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Future offshore wind farm construction and maintenance strategies

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Master Thesis

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Abstract

With the wind farms moving further from shore, new challenges arise. Technicians must visit the turbines almost daily because of the constant need for maintenance. But when the transport time from shore to the wind farm turns into hours is some kind of permanent accommodation required at the farm for the technicians to live on. Apart from accommodation the deep water is a big challenge. This paper aims to put up solutions to the future of accommodation which involves both the near future when wind farms are still built in shallow waters and the, as of now, still experimental wind turbines installed on floating foundations.

To make a credible prediction for future operation of offshore wind industry, several parameters were studied and analyzed. How turbines are assembled was briefly touched on to understand what goes in when designing the size on an installation vessel and how much time is needed per turbine in the installation process. General operation and maintenance is explored as well as the new and upcoming permanent accommodations put up at Horns Rev and DanTysk. Very important but also the least explored topics of failure rates and dayrates for vessels were compiled from as much information as is available. More information was found regarding the vessels themselves, in the sense of what they look like and how they operate, while information on their building costs were quite scarce.

From the collected data were different models put up as close to land, medium distance and long distance, which pretty much corresponds to present day, near future and future. These models were boiled down to five scenarios that can fit different wind farms and their prerequisites. The scenarios were tested on three different wind farms to see which solution fares better and the results showed that a mothership could not hold the candle to neither the crane vessel for deep water nor the platform in shallow water.

Acknowledgments

I would like to thank Anders Nilsson of Blekinge Offshore, who came up with the idea of the paper and provided material.

I would also like to thank my supervisor at Lund University, Jörgen Svensson, who helped me a lot with brainstorming and pointing me in the right direction when it came to figures and numbers as well as general course of action for offshore wind power.

Jesper Strid

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Contents

Nomenclature

APT Deck space occupied by one turbine

BE1T – Bunny ears, full tower

BE2T – Bunny ears, two-part tower

CVCC Crane vessel capital cost

CVD Crane vessel dayrate

CCDC Capital cost to dayrate coefficient

CTVD Crew transfer vessel dayrate

DA Deck area

DBT Distance between turbines

DC Decommissioning coefficient

DJUD Duration for jack-up/down

DP Dynamic positioning

DPS Duration for travel between port and site

DTP Distance to port

DTTT Duration of travel from turbine to turbine

ECN Energy research Center of the Netherlands

EP Energy production

ER Electricity revenue

FR Failure rate

FRD Failure rate downtime

IPDC Idling in port dayrate coefficient

JS Jack-up speed

JUBD Jack-up barge dayrate

LBD	Liftboat dayrate
LDO	Lifting duration offshore
LDP	Lifting duration in port
LWK	Landwirtschaftskammer Schleswig-Holstein
MC	Mobilization cost for 1000nm
MSD	Mothership dayrate
NOL	Number of offshore lifts
NOTR	Number of tours between site and port
OAG	Operational air gap
OCC	Operating cost coefficient
OD	Operational days
OY	Operational years
O&M	Operation and Maintenance
POVRT	Project owned vessel failure repair time

R2T – Full rotor in one lift, two-part tower

RD	Rotor diameter
ROI	Return of investment
SBP	Sea bed penetration
SD	Sea depth

SP5 – Individual parts, 5 lifts (full tower)

SP6 – Individual parts, 6 lifts

SPIV	Self-propelled installation vessel
SPIVD	Self-propelled installation vessel dayrate
SS	Service speed
SWL	Safe working load

TDC	Total number of days for construction
TDR	Total number of days for repairs
TIF	Turbines in farm
TIV	Turbine installation vessel
TLP	Total leg protrusion
TOD	Number of turbines on deck
TSAP1	Time spent at port per turbine
WMEP	Wissenschaftliches Mess- und Evaluierungsprogramm

1. Introduction

1.1. Background

Construction of wind farms out at sea are becoming more viable since the demand for renewable electricity is rising and many of the best spots on land are already taken. The problem is quite the same for the nearest spots at sea, they are all taken. As such are wind farms placed increasingly further from land in what still is relatively shallow waters. But with nearly daily maintenance being mandatory and trip lengths being in the hours, accommodation in some form becomes relevant. Furthermore, is the landscape of construction everchanging, with new turbines being tested all the time. The size of the turbines puts pressure on the construction vessels to evolve and the distance to shore is changing how operation and maintenance is handled, and at the core of everything are costs. Combining the vessels used for construction with what is needed for operation and maintenance could save money.

1.2. Assignment

The project explores present methods of constructing and handling operation and maintenance from the perspective of seaborne vessels for the purpose of finding solutions for the future development of wind farms. Furthermore, are different scenarios for the future discussed and set up. Economic findings from the present are evaluated and brought into a calculator used to compare the different future scenarios. The calculator is then used on three different wind farms to see how it holds up.

1.3. Problem statement

As this field is fairly unexplored will information be scarce. Costs and numbers in general are company secrets and hard to get by. Vessel costs and dayrates are hard to get by and even more detailed information such as the components of dayrates is further shrouded. Information on the vessels, which is essential to compute construction time, is not hard to get by. Things like their size and speed are found on the owner's homepages.

The vessels will build the basis for the project. Information on construction time is important and so is the failure rates for wind turbines. More information needed for the economic calculator is how the spot market works for vessels, how fast one can be leased when a part in the wind turbine fails. Furthermore is costs for electricity needed and vessel construction costs. Identifying the future problems and finding solutions will require some brainstorming.

