spreader is proposed based on the wind turbine installation performed by the Rambiz (Figure 12). This should be a re-usable spreader which lifts the wind turbine from the bottom of the tower. Only a small support structure is needed for supporting the bottom of the wind turbine tower during lifting and after installation. Due to waves and wind, the vessel with the wind turbine will move in different directions. Different designs have been discussed to safely install the wind turbine on the foundation. The separation of the vertical motions compensated with the cranes and the horizontal motions compensated with the control point structure result in safe wind turbine installation.

The wind turbine will move proportional to its size. These movements are estimated to be solvable and feasible to work with in future. Important is the possible relation between the roll motion of the vessel and wind turbine movements which result in excitation of the overall motions during installation. A motion compensation system is proposed at the bottom of the wind turbine which is based on the PWT configuration. A quick connector is needed to safely hold the wind turbines in place during bolting the wind turbine on the foundation.

The PWT installation vessel has a flexible lay-out which can be used for wind park installation and other applications too (Figure 114). The vessel is able to install jackets using one of its cranes due to the relatively low weight of the jacket. Monopile installation is also possible with piles over 100 meters in length. For single lift installation, the monopiles could way up to 2,000 tons. The offshore substation installation is feasible and can be performed in calm water conditions. Under these

conditions, the vessel can move the barge near the stern to install the foundation and the offshore substation itself using the main hoists of the cranes. Small wind turbine installation is possible too and no minimal size is identified. Comparable with the monopile is the ability to install small wind turbines using one of the cranes.

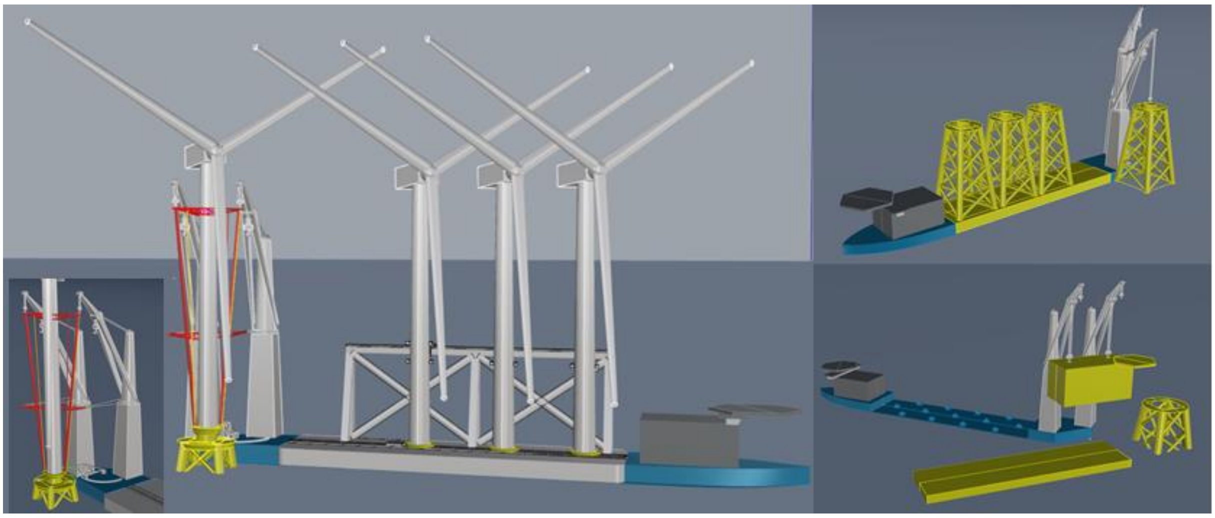


Figure 114 PWT installation vessel application wind turbines, jackets and offshore substation installation

The PWT installation vessel modifications be used for other applications due to the flexible lay-out of the vessel. If invested in a special fabric hall barge, pipe or cable laying applications are possible. At the stern of the vessel, a laying device can be mounted to lower the pipe or cable. This application can be used for cable laying for wind park installation or during the period that wind turbine installation is not possible due to weather conditions. Transport and heavy lift applications are feasible with the PWT installation vessel. The cranes can install large structures over the stern of the vessel. The submersible deck can be used to transport heavy loads without using the cranes for (un)loading. Note that the pin lay-out for sea fastening of the barge influences the usability of the deck itself. A consideration has to be made for sea fastening of the barge and usability of the submersible deck. Still the deck can be used efficiently with the barge exchange mechanism.

The PWT installation vessel can be built using another semi-submersible vessel as a base. This vessel should the properties needed for the crane configuration which is a relatively small width proportional to the size of the cranes. Example of such vessels are the Black Merlin of Boskalis which can be used for wind turbine installation using the PWT configuration. The conversion of vessels in crane vessels is a trend in offshore industry and can create a first step into realization of the PWT installation vessel.

9. Discussion

Wind turbine installation can be performed in various ways using different sorts of wind turbine installation vessels. Most of these vessels were found to be used in and around Europe, additional examples were found in Asia. The possibility exists that existing vessels were not identified and therefore are not included in this research. This study has focused on vessels that provide floating and crane solutions for fully assembled wind turbine installation although some vessels do not satisfy all these three properties. The goal of this part of the research was to identify differences in installation processes used today or proposed for the future. The purpose was not to give a complete overview on installation vessels for wind turbine installation.