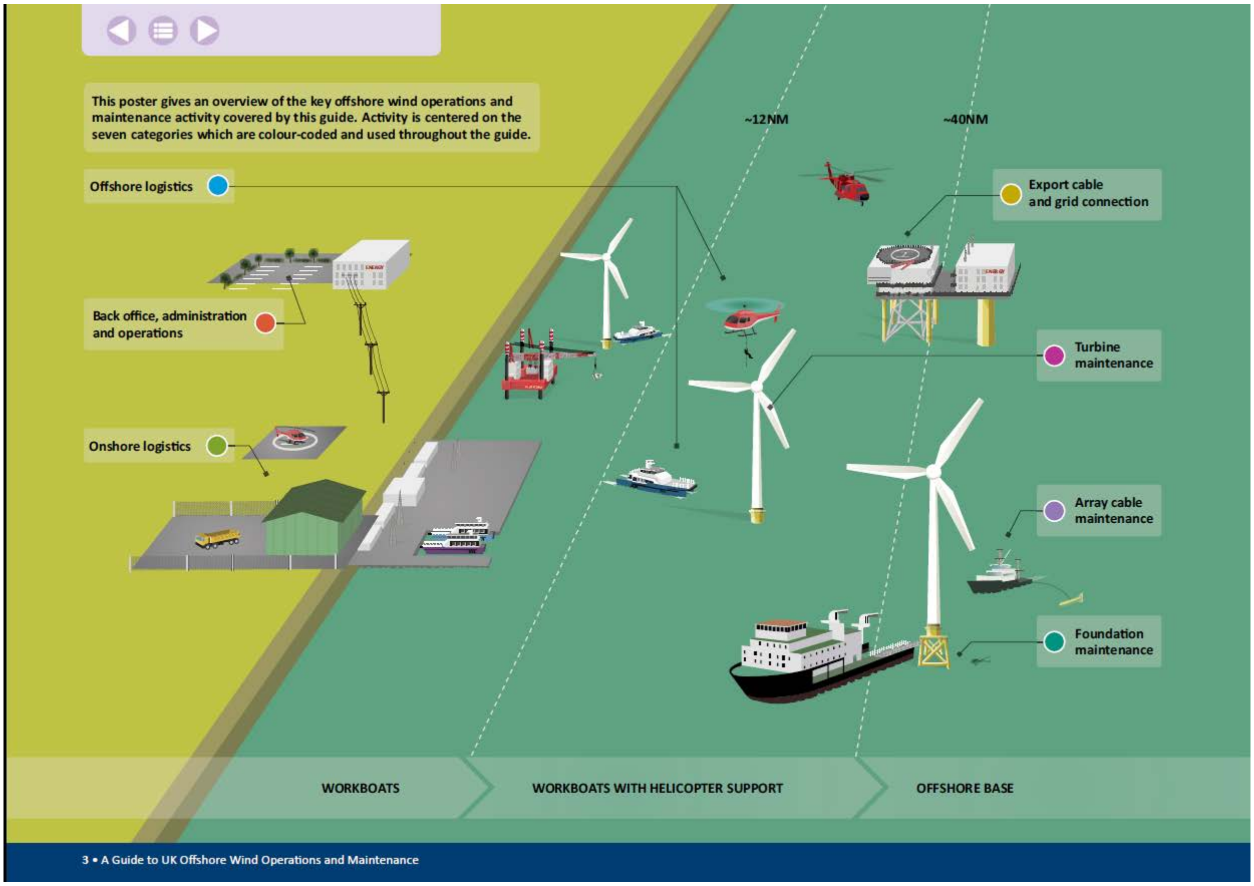


Figure I. Offshore wind farm operation and maintenance (GL Garrad Hassan, 2013).

Different scenarios for the future are found in figure I. Close to land where the conventional method of today is being used, a bit further out where workboats are starting to lack and far from shore where accommodation is not up for question, it is mandatory.

1.4. Purpose

The purpose of the project is to create solutions for the future of offshore wind farms regarding installation vessels. The work will include, among other things:

- Compilation of existing solutions
- Proposals for future solutions
- Creation and testing of an economic calculator

2. Literature breakdown

The literature will concentrate on what is important to know for an offshore wind farm, the vessels used and where the costs emerge.

2.1. Construction

Construction is the phase when turbines are put together and installed. It is very hectic and many people and vessels are involved at the same time.

2.1.1. Turbine assembly

The vessels used today during construction utilize a variety of methods to get the wind turbine in place at sea. The turbine can be put together according to a couple of ways. Most common is piece by piece or partially constructed with some variations. An all-out piece by piece approach requires more time at sea for construction but minimizes the risk which is associated with lifting bigger pieces. The individual pieces of a wind turbine consist of the following: upper and lower part of the tower, nacelle, hub, and three blades. Different vessels have different solutions to putting the turbine together; the upper and lower part of the tower can be transported in one piece, the nacelle, hub and two blades can be pre-assembled on land, this is called a bunny ears arrangement and is displayed in figure 1, the hub and three blades can be pre-assembled which is displayed in figure 2, or the complete turbine can be transported all pre-assembled.

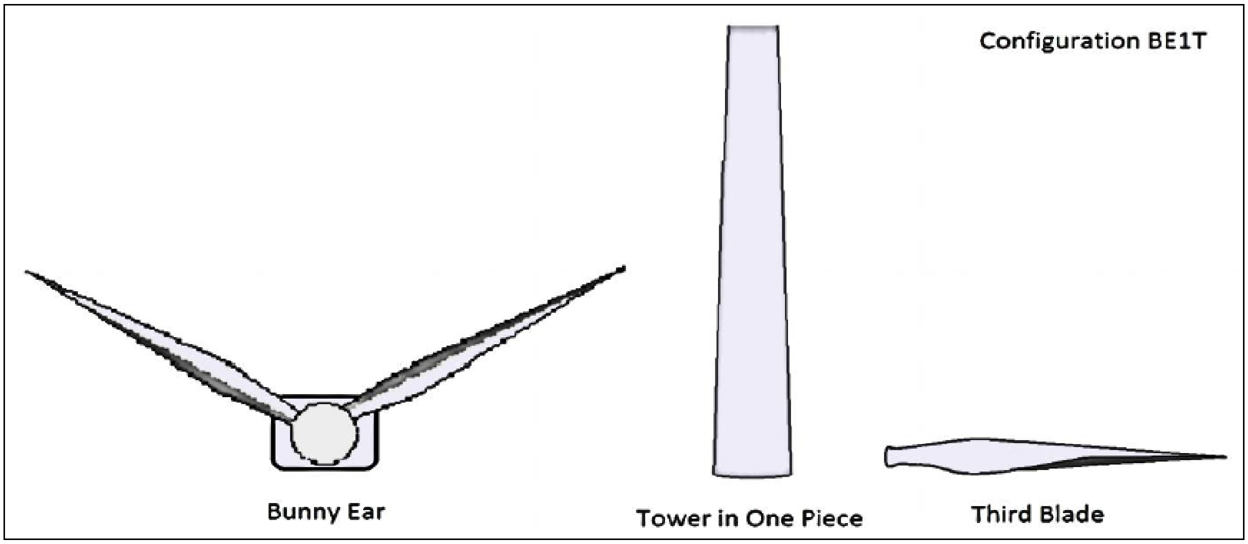


Figure 1. The Bunny ear configuration with the tower in one piece (Uraz, 2011).

The different ways of doing it comes with different kinds of drawbacks such as while the bunny ears approach requires less amount of lifts, the one big lift is very vulnerable to wind conditions. The more the turbine is pre-assembled on land, less time is spent at sea putting it together. While this seems like a desired approach, bigger pieces amount to less practical storage aboard the vessels, namely the hub with all three blades pre-assembled on land can take up all storage space on a vessel. An on land fully constructed wind turbine requires less time being put in place compared to the alternatives but it is very sensitive to strong winds and waves when doing the crucial lift.

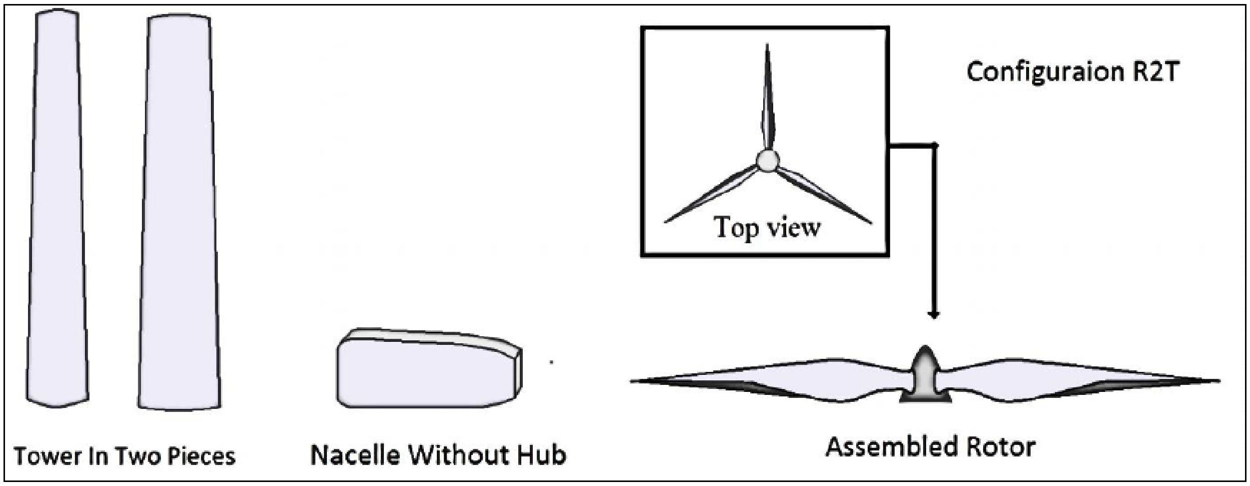


Figure 2. Hub and all three blades pre-assembled and the tower in two pieces (Uraz, 2011).