The expectation is that many solutions for wind turbine installation are confidential and not publically available. It is reasonable that these are held confidential for future innovations. In addition, public available information is used such as news articles and concepts proposed by shipbuilders. The overview given in chapter 2 and 3 could be incomplete and the proposed Principles 1 till 9 could already be unknowingly in development. The scope of this research was fully assembled wind turbine installation using cranes on a floating vessel.

The growth of the wind turbines discussed on this report are based on a few reference wind turbines (15 MW and 20 MW capacity). For this research it is assumed that the industry growth suggested in literature is a realistic future image. The 450 GW wind turbine capacity foreseen in 2050 is a prospect needed to reduce climate change. The current Corona crisis can influence this vision positively and could increase the interest in wind turbine energy offshore. Which wind turbine size has the best levelized cost of energy (LCOE) is yet unknown, but there is a probability that wind turbine growth stops under certain conditions, such as wind directions. Furthermore, the growth of wind turbine sizes can also be limited due to lack of (future) innovation in the installation process.

Besides fixed foundations, floating foundations are also used in projects or are suggested to be used in future projects. This type of foundation has a growing interest and is well suited for specific locations. However, fixed foundations are currently widely applied and understood in contrary to floating foundations. A benefit of a floating foundation is the possibility of towing from the marshalling port to the wind park location. Towing can be performed with the wind turbine on top. It is observed that there also exist floating foundation concepts on which wind turbines need to be installed in the same way as on fixed foundations. Floating foundations are a novel opportunity to apply wind energy in areas which are outside of the boundaries of current installation methods. The discussed wind turbine installation methods could thus possibly partly be applied on floating foundations. This observation means that the PWT installation vessel could also be used for floating foundations. Installation of wind turbines on a floating structure could set higher requirements on the motion compensation system and limit the workability of the vessel.

The data used for the comparison is an estimation. The data is not directly verified with each installation concept. The reason behind is that some concepts were proposed based on certain wind turbine sizes which are currently installed using state-of-the-art installation vessels. Furthermore, the goal of the comparison was to identify (a new combination of) solutions that have a subsequent better installation rate. The comparison was not conducted to judge which solution is the best. Each concept has its own advantages and disadvantages and are thereby all interesting. The PWT installation vessel is the most interesting within the scope of this research. The data of the comparison is estimated based on jack-up solutions. Each concept has influence on installation rates and relative improvement was the intention of the comparison with estimated data.

The proposed and discussed nine principles are assumed to be feasible for realization. The concept development was needed as input of the later comparison with data and thoughts. The provided solutions related to these concepts could be adapted later in industry. Especially the wind turbines on the barge show a promising range of applications. Assumed is the feasibility to load such large wind turbines on a barge while currently often structures are loaded on barges that have a relatively low CoG (Center of Gravity). The comparison has been started with a scenario comparison to indicate the efficiency of installation with the state-of-the-art installation method. These results are used for analysis in terms of flexibility and scalability of a wind turbine installation vessel. The order of comparisons determines the interest for a PWT installation vessel.

The onshore logistics that are responsible for assembling the wind turbines are very important. It is assumed that by the time 20 MW wind turbines are used, onshore logistics have been growing with these wind turbines sizes. The large wind turbines require large assembling facilities such as cranes. In future, there is a possibility that special lifting equipment is made to assemble wind turbines such as used in Figure 17. Note that once wind turbines are installed fully assembled at location, assembling cranes or assembling installations are needed for wind turbine assembly before loading on vessels. This assembly shift positively influences the installation rate of wind turbine installation.

The maximum distance for the scenario comparison is based on the large (nearest) port to wind park distance in the map of 4C offshore. It is possible that there are wind parks with near ports that cannot be used for wind turbine assembly and loading. Other ports need to be used for this process, which is briefly explained in Figure 79 (large distance installation of PWT installation vessel. Within this research, it is concluded that the transport capacity is not subsequently improving the installation rate under the circumstances of the North Sea and Baltic Sea.

10. Conclusion

The European Commission estimates that between 240 up to 450 GW offshore wind power is needed to keep temperature rises below 1.5°C (European Commission, 2020). To achieve the goal of 450 GW in 2050, the installation rate (GW/year) in 2035 needs to be the eightfold of 2020 (Freeman, et al., 2019). [redacted] In near future, 15 MW and 20 MW wind turbines seem to be milestones in terms of wind turbine power.

Cranes are growing in size and many vessel are upgraded. Different installation processes are used in the past for wind turbine installation. A couple of floating installation vessels have already installed wind turbines fully assembled. Future concepts show interest in this type of installation. Although several concepts are published during the past years, few of them will be realized. There is still a need for 1,000 wind turbine installations a year extra (Freeman, et al., 2019) and current vessels can be upgraded for future demand to a certain extent but this is not enough for future demand (Paulsson, Hodges, & Martin, 2019). 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. Three properties of a wind turbine installation vessel were chosen beforehand. Firstly, a floating installation vessel is preferable over a jack-up vessel due to the lack of the jack-up process. The second property is installation using cranes. Cranes are used often for offshore installation activities and have proven to be flexible. This means that if cranes are used on a vessel, many other activities can be performed using the same vessel which makes the vessel versatile. The final property is the fully assembled installation of wind turbines. This property reduces the offshore activities (lifting and component handlings) since one lift is needed for wind turbine installation.