Installation time varies from turbine to turbine and between vessels. Installation time for each major piece, i.e. tower, nacelle and rotor, takes about eight hours each, using the A2seas Sea Installer (Fact sheet - Industrialization of Offshore Logistics, 2013). For the Lillgrund offshore wind farm, one turbine took approximately 16 hours (Flodérus, 2008). The time it takes at the site to assemble the turbine is shown in figure 3. Noteworthy is that the wind speed must be lower than 8 m/s for all cases and the wave height must be lower than 2 meters for all cases except the fully assembled turbine. The reason for the lower wave height in the last case is that the vessel used does not have any jack-up legs and is as such a bit vulnerable to higher waves. The requirement of lower wave height makes the window of operation a bit slimmer but the time it takes to erect the turbine is in turn much faster.

	Min. duration [h]	Max. duration [h]	Avg. Duration [h]	Wind speed limit [m/s]	Hs limit [m]
Individual components	30	39	34.5	8	2
Bunny ears with 2-part tower	21	28	24.5	8	2
Bunny ears with 1-part tower	15	20	17.5	8	2
Pre-assembled rotor with 2-part tower	24	30	27	8	2
Pre-assembled rotor with 1-part tower	18	22	20	8	2
Fully pre-assembled	8	8	8	8	0.75

Figure 3. Time estimations for assembling a turbine at sea (Maples, Saur, Hand, van de Pietermen, & Obdam, 2013).

Table 1 displays the mean wind turbine installation time for different wind farms. The different farms used between one and two installation vessels and the installation time is including transport from port, loading in bay etc. The number in parenthesis is the number of days per installation vessel and turbine. The installation methods are quite analogous with figure 3 with SP6 being Individual components, SP5 being Individual components with the exception of the tower being assembled on land, R2T being Pre-assembled rotor with 2-part tower, BE2T is the Bunny ears with 2-part tower and BE1T being Bunny ears with 1-part tower.

Table 1. Installation rate for a selection of wind farms (Kaiser & Snyder, 2010).

Project	Number of major vessels	Duration of Installation (months)	Number of turbines total	Installation rate (days/turbine)	Installation method
Lillgrund	1	2.5	48	1.6	R2T
OWEZ	1	3.5	36	2.9	BE1T
Kentish flats	1	4	30	4.0	BE2T
Scroby Sands	1	3	24	3.8	BE2T
Nysted	1	3	72	1.3	R2T
Horns Rev 1	2	4	80	1.5 (3.0)	BE2T
Burbo Bank	1	1.5	25	1.8	SP5
Princess Amalia	2	11	60	5.5 (9.5)	BE1T
Middlegrunden	2	1.25	20	1.9 (3.8)	R2T
North Hoyle	2	3	30	3.0 (6.0)	BE2T
Alpha Ventus	1	1.5	6	7.5	R2T
Thornton Bank	2	2.5	6	12.5 (25.0)	R2T
Robin Rigg	2	9	60	4.5 (9.0)	BE2T
Horns Rev 2	1	6	91	2.0	R2T
Lynn and Inner Dowsing	1	3.5	54	1.9	SP6
Barrow	1	5	30	5.0	BE2T
Arklow	1	2	7	8.6	R2T
Average				4.1 (5.7)	

SP6 – Individual parts, 6 lifts

SP5 – Individual parts, 5 lifts (full tower)

R2T – Full rotor in one lift, two-part tower

BE2T – Bunny ears, two-part tower

BE1T – Bunny ears, full tower

Foundations

When installing foundations, a wider variety of vessels can be utilized. Though much heavier than the turbines, because of their simplicity when installing much less sophisticated vessels such as barges are suitable. The most important foundations are gravity-based, monopile, tripod and jacket. Gravity-based are best used in quite shallow water because of their immense size and weight. Though made from cheap materials, the gravity-based foundations must be carried by a very large vessel in which cases barges come in handy. A large barge can carry several foundations with the help of a tug boat. Monopiles are used in deeper water and have to be hammered into the ground by a vessel with specialized equipment. The monopiles are transported via the same vessel that carries the hammer or by floating and being pulled by a tugboat. Installing a monopile cannot be done if the seabed is made up of hard rock in which case the hammer will not be able to drive the monopile into the ground. All but the gravity-based foundation requires a transition piece onto which the turbine is installed. This transition piece amounts to yet another transport.

2.1.2. Turbine models

Turbines used today

Figure 4. A Siemens swt-3.6-120 (Siemens, 2015)

Most common turbines used today produce effects in the range around 3 MW. Common features are upwind, three blades and heights of around 90 meters. One such turbine is the Siemens swt-3.6-120, displayed in figure 4. These turbines produce an effect of 3.6 MW which is in its name and has a diameter of 120 meters. Cut-in speed is 3-5 m/s and nominal speed is 12 m/s. The rotor weighs 100 tonnes and the nacelle 140 tonnes (Siemens, 2015).

Turbines in the future

At very long distances from land, foundations and construction as a whole can be completely different due to the depth and most likely will all foundations be floating. Configurations range from a single foundation in the shape of a monopile being tugged to site, floating tripods housing one turbine to bigger constructs suited for several turbines at once. Figure 5A shows a turbine installed off the coast of Portugal which was fully constructed on shore before being tugged to the site. Fully functional and connected to the grid, the turbine produced 10 GWh between 2012 and

2014 (Carrington, 2014). In 2009 a floating foundation was constructed in Norway named Hywind which after construction was being tugged to Åmøy Fjord where in the calm waters a turbine was assembled on top of the foundation. The turbine was tugged to site where it was moored according to figure 5B at a depth of 200 m (Patel, 2009).

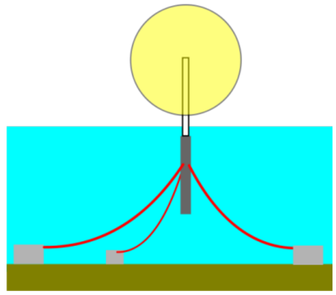
A)  B) 

Figure 5A. A single turbine mounted on top of a tripod off the shore of Portugal. (Hill, 2015); Figure 5B. Concept of a turbine mounted on top of a spar buoy moored to the sea bed. (Wikimedia Commons, 2009)

After the foundations are produced onshore they are either tugged to site by a tugboat or possibly in the future, self-propelled. As seen in the Hywind case where the foundation reached 100 meters below surface the turbine had to be mounted offshore whilst the tripod solution only dipped 20 meters below surface and thus the turbine being able to be mounted close to shore or in shallow water. As such a crane mounted onshore with the tripod moored or in a dry dock could be used when assembling the turbine. Alternatively, a jack-up like the ones used today could be used if the tripod can be reliably still during assembly through the means of mooring to the seabed or a solution where the vessel is connected to the foundation. A situation such as the Hywind would require a construction vessel with a long and strong crane that can do all the heavy lifting without jack-up legs.