The following research question was defined based on the three wind turbine installation vessel properties to find a new wind turbine installation method:

In which way is it possible to install pre-assembled large offshore wind turbines in a scalable, flexible way using a floating installation vessel equipped with one or multiple cranes?

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. This vessel lay-out makes it possible to install wind turbines in diverse sizes and can also be used to perform other large installations. Cranes are used for the installation in a new set-up to not depend on the size of the wind turbines. The PWT (diagonal) crane configuration makes this possible since installation is performed without movements over the cranes of wind turbine blades. Typical is the lifting along the tower and not to lift the wind turbine from above. The vessel is scaled to install up to 20 MW wind turbines which requires total lifting capacities up to 4,000 tons above 150 meters waterline.

Fully assembled wind turbine can be installed in various ways. One of the challenges is the required lifting height for fully assembled wind turbine installation. The usage of twin lift along the tower is more feasible over single lift for large wind turbines. Furthermore, the barge exchange mechanism is proposed based on swap bodies of trucks. This system makes it possible to (un)load relatively fast in the port without additional lifting of wind turbines. Finally, the PWT crane configuration is proposed. This Parallelogram Wind Turbine crane configuration makes it possible to load and install wind turbines in twin-lift configuration without the need for lifting over the cranes. The configuration makes it possible to install a variety of wind turbine sizes with the same vessel. Smart usage of different solutions should provide an overall solution which is scalable and flexible.

Wind turbines need to be installed at different locations. The different proposed concepts from literature and proposed principles in this report are evaluated in a morphological analysis from which eight concepts are defined for further comparison. Three different scenarios are analyzed with different distances from port to shore. These are around 100, 200 and 300 kilometers of which the 300 kilometers is for now one of the largest distances that need to be travelled (in Europe) in future if certain wind parks are developed. The installation rate is estimated based on these scenarios from which it became clear that a barge exchange mechanism reduces the (un)loading time in the harbor. Furthermore, it is identified that the transit speed plays an important role. The barge exchange in combination with the slender hull has a good installation rate. The combination of barge exchange and a slender hull with the PWT crane configuration makes the Barge PWT (PWT installation vessel) concept a flexible and scalable installation vessel with a high wind turbine installation efficiency. Furthermore, the concept can be scaled up to a maximum wind turbine installation size and is able to install all the smaller sizes. Foundation and offshore substation installation is also possible with the PWT installation vessel.

The PWT installation vessel is proposed for usage in the installation area North Sea and Baltic Sea. Different passage options are available but limit the height of the vessel or the draft of the vessel. The Øresund passage is found useful for the passage due to limit draught with no limitation for overall vessel height. Offshore mast cranes on high pedestals can be used for the PWT configuration. The barge can be made scalable by introducing a fixed sea fastening frame to fasten wind turbines during transit and aid the installing equipment during installation. Different motion compensation systems are proposed which interact well with the PWT configuration. These systems can be used for other applications such as the foundation installations. Due to the barge exchange mechanism, all the required applications are fulfilled using one installation vessel.

Floating installation vessels can be used for wind turbine installation to increase installation rates to fulfill the foreseen 450 GW required wind turbines capacity in 2050 in Europe. One vessel for all the installation process required for a wind park could be an interesting option to optimize wind turbine and wind park installation. Detailed analysis is required to evaluate the vessel further. In future, the proposed solution could look like Figure 115 which is a new step in wind turbine installation.

Figure 115 Detailed 3D model of PWT installation concept ©Marc Brinkman

11. Recommendations

A concept has been proposed for wind turbine installation with preliminary designs for wind turbine installation. The combination of solutions could contribute to the growing demand in wind turbine installation in the future. The following recommendations are identified:

1. Detailed calculation and design of motion compensation systems. Installation of large components or fully assembled turbines could be a future solution for efficient installation. Fully assembled wind turbine installation from a floating vessel in general requires motion compensation for safe and accurate installation. Special systems can be designed for motion compensation at least to reduce the roll motions of the vessel. Examples are anti-rolling gyros, active stabilization by ballasting or stabilizer fins used on cruise ships (only during sailing). Detailed calculations need to be made to estimate the needed properties for motion compensation systems for wind turbine installation.
2. It is assumed that it is feasible to use the PWT configuration on a semi-submersible vessel. The structure of the vessel in combination with its response amplitude operator (RAO) need to be calculated and designed in detail. Research should provide insight in the required design and identify limitations of the proposed concept. This research is beneficial for both the PWT installation vessel and other vessels with a submersible deck.
3. The proposed cranes for the PWT configuration need to be designed in detail. 2,000 tons auxiliary hoist is required for 20 MW wind turbine installations. Heave motion compensation systems are needed on the cranes to reduce the motions of the wind turbines. Note that the purpose of the PWT installation vessel is wind turbine installation which should be the first design application (auxiliary hoist). The main hoist is for later design which probably has enough lifting capacity for offshore substation installation or topside removal of oil platforms due to the requirements for wind turbine installation. If needed, it is probably possible to fit one of the cranes with an additional tip hoist which can lift parts from the nacelle of the wind turbine for maintenance.
4. A wind turbine installation vessel 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 any fully assembled wind turbine vessel need to be investigated. Assembling a 20 MW wind turbine in future requires a large crane (hook height over 170 meters). Possibly, older jack-up vessel can be used for this purpose.
5. The existing vessel conversion into a PWT installation vessel could be possible if the foreseen vessel has the right properties for such a conversion. The semi-submersible part of the vessel should get enough strength to withstand the PWT configuration stern. Detailed analysis is needed of state-of-the-art semi-submersible transport vessels to verify whether a PWT conversion is feasible.
6. Wind turbine installation performed by a PWT installation vessel has influence on the lifetime of the cranes and other equipment. The installation process and crane activities need to be identified to design the equipment for its usage. The usage of the cranes on the PWT installation vessel is regularly due to the high installation rate of the vessel. This influences

the reliability of the individual used components and overall installation vessel. Research can be performed on the PWT installation vessel as proposed in the research assignment Reliability assessment of continuous cranes. This research identified that subsequent usage of different components of equipment can influence the reliability of a total asset (Hoogendoorn, 2020). In this research is explained that identification of the operating processes can give insight in the usage of the different components. From this point of view, the designs of the components can be adjusted to fulfill the required reliability over lifetime.

7. The barge design should fit the purpose of the wind turbine application. The required sea fastening for safe transits needs to be investigated in detail. Sea fastening of the barge could have similarities with the proposed pin fixation, which is a dimensionally stable solution.
8. 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. Ideally, the spreader design fits the wind turbine design well and collaboration is needed to fulfill this. If manufacturers of the wind turbine industry and installation industry collaborate well, installation processes can increase in efficiency. If the following process is in line with the previous process, wind turbines can be installed smoothly.

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Appendix A: Scientific Research Paper

Design in principle for flexible fully assembled wind turbine installation

Offshore installation of wind turbines

Master thesis – Research paper
To be defended publicly on Friday September 11

G. Hoogendoorn - BSc, Ir. W. Van den Bos, Ir. E. Romeijn, Dr. ir. H. Polinder

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. The center of gravity of a fully assembled wind turbine is relatively low and thus lifting above the wind turbine is not necessarily for fully assembled wind turbine installation. 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. To identify these solutions, principles are proposed and compared with state-of-the-art vessels for wind turbine installations. A morphological analysis is used to identify promising solutions for fully assembled wind turbine installation. Eight concepts are compared in a scenario comparison with varying distance between nearby marshalling ports and the wind turbine park location. Several solutions show subsequent improvement in installation rates. One new concept, the PWT installation vessel, shows overall improvement in installation rates. This solution, developed by the author of this report, is proposed for flexible and scalable fully assembled wind turbine installation.

Keywords

Offshore wind turbine installation; fully assembled wind turbine installation; PWT installation vessel; crane vessel; semi-submersible vessel

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 (Naschert, 2019). It is expected that by 2023 the amount of GW wind turbines installed is doubled compared to 2018 (Ohlenforst, et al., 2019). 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 (Freeman, et al., 2019). 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 (Freeman, et al., 2019). State-of-the-art vessels can be upgraded to a certain extent to meet this demand but this will not be enough (Paulsson, Hodges, & Martin, 2019). 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 (Hopson, 2020) which seems to be a next step in wind turbine installation. In 2011, a 20 MW turbine seemed to be possible in the future (European Wind Energy Association 2011, 2011). 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, fully assembled wind turbine installation was set as a condition during the research, to reduce the number of liftings on location which lead to reduced installation time. The reduced installation time due to pre-assembled wind turbine installation 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 liftings 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. These conditions and considerations are formulated in the following research question:

In which way is it possible to install pre-assembled large offshore wind turbines in a scalable, flexible way using a floating installation vessel equipped with one or multiple cranes?

Focus in this research is conceptual development of an installation vessel that is able to install large wind turbines fully assembled. The focus region where the concept could be used is mainly Europe in the North Sea and Baltic Sea since these regions show large potential in wind turbine industry. The passage between the seas is the Kattegat located between Denmark and Sweden. The usage of the difference in operational windows of these two seas (difference in wind and ice) could create a longer operational window for the installation vessel. Excluded are floating wind turbines which are required for specific areas (such as Southern France or Norway) due to geological circumstances. The focus of this research is on fixed foundations which can be applied in the focused region.

Methods

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 (Rumes, Erkman, & Haelters, 2016). 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.