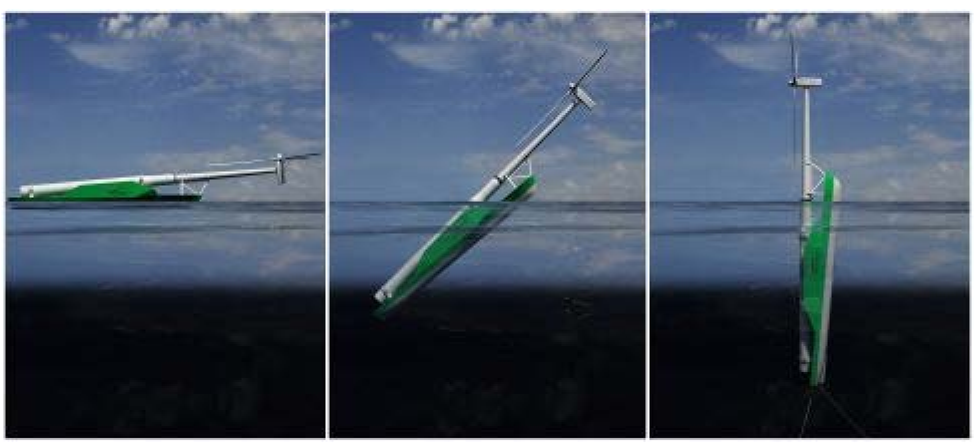


Figure 6. The concept Windflip, a vessel transporting a fully assembled, floating wind turbine. (Barker, 2012)

Other solutions for the future include the Windflip concept, where one turbine at a time, fully constructed, is transported from port lying down on the vessel. After reaching the desired location is the vessel starting to take in water so that it flips into an upright position according to figure 6. The benefit would be that the wind turbine is completely constructed on land and also that the Windflip barge can travel at speeds eight times faster than what is possible today for floating wind turbines.

2.1.3. Construction time estimates

A study from Visby, Sweden, compiled a lot of data from different wind farms and derived a formula to calculate construction time which is displayed in table 3. The construction time is directly dependent on the vessel and the construction configuration and partially to the size of the turbine. Firstly, the leg length could be a limiting factor but most vessels that are used have legs supporting water depths well above where turbines are installed today. Important differences between vessels are their service speed which can range between 10-14 knots but some are as low as 8 knots. This increases the time travelling from port to site. The vessels also differ in jack-up speed but it is not as big of a factor. Deck space and turbine configuration play a big part in the construction time. As stated before, having more parts assembled on land decreases the time required on sight but the tradeoff is that some of the lifts can be more dangerous and more deck space is used and thus fewer turbines can be transported every roundtrip. Larger vessels have larger deck spaces and are generally also faster. The different properties and their abbreviations are found in table 2. (Uraz, 2011)

Table 2. Parameters used for calculating the construction time (Uraz, 2011).

Parameters		
LDP	Lifting Duration-Port	= 3 hours (variable)
LDO	Lifting Duration-Offshore	= 3 hours (variable)
NOL	Number Of Offshore Lifts	BE1T → 3 BE2T → 4 R2T → 4 SP5 → 5 SP6 → 6
APT	Deck space occupied by one Turbine	BE1T → 510 m^2 (averaged) BE2T → 648 m^2 (evaluated) R2T → 369 m^2 (averaged) SP5 → 353 m^2 (averaged) SP6 → 491 m^2 (averaged)
Boat Properties		
DA	Deck Area (open space for Cargo)	**Variable**, $meter^2$
JS	Jack Up Speed	**Variable**, meter/minute
SS	Service Speed	**Variable**, knots
OAG	Operational Air Gap	**Variable**, meters
SBP	Sea Bed Penetration	5 Meters (assumed)
TLP	Total Leg Protrusion	= SBP + OAG + SD (meters)
Farm Properties		
TIF	Number of Turbines in the Farm	**Variable**
DTP	Distance to Port	**Variable**, miles
SD	Sea Depth	**Variable**, meters
DBT	Distance Between Turbines	= 6 x RD (meters)
Turbine Properties		
RD	Rotor Diameter	**Variable**, meters
Case Specifics		
TOD	Number of Turbines on the deck	= DA / APT (Rounded)
NOTR	Number of Tours between port and site	= TIF / TOD (Rounded Up)
DPS	Duration of Travel port and site	= DTP / SS (hours)
DTTT	Duration of Travel from Turbine to Turbine	= (DBT /1852)/(SS/3) (hours)
DJUD	Duration of Jacking (elevation and lowering. per turbine)	= (TLP / (JS x 60)) x 2 (hours)
TSAP1	Time Spent at Port per turbine	= LDP x NOL (hours)

The site properties also influence the construction time. Apart from the obvious parameter, the number of turbines, is the distance to port very important. Less important for the turbines is the water depth which is a bigger factor when placing the foundations. The distance between turbines is the standard approximate distance of six times the diameter of the rotor and it adds to the travel time.

Table 3. Time estimations calculated from parameters found in table 2 (Uraz, 2011).

A1	**Total duration**	= (DTTT x (TIF - 1)) + (TIF x (TSAP1 + DJUD + (LDO x NOL))) + (NOTR x DPS x 2)
B	**Total time spent on sailing**	**= (DTP/SS) x 2 x NOTR**
C	**Total time spent on the installation**	= (TIF x (DJUD + (LDO x NOL))) + (DTTT x (TIF - 1))
D1	**Total time spent at the port**	**= TSAP1 x TIF**

The time spent travelling between port and site depends on the number of turbines, how many turbines per batch, the speed of the vessel and the distance. Time spent on site depends on the number of lifts per turbine, the number of turbines, jack-up speed and the water depth. Time spent in port depends on configuration and how many turbines per batch.

2.2. Operation and maintenance

Operation and maintenance, O&M, is the longest phase for any wind farm or single turbine. It is during this time the turbine produces energy and when many of the unforeseen problems come to light.

2.2.1. Operation and maintenance concepts

The most prominent problems when dealing with operation and maintenance is the transport time from port to the wind farm and the availability in accordance with the weather. Transport vessels are limited to a certain height of waves when it is no longer possible to gain access to the wind turbine or hoisting spare parts. As wind farms are moved farther out to sea, less time during a working day can be spent doing repairs. (GL Garrad Hassan, 2013)

Maintenance can be both scheduled and unscheduled. All turbines have regular scheduled maintenance according to standards and experience taken from earlier projects. These repairs and/or inspections can be planned out to take place when work force, spare parts and vessels are available and more importantly, when the weather tends to be most suitable. Unscheduled maintenance causes a substantial amount of downtime and even more so when large parts have to be changed because of the long wait that is involved with getting new spare parts and getting a hold on a vessel that is capable of changing it. Waiting time for jack-up vessels can be quite severe and strong weather can greatly affect the cost for repairs.

Helicopter support has been tried out for wind farms and is mainly deployed when the weather is not suitable for transport vessels on the sea. Use of helicopters decreases transport time to the wind farm but cannot carry or install any parts larger than what the mechanic can carry in the toolbox. To be able to land a worker onto a turbine, the turbine has to be fitted with railings on the top of the nacelle. (GL Garrad Hassan, 2013)

When the port from where the workboats departure is stationed far away from the wind farm, a purpose-built port could be a suitable solution. A new purpose built port need not to be very sophisticated but just enough to support the transportation vessels and store some of the basic spare parts. Cutting the travel time from port to wind farm can have a big impact on the cost from turbine downtime. During larger, scheduled repairs, a larger port with more options to load larger spare parts onto the vessels can be used since travel time is not of the essence.