Installation of wind turbines

Installing relatively large assemblies can be performed by first installing the whole tower and afterwards the nacelle and rotor in one lift. This installation is proposed where the Thialf is installing the nacelle rotor assembly on a dummy tower (Tacx, 2019). 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 (Leenaars BV, 2018). The installing technique on which this study is focused is fully assembled wind turbine installation. Since this is only 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. This estimation of the CoG can be used in a later stage of this research when detailed properties are needed for lifting. The CoG of different components is shown below in Figure 1. Larger assemblies used for installation mean a lower CoG of the assembled components but larger weights. State-of-the-art installation requires lifting up to nacelle heights while fully assembled wind turbine installation requires around 75% of the nacelle height. The estimated CoG relative to the tower floor is shown in Table 1 (Peeringa, Brood, Ceyhan, Engels, & Winkel, 2011), (Pontow, Kaufer, Shirzahdeh, & Kühn, 2017) & (Gaertner, et al., 2020).

10 MW	15 MW*	20 MW	← Mass (tons) & CoG (m) →	10 MW	15 MW*	20 MW
987	1300	1780	Tower	48	60	67
674	1017	1730	Nacelle including rotor	119	150	168
592	780	1068	Tower bottom	24	38	42
1069	1537	2442	Tower top incl. nacelle rotor	106	135	153
1661	2317	3510	Tower nacelle rotor	77	102	119

Table 1 CoG masses and heights of different combined components of wind turbine installation

* For this research, the weight of the tower of the 15 MW wind turbine is assumed to be proportional with 10 MW and 20 MW growth

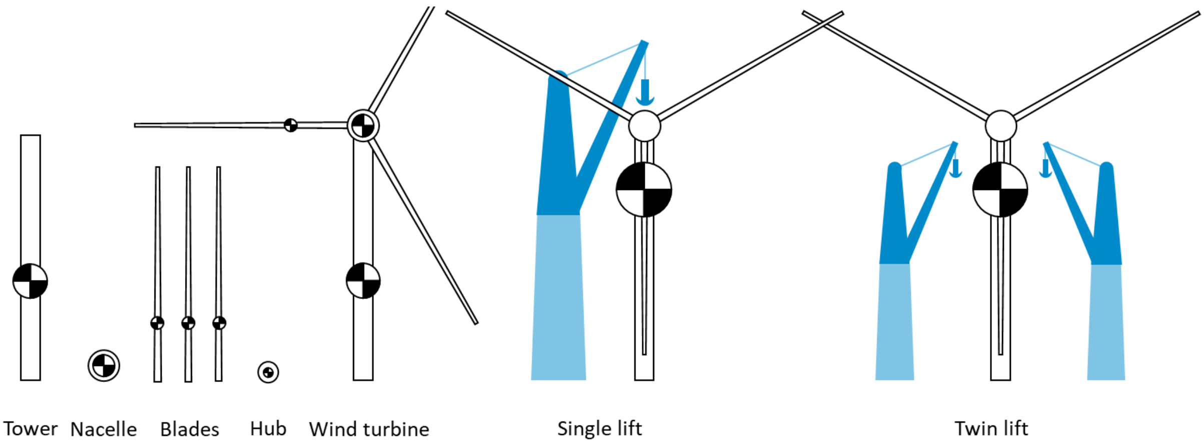

Figure 1 Single crane or double crane wind turbine installation

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 has not 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 (Figure 1). 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 20 MW of 150 meters is enough for wind turbine installation on top of a 20 MW 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.

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 (4C Offshore, n.d.). 4C Offshore (n.d.) 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. Many (possible marshalling) ports are located around the southern part of the North Sea and western part of the Baltic Sea, but not all wind parks have a close connection with usable ports for offshore wind turbines.

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 is limited by 65 meters height and depth of approximately 15 meters (DanPilot, n.d.). The other large strait is the Øresund which has a bridge with more limited height, but when the vessel draft is limited (less than 8 meters), height could not be problem when passing the Øresund over the Drogden Tunnel (Swedish Maritime Administration, 2015). The Øresund is located near the capital Copenhagen while The Great Belt passage is located within Danish territorial waters. Øresund and The Great Belt passage do have a relatively large open area for a large vessel to maneuver through both large passages.

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 workability's
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

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. This results in an overview of how the solutions relate to each other once they are used. A combination of solutions forms a concept, marked in colors in Table 2. The following five operations (A till E) with different solutions (1 till 4) are identified for the investigation in for (fully assembled) offshore wind turbine installation:

	Operations				
Solutions	Assembling A	(Un)loading B	Transportation C	Sailing D	Installation E
1	X	Vessel equipment	2 Wind turbines	Barge	Vessel equipment
2	Onshore crane	Crane vessel	4 Wind turbines	Monohull	Crane vessel
3	Crane vessel	Barge exchange	8 Wind turbines	Multi-body	
4	Jack-up vessel		Supply vessel		

Table 2 Morphological overview of concepts

Jack-up	**Shuttle (WTS)**	**Sheerleg**	**Windlifter**
Barge crane	**PWT 4**	**PWT 8**	**Barge PWT**

A. Solutions for assembling operation

1. None - *The state-of-the-art installation vessel (jack-up) does not use an assembling crane due to the installation method.*
2. Onshore crane - *A possibility for wind turbine assembly onshore is a large onshore crane. The crane is located on the quay and needs to provide enough lifting capacity for wind turbine assembly*
3. Crane vessel - *It is possible to use a sheerleg for wind turbine assembly (and loading). This crane is movable over the water and thus makes no use of limited quay area. The vessel can relocate itself for other activities.*
4. Jack-up vessel - *Existing jack-up vessels could be used for future wind turbine assembly. Current vessels probably have enough lifting capacity for wind turbine assembly and can raise themselves high above the waters to reach the required lifting height. Furthermore, they can be relocated to another port after finalization of the wind turbine park project.*

B. Solutions for (un)loading operation

1. Vessel equipment - *A self-loading vessel (such as a wind turbine shuttle) does not require other crane vessels for wind turbine loading*
2. Crane vessel - *The sheerleg used for wind turbine assembly could also be used for wind turbine loading of transport vessels or barges.*
3. Barge exchange – *Swap bodies of trucks applied on (un)loading activities of vessels, beneficial for limiting loading times. The usage of this system does not require additional fully assembled wind turbine lifting or movements, due to the absence for the need of fully assembled wind turbine loading.*

C. Solutions for transportation operation

1. 2 Wind turbines - *The smallest transport vessel found in literature (wind turbine shuttle) is able to transport 2 wind turbines, the vessel will be introduced in the next chapter.*
2. 4 Wind turbines - *4 wind turbines is taken as normal transport capacity. This transport capacity is feasible for a jack-up vessel, Windlifter or other compact installation vessel.*
3. 8 Wind turbines - *Transport 8 wind turbines which is double the 'normal' capacity used in this research. This transport capacity is included for further investigation on whether transport capacity influences the wind turbine installation efficiency.*
4. Supply vessel - *It is possible to use a crane vessel offshore which only installs wind turbines while being fed by supply vessels. Several already existing vessels are suitable for this activity.*

D. Solutions for sailing operation

1. Barge - *The hull design for sailing is mentioned in this morphological analysis. The barge means a relatively wide body (such as a sheerleg) which has worser sailing properties and a lower transit speed.*
2. Monohull - *Vessels with a relatively small but long hull design: slender vessels.*
3. Multi-body -*The wind turbine shuttle uses a special SWATH (Small-waterplane-are twin hull) hull to increase sailing efficiency.*

E. Solutions for installation operation

1. Vessel equipment - *The installation is performed by on board equipment on the vessel*
2. Crane vessel - *The sheerleg can be used as a crane vessel at location for wind turbine installation. This solution is included in the overview.*

Results

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.

Overview of concepts for comparison

Assembling, loading, transportation, sailing and installation solutions are used in the morphological analysis (Table 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.

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. The jack-up vessel does not require additional assembling cranes onshore but shifts this part of the process to the location of installation. This reduces the installation rate of the jack-up vessel. The overview of installation is shown in Figure 2. If the components for the jack-up vessel are delivered in smaller pieces, an additional crane is still needed, which is also required if the transportation vessels of wind turbine components (from factory to port) cannot unload themselves.

Figure 2 Jack-up vessel installation method – fleet overview

Shuttle (WTS)

The wind turbine shuttle can transport two fully assembled wind turbines and is specialized for this application (Huisman, n.d.). 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. The fleet overview is shown below in Figure 3. The lay-out of the wind turbine shuttle requires a special quay to load the wind turbines which is an extra requirement for onshore activities of the wind turbine shuttle.

Figure 3 Shuttle (WTS) installation method – fleet overview

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. Sailing multiple supply vessels for the wind turbine installation requires multiple handling of the wind turbine before final installation (multiple lifts and risks) which is a complex solution. Besides, if it is financially possible to use two sheerlegs with supply vessels, it would be wise to invest in multiple wind turbine installation vessels (such as two WTS vessels). Multiple wind turbine installation vessels combined could be more efficient than using the sheerleg at location and another one in the harbor. The sheerleg installation method is shown below in Figure 4. Due to the usage of two sheerlegs, the installation rate and related numbers need to be doubled in the further comparison.

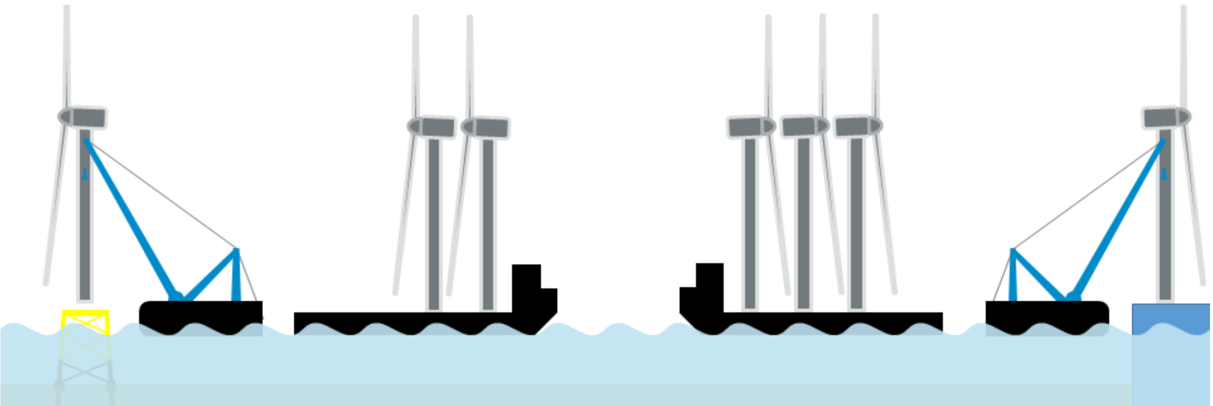

Figure 4 Sheerleg installation method with supply vessels – fleet overview

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(Ulstein, n.d.). The vessel will compensate the motions itself for safe wind turbine installation. This vessel for wind turbine installation can be used on fixed and floating foundations. The fleet overview of the Windlifter is shown below in Figure 5.