Operation and maintenance is divided between the project owner and the company delivering the wind turbines. This is especially true for the first few years of O&M when most of the technicians are employed by wind turbine manufacturer. (GL Garrad Hassan, 2013) After the first set of years more people employed by the project owner are integrated in the O&M workforce and eventually the team solely consists of workers from the project owner. This approach is due to that the expertise regarding the wind turbines are found in the manufacturers own contracted workers. The project owner can choose to either have this knowledge taught to its own workforce or to keep contracting the workers from the manufacturer. A third option would be to contract a third party. This would be a company with extensive knowledge in O&M and specifically for the type of wind turbine that is used. This third option is not highly exploited for various reasons such as the turbine manufacturers hold on intellectual property and the need for special knowledge on specific turbines. A significant problem when it comes to dividing responsibility for O&M is sorting out the risks. The project owner is ultimately the one who has to deal with lost revenue and working that risk into a contract with the O&M provider can be a hardship. Thus, this works as another incentive, besides possibly lowering costs, to bring the O&M in-house.

ECN, Energy research Center of the Netherlands, is providing an easy to use program, O&M Tool, which can estimate cost and failure rates for the first few years of a wind farm (Obdam, Rademaker, Braam, & Eecen, 2007). The tool uses input such as weather conditions and SCADA system outputs and converts it to a detailed list of useful information such as costs, downtime and required materials and vessels (Maples, Saur, Hand, van de Pietermen, & Obdam, 2013). An even more extensive tool has been developed by ECN called O&M Calculator. The O&M Calculator provides more detailed output information, giving examples of more realistic repair strategies because of the improved assumptions the tool is able to do (https://www.ecn.nl, Retrieved 2015-7-21).

Accommodation platform

A new concept of dealing with daily maintenance is that of an accommodation platform. This structure is situated at the wind farm, thus cutting travel from port. The accommodation platform is outfitted with daily necessities such as living quarters, a mess hall, living room spaces etc. The crew transfer vessels are moored to the structure and easily accessible. A permanent accommodation on site can house service workers all year round. The situation becomes very similar to an oil rig where personnel stay for period of a couple of weeks and work in shifts. Depending on the size of the wind farm and subsequently the accommodation, anything from small spare parts to very big ones such blades or gearboxes can be stored on site.

Figure 7. The transformer station and permanent accommodation at Horns Rev 2. (Oglaend System, u.d.)

This solution has been tried out at Horns Rev 2, seen in figure 7, where it accommodates 24 people as well as small spare parts and is easily accessible to the transformer station via a gangway (Dong, u.d.). Each of the 91 turbines are visited approximately 10 times every year and the 60 km one way trip takes two hours for a service boat (Krøyer, 2009). If the accommodation is built in conjunction with the transformer station as at Horns Rev 2, the space atop said building can be utilized as well and in the case of Horns Rev 2 it is being used by a helipad which can be used to transport people from land to the platform.

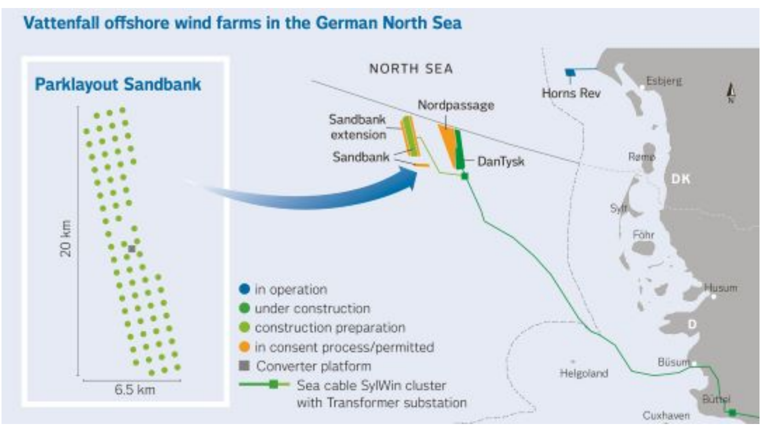


Figure 8. The three wind farms Horns Rev, DanTysk and Sandbank. (Subsea World News, 2015)

Vattenfall did in 2015 build a more than thrice as big accommodation for their DanTysk wind farm being able to house 50 people for the price of $56 million (Wittrup, 2015). In close proximity to the DanTysk wind farm is Sandbank wind farm which is also owned by Vattenfall. As such is the accommodation platform being shared by the two wind farms. A one-way trip for a workboat to Sandbank takes 3.5 hours and 6 hours for a larger vessel (Vattenfall, 2015). The doubling in manpower that can be housed on the DanTysk accommodation comes with a five times increase in weight as can be seen in the comparative table 4. A site housing several hundred turbines could require double the manpower and following the trend seen in table 4 could that platform be quite enormous.

Table 4. Comparing size and accommodation capacity for Horns Rev 2 and DanTysk.

	Horns Rev 2	DanTysk
Housing	24	50
Size	750 m2	2500 m2
Weight	422 tonnes	2500 tonnes
Distance	60 km	70 km
Turbines	91	80+72

2.2.2. Failure rates

The parts that need a jack-up vessel are the nacelle, the blades and hub, the generator, the drivetrain and the transformer (Salomonsen, 2015). Despite only amounting to 25% of the failures, these parts are responsible for 95% of the downtime (Sheng, 2013). Figure 2 showcases the failure rates for the different parts of the turbine in failures per year and turbine. On the right-hand side is the number of days the turbine is not producing power every time it breaks down. The two studies referenced in the figure are WMEP, Wissenschaftliches Mess- und Evaluierungsprogramm, and LWK, Landwirtschaftskammer Schleswig-Holstein. WMEP are made up of data from 1500 on-shore wind turbines from 1989 to 2006 and LWK is comprised of data from 650 wind turbines situated in the northern parts of Germany taken from 1993 to 2006.

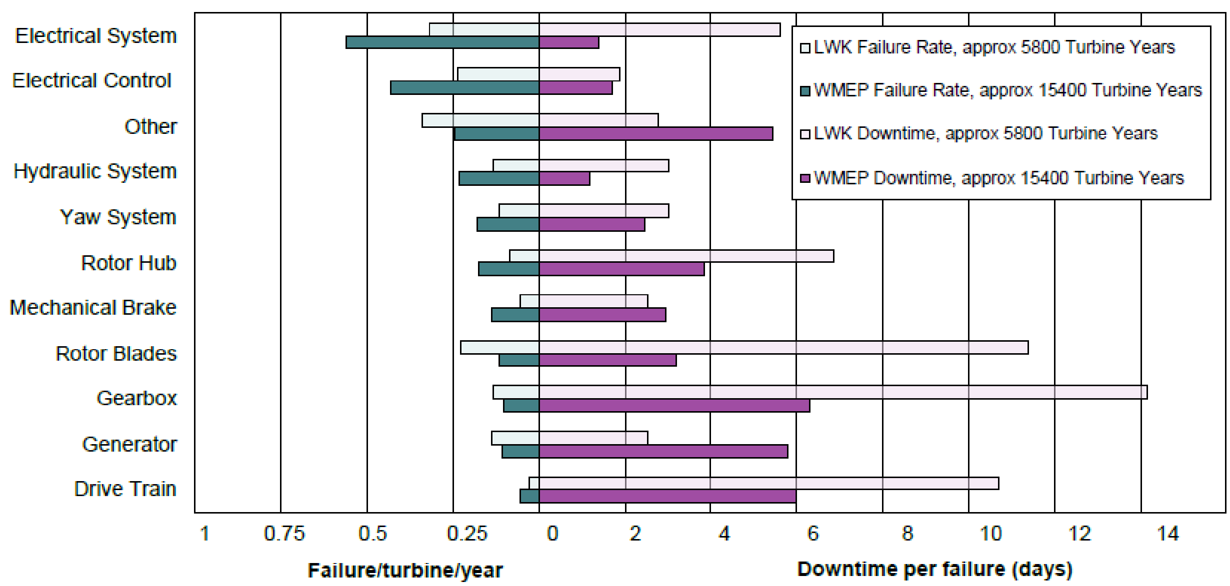


Figure 9. Failure rates for different components and the downtime they generate (Sheng, 2013)

When comparing the failure rates between the two, no conclusive pattern can be seen. The same is true regarding the downtime even though the bigger parts seem to generate a substantially longer downtime in the LWK study. This could be because that some of the turbines are situated off-shore which complicates the repairs.