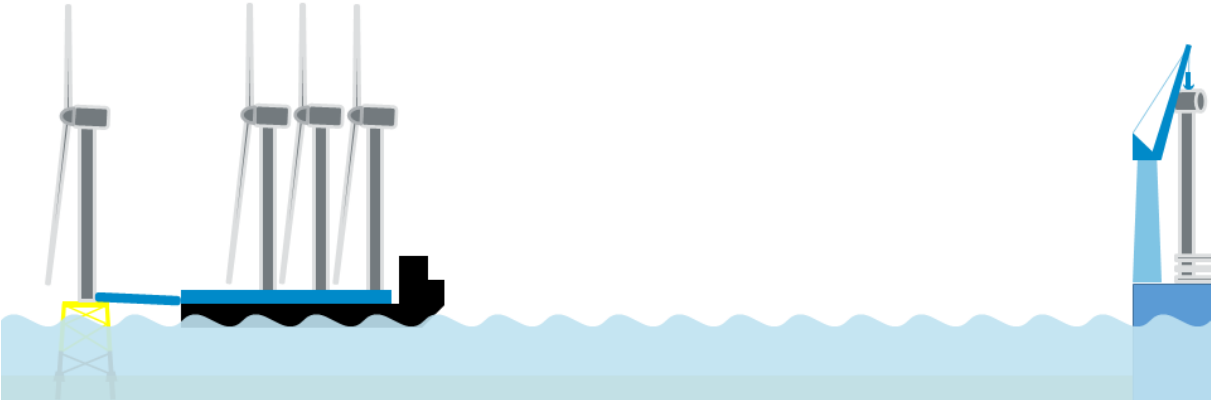

Figure 5 Windlifter installation method – fleet overview

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. The barge exchange loading process is shown in Figure 6. 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.

Figure 6 Barge crane installation method – fleet overview

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 (Figure 7).

Figure 7 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 due to the technical difference which is used in later analysis. Therefore, the PWT 4 is included in the total comparison. The comparison between these vessels will indicate whether there is a subsequent improvement when upscaling the transport capacity. These two vessels have a similar installation method compared with the Windlifter, no figure is included for these two vessels.

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. Furthermore, the cranes can work independently with other applications. When slewed 180 degrees over the stern of the vessel they can be used at their maximum lifting capacity. No other crane arrangement is found for a vessel with a small hull without wind turbines moving over the cranes.

It could be possible to use existing jack-up vessels as a crane in the ports to load the barge with wind turbines. The jack-up vessels are used as a stable movable crane vessel which is not dependent on a specific port (which is the case for a quay crane). The PWT installation vessel with barge exchange and jack-up crane vessel is shown in Figure 8 below.

Figure 8 PWT installation vessel with jack-up crane vessel – fleet overview

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 (Stamoulis, 2020) and a joint interdisciplinary project of Delft University of Technology (Guha, Thomas, Vega, & Zeijl, 2019) both in cooperation with Huisman Equipment Schiedam. 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. The estimation for loading, sailing and installing for the different concepts is shown in Table 3.

	Number of wind turbines	Weather factor	Prepare harbor	Loading of one turbine	Prepare sail out	Weather factor	Vessel speed	Vessel speed	Weather factor	Prepare installation	Installation of one turbine	Prepare sail to other location
Unit	-	-	h	h	h	-	knots	km/h	-	h	h	h
Jack-up	4	1.5	0.5	6	0.5	1.6	11.5	21.3	1.4	2.5	24	2
WTS	2	1.2	0.5	5	0.5	1	14	25.9	2	1	4	1
Sheerleg	0	1.5	0	0	0	2	7	13.0	3	3	6	1
Windlifter	4	1.5	0.5	5	0.5	1.4	14	25.9	2	1	4	1
PWT 4	4	1.5	0.5	8	0.5	1.2	14	25.9	2	1	4	1
Barge crane	4	1.2	12	0	12	1.8	8.5	15.7	2.5	2	6	1
PWT 8	8	1.5	0.5	8	0.5	1.2	14	25.9	2	1	4	1
Barge PWT	4	1.2	12	0	12	1.2	14	25.9	2	1	4	1

Table 3 Logistical comparison data of concepts

The installation rates of the concepts are calculated for all distances (Figure 9): 0 kilometers up to 500 kilometers. 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 these solutions are the installation method and usability of the vessels. This will be discussed in the following section. 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.