Table 5. Failure rates in failure/turbine/year and downtime in days/turbine/year.

	Failure rates		**Downtime**		**Combined**	
	(WMEP)	(LWK)	(WMEP)	(LWK)	(WMEP)	(LWK)
Drivetrain	0,059	0,029	6	10,706	0,354	0,310474
Rotor blades	0,118	0,235	3,176	11,412	0,374768	2,68182
Generator	0,103	0,14	5,882	2,588	0,605846	0,36232
Gearbox	0,103	0,14	6,353	14,118	0,654359	1,97652
Sum	0,383	0,544			1,988973	5,331134

The failure rate and downtime presented in table 5 corresponds to what is found in figure 10. The sum of all failures for WMEP, 0.383 failures/turbine/year, means that a turbine breaks down 7.66 times over the course of 20 years. This is a quite high number comparing to another study reporting major breakdowns that require a jack-up vessel in the numbers between one and four times in 20 years (Jack-up vessel optimisation, 2014). Additionally, failures can be repaired in batch, which can be difficult to quantify. The downtimes displayed in table 5 are very low considering that these parts require a jack-up vessel which has a lead time that depends on if the failure is known to happen before it actually happens. These unscheduled repairs can cause a downtime of three to six months depending on the state of the vessel market (Jack-up vessel optimisation, 2014).

2.3. Vessels used

The vessels used throughout the wind farm lifetime varies greatly. For this project though is only the construction vessels and crew transfer vessels of interest.

2.3.1. Construction vessels

The construction vessels are all comprised of a large deck space where the turbines are stored in a certain way, a building from which the vessel is controlled as well as the housing for the personnel, a crane used to put the pieces in place and a number of legs used to elevate the vessel above the surface of the water. The choice of construction vessel is dependent on the number of turbines and the size of said turbines. Whilst larger vessels cost more, they are generally faster both in transit and in regard to putting up the turbine.

Liftboat

The smallest vessel used for construction is the liftboat, displayed in figure 10 with specific information displayed in figure 6. It is not very common in Europe and is predominantly used in the oil and gas industry. It is self-propelled, has a travelling speed of 4-6 knots and has three legs. The crane is usually not very long and as such are the legs instead very long to reach all the way to the top of the nacelle. The crane is however strong enough to lift all pieces one by one. The deck space is fairly small and can at most carry 1-2 full turbines (Kaiser & Snyder, 2010).

Figure 10. The liftboat Titan 2 (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Table 6. Specific information for the liftbaot Titan 2 (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Vessel Name	Titan 2
Vessel Type	Liftboat
Status	Operational
Owner	KS Drilling
Flag	Panama
Yard	Semco Shipyard Lafitte Louisiana (US)
Year Built	2007
Length [m]	52
Breadth [m]	35
Max. Draft [m]	2.9
Max. Water Depth [m]	40
Cargo Area [m2]	-
Payload [t]	-
Main Crane Load [t@m]	176 t @ 12 m
Crane Height [m]	-
Speed [knots]	7.0
Jackup Legs	3
Accommodation [persons]	-
Dynamic Positioning System	-
Known Offshore Wind Projects	Gunfleet Sands (UK)

Jack-up barges

The jack-up barges are not self-propelled which leaves some extra space on deck depending on accommodation facilities. The size varies from barges as small as a liftboat such as the one in figure 11, to barges like the one in figure 12 that's able to carry several wind turbines. All barges have four legs and the cranes also vary in size depending on the size of the barge.

Figure 11. The jack-up barge Vagant is one of the smaller vessels in that class (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Table 7. Specific information for the jack-up barge Vagant (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Vessel Name	Vagant
Vessel Type	Jackup Barge
Status	Operational
Owner	Geosea
Flag	Netherlands
Yard	IHC Merwede (Netherlands)
Year Built	2002
Length [m]	44
Breadth [m]	23
Max. Draft [m]	4.2
Max. Water Depth [m]	30
Cargo Area [m2]	-
Payload [t]	1,000
Main Crane Load [t@m]	-
Crane Height [m]	-
Speed [knots]	-
Jackup Legs	4
Accommodation [persons]	10
Dynamic Positioning System	None

Figure 12. The jack-up barge Sea Jack is in the higher end of sizes (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Table 8. Specific information for the jack-up barge Sea Jack (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Vessel Name	Sea Jack
Vessel Type	Jackup Barge
Status	Operational
Owner	A2SEA
Flag	Denmark
Yard	-
Year Built	2003
Length [m]	91
Breadth [m]	33
Max. Draft [m]	5.5
Max. Water Depth [m]	30
Cargo Area [m2]	2,500
Payload [t]	2,500
Main Crane Load [t@m]	800 t
Crane Height [m]	-
Speed [knots]	-
Jackup Legs	4
Accommodation [persons]	23
Dynamic Positioning System	None
Known Offshore Wind Projects	Ormonde (UK) Sheringham Shoal (UK)

The difference in size between jack-up barges is displayed clearly when comparing table 7 and 8 where the length is more than doubled for Sea Jack compared to Vagant.

TIV

Turbine Installation Vessel, TIV, or Self-propelled Installation Vessel, SPIV, is the largest type of vessel used during construction. The size ranges from the bigger jack-up barges up to vessels over 150 meters in length. The smaller sizes are reminiscent of a jack-up barge only that it is self-propelled, hence the name. Vessels in the upper range generally have six legs, a large deck space, accommodation for upwards of hundred persons, long and very strong cranes and helipad. The transit speed is faster than both liftboats and the combination of jack-up barge and tug and reaches 8-12 knots. The TIV Sea Installer, displayed in figure 13, is in the middle of the segment with its four legs and length of 132 meters (table 9).

Figure 13. The TIV Sea Installer (Sustainable News, 2014)

Table 9. Specific information for the TIV Sea Installer (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Vessel Name	Sea Installer
Vessel Type	TIV
Status	Operational
Owner	A2SEA
Flag	Denmark
Yard	Cosco (China)
Year Built	2012
Length [m]	132
Breadth [m]	39
Max. Draft [m]	5.3
Max. Water Depth [m]	45
Cargo Area [m2]	3,350
Payload [t]	5,000
Main Crane Load [t@m]	800 t @ 24 m
Crane Height [m]	102
Speed [knots]	12.0
Jackup Legs	4
Accommodation [persons]	35
Dynamic Positioning System	DP 2

Floating sheerleg

A notable floating sheerleg vessel is the Rambiz 3000, displayed in figure 14 which was used in the Beatrice wind farm where two large 5 MW wind turbines were completely pre-assembled and lifted in place on top two jacket foundations. A floating sheerleg vessel utilizes two cranes to lift structures in place. The two cranes can be used separately or in conjunction for a dual lift making it able to lift clunky or very heavy objects with a weight up to 1700 tonnes (table10). Rambiz 3000 is not relying on jack-up and is more barge-like in its appearance and function. This makes it suitable for use in shallow as well as deep waters. (Scaldis SMC, 2013)

Figure 14. Rambiz 3000 lifting a transition piece in place (Deme-Group, u.d.)

Table 10. Specific information for the floating sheerleg vessel Rambiz 3000 (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Vessel Name	Rambiz
Vessel Type	Heavy Lift
Status	Operational
Owner	Scaldis SMC
Flag	Belgium
Yard	Huisman-Itrec Schiedam (Netherlands)
Year Built	1995/2000
Length [m]	85
Breadth [m]	44
Max. Draft [m]	3.6
Max. Water Depth [m]	-
Cargo Area [m2]	1,500
Payload [t]	-
Main Crane Load [t@m]	1,700 t
Crane Height [m]	79
Speed [knots]	6.1
Jackup Legs	-
Accommodation [persons]	70
Dynamic Positioning System	None

Heavy lift vessel

Heavy lift vessels are very big reaching well over 150 meters in length and are used mostly to install the very heavy transformer station and gravity foundations. This type of vessel is predominantly used in the oil and gas industry to install oil rigs. Heavy lift vessels have no jack-up legs but instead utilizes dynamic positioning and a strong crane to get the pieces in place. One such enormous vessel, Elog Strashnoy displayed in figure 15, can lift 5000 tonnes (table 11).

Figure 15. The heavy lift vessel Oleg Strashnov (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Table 11. Specific information for the heavy lift vessel Oleg Strashnov (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

Vessel Name	Oleg Strashnov
Vessel Type	Heavy Lift
Status	Operational
Owner	Seaway Heavy Lifting
Flag	Cyprus
Yard	IHC Merwede (Netherlands)
Year Built	2011
Length [m]	183
Breadth [m]	47
Max. Draft [m]	14
Max. Water Depth [m]	-
Cargo Area [m2]	4,000
Payload [t]	-
Main Crane Load [t@m]	5,000 t @ 32 m
Crane Height [m]	102
Speed [knots]	14
Jackup Legs	-
Accommodation [persons]	220
Dynamic Positioning System	DP 3

2.3.2. O&M vessels

Many of the failures occurring in the wind turbine can be fixed by service personnel without the need of changing large components. Thus, in most cases a transportation vessel is enough to get the technicians onto the turbine to make the necessary repairs. Occurrences when parts less than two tonnes in weight have to be replaced, the same kind of transportation vessel could suffice in transporting both technicians and spare parts. The spare parts are hoisted up by the internal crane on the wind turbine. Wear and other complications regarding the foundations require a vessel with diving equipment and divers. During the less frequent instances when larger parts such as the gearbox or blades have to be changed a larger vessel must be deployed. Such vessels are mostly the same kind that is used when installing the wind turbine, i.e. a jack-up.

Figure 16. Personnel Transfer Vessel from Windcat (Windcat, u.d.)

Crew transfer vessels range from smaller rigid hull inflatable boats to larger catamarans such as the ones supplied by Windcat, displayed in figure 16. The catamarans from Windcat are over 20 meters in length and reach over 20 knots in service speed. The oldest models can carry a cargo of 4 tonnes and the newer ones can carry 10 tonnes and 50 passengers (Windcat, u.d.). They can manage wave heights up to 1.5 meters and the reach is 60 nautical miles in accordance to MCA Area category 2 (GL Garrad Hassan, 2013). The crew transfer vessels are also used during the construction phase and not only to carry personnel but also for conducting environmental studies, supporting divers and setting up safety zones (Kaiser & Snyder, 2010). The crew transfer vessels are most often leased from the owners for five years at a time (Assessment of vessel requirements for the U.S. offshore wind sector, 2013).

2.3.3. Vessel spreads

Several different vessels are used during the construction phase, and this composition is called the vessel spread. At least one main installation vessel is present through the whole construction phase. Be it a TIV or a liftboat no tugs are necessary to that length while a jack-up barge needs one tug. Foundation installation is done either by a feed-barge, which is a barge carrying the foundations but with no capacity to install said foundations which is done by the installation vessel and as such requires a tug or by a heavy lift vessel. In the case of monopiles, at least two tugs are most often used.

Other than installation vessels and tugs, a couple of crew transfer vessels are used as well as cable laying vessels. The amount of vessels fluctuates during the construction phase, e.g. the cable laying vessel is not present for the first weeks but by the end several could be deployed.

The wind farm Thanet is situated off England's coast and contains 100, 3 MW wind turbines installed in 2009. The projects vessel spread is shown in figure 17.