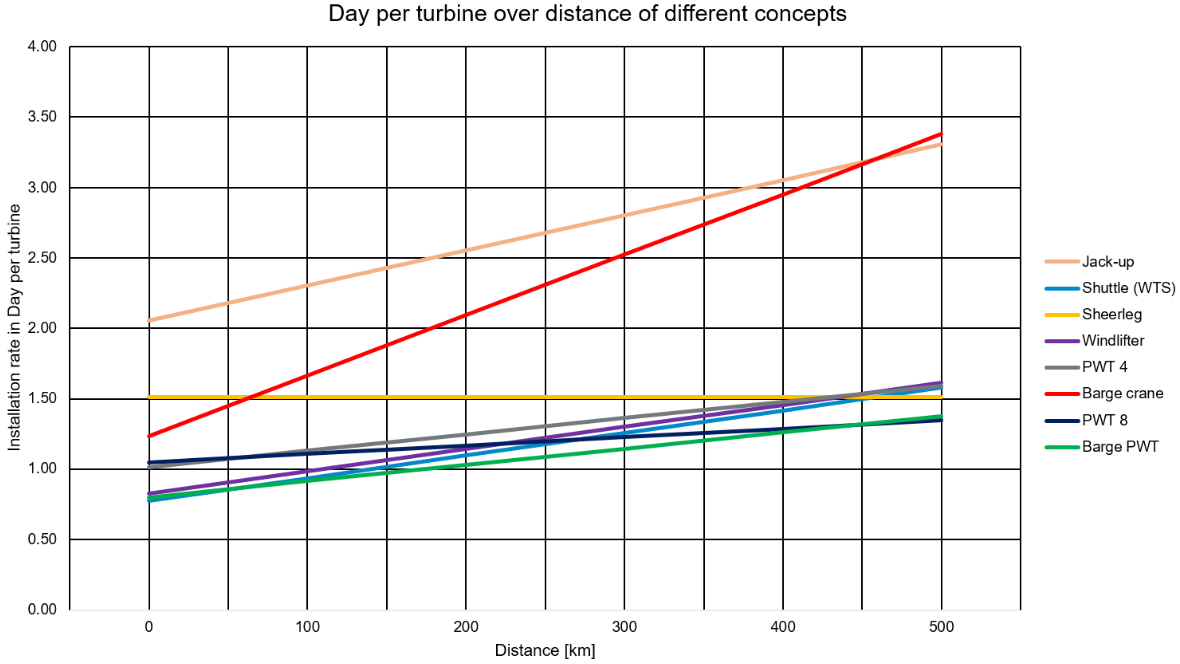

Figure 9 Installation rate (Day per turbine) over distance for all concepts

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. 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. An additional advantage of the barge exchange is the possibility to use existing jack-up vessels for wind turbine assembly on the barge in the harbor.

An overview of applications of the Barge PWT or PWT installation vessel (Parallelogram Wind Turbine installation vessel) are schematically drawn in Figure 10. The figure shows how the base of the vessel and the applications could look like. The base of the vessel 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.

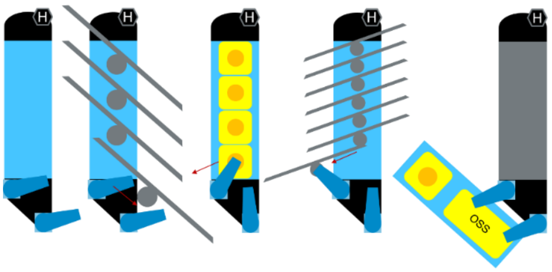

Figure 10 Schematic drawing of PWT installation vessel base and diverse applications

Discussion

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.

Conclusion

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. This vessel lay-out makes it possible to install wind turbines in diverse sizes and can also be used to perform other large installations. Cranes are used for the installation in a new set-up or PWT crane configuration. This configuration makes it possible to not depend on the size of the wind turbines since installation is performed without wind turbine blade movements over the cranes. Typical is the lifting along the tower and not to lift the wind turbine from above. The concept only requires one installation vessel and can be used in many applications. The technical solution of PWT installation is chosen due to the flexible arrangement of the cranes. Since the wind turbines do not have to be moved over the cranes, the vessel should be able to install all wind turbine sizes up to its maximum installation capacity. Furthermore, the cranes can work independently on other applications. When slewed 180 degrees over the stern of the vessel they can be used at their maximum lifting capacity.

Recommendations

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. The following recommendations are identified:

1. 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. Towering on their legs in the harbor to fulfill the required lifting height for assembling wind turbines.
2. 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.
3. 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. Ideally, the spreader design fits the wind turbine design well and collaboration is needed to fulfill this. If manufacturers of the wind turbine industry and installation industry collaborate well, installation processes can increase in efficiency. If the following process is in line with the previous process, wind turbines can be installed smoothly.
4. Wind turbine installation performed by a PWT installation vessel has influence on the lifetime of the cranes and other equipment. The installation process and crane activities need to be identified to design the equipment for its usage. The usage of the cranes on the PWT installation vessel is regularly which influences the reliability of the individual used components and overall installation vessel. Research can be performed on the PWT installation vessel as proposed in the research assignment Reliability assessment of continuous cranes. This research identified that subsequent usage of different components of equipment can influence the reliability of the equipment (Hoogendoorn, 2020). Explained is that identification of the operating processes can give insight in the usage of the different components. From this point of view, the designs of the components can be adjusted to fulfill the required reliability over lifetime.

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