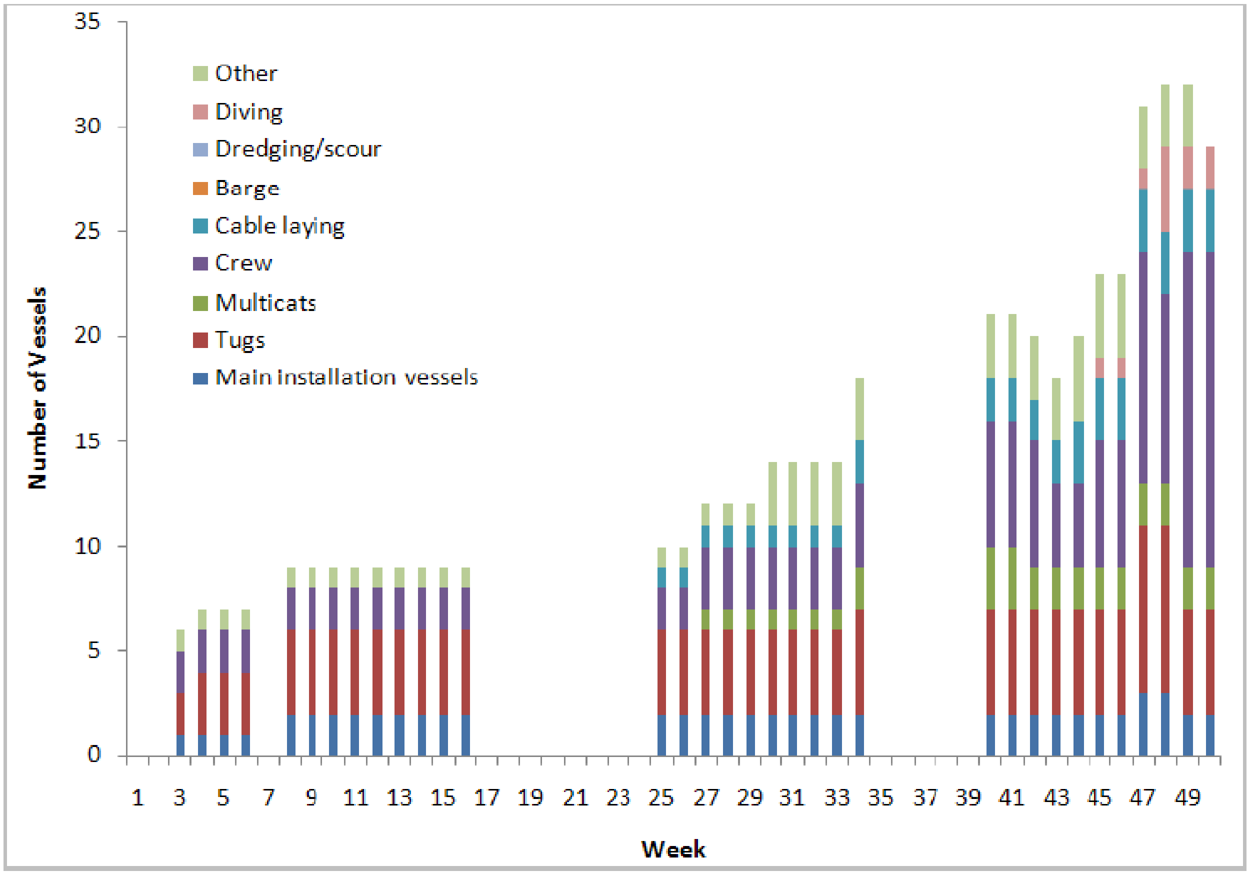


Figure 17. Vessel spread for the Thanet Wind farm over the weeks of installation. (Kaiser & Snyder, 2010)

For the first few weeks only one installation vessel is used, namely the jack-up barge Sea Jack, which incidentally called for a tug. As the project went on more vessels were added, such as the TIV Resolution, several crew transfer vessels, a heavy lift vessel and cable laying vessels. The number of vessels spiked towards the end with 32 different vessels (Kaiser & Snyder, 2010).

2.3.4. Vessel components

There are a number of components of importance when it comes to constructing wind turbines at sea. The most optimal way to put together a construction vessel depends on the circumstances of the wind farm, but construction vessels are not built on demand. As such are the vessels dimensioned to suit different kinds of spots but generally not prepared for the future. When turbines grow in size more deck space is required, and when the water gets deeper longer legs or cranes is a must. This chapter deal with the most important macro components on a construction vessel.

Jack-up legs

The jack-up legs are very important to stabilize the vessel. By raising above the water, waves have no impact on the vessel. The number of legs differ from three on liftboats, four on jack-up barges and smaller TIVs and six on the larger TIVs. Length of the legs range from 70 to 100 meters. The legs are lowered to the bottom of the sea and then dig into the seabed, see figure 18. The sum of the air gap, water depth and seabed penetration is called leg protrusion. Where the maximum leg protrusion is equal to the length of the legs would be the maximum water depth that vessel can operate in. The required air gap is proportional to the height of the crane and the height of the wind turbine.

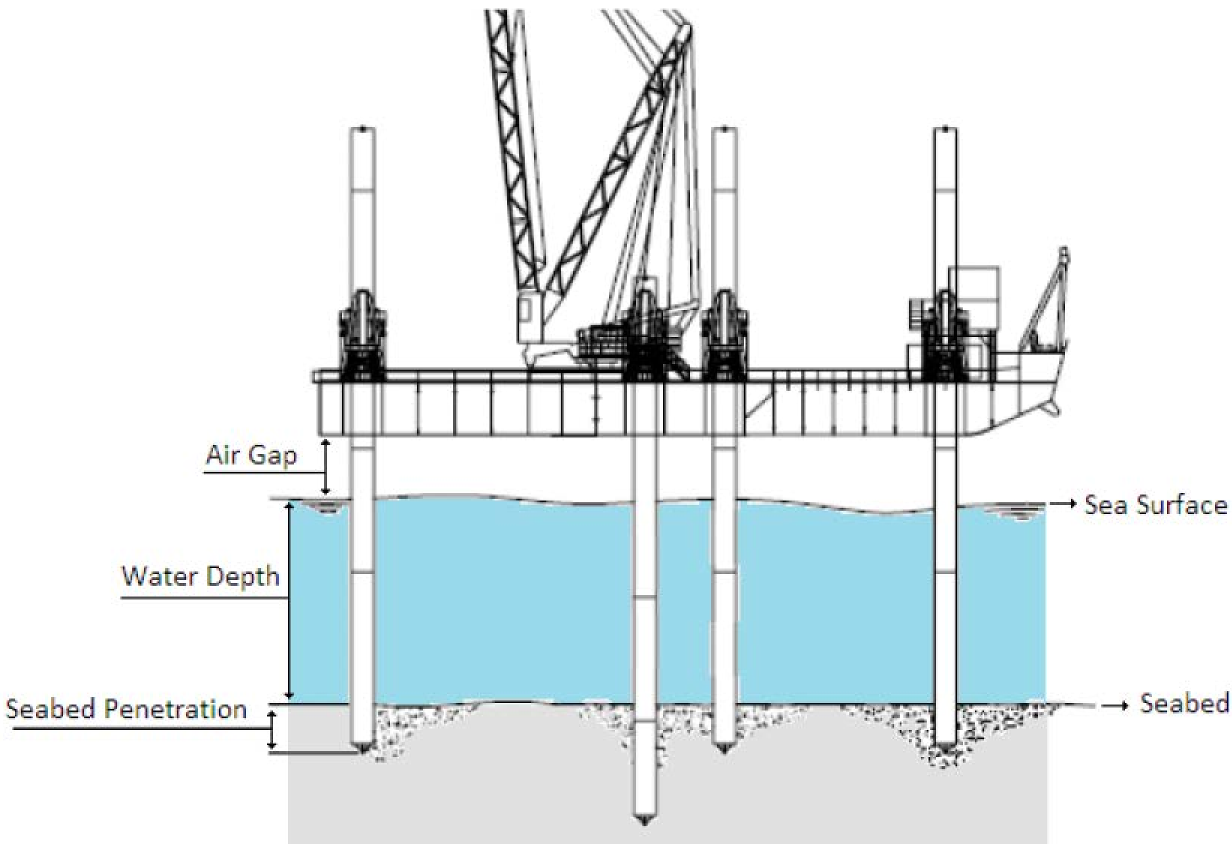


Figure 18. Air gap, water depth and leg protrusion (seabed penetration) (Uraz, 2011).

The maximum water depth the vessel is capable of operating in is the important factor to look at when choosing a vessel that is compatible with the site specifics. Wind farms in operation are generally built in shallow waters with water depths in the 20s or 30s and a few reaching the 40s. The Bard offshore 1 is operating in waters where the depth is 40 meters, and the vessel Wind Lift

1 which is built specifically for that wind farm has a maximum depth of 45 meters. Some vessels are capable of water depths of 65 to 75 meters, see table 12. (Uraz, 2011)

Table 12. Specifics for a range of TIVs (Uraz, 2011).

Name	Year	Deck Space m^2	Capacity (tons)	Speed knots	Leg Length (m)	Water Depth (m)	Jacking speed (m/min)
Sea Energy	2002	1020	2386	7.8	32	24	Semi jack up
MPI Resolution	2003	3200	8950	11	71.8	35	0.5
Leviathan	2009	900	1300	8	85.6	41	0.8
Wind Lift 1	2009	2000	2600	8	71	45	0.35
MPI Adventure	2011	3730	3750	12.5	71.5	40	0.35
MPI Discovery	2011	3730	3750	12.5	71.5	40	0.35
Zaratan	2012	2000	2850	9.1	85	45	0.4
Windcarrier 1 & 2 (sister)	2012	3200	5300	12	81.5	45	0.4
Seafox 5	2012	3500	7000	10	106	65	1
Sea Installer	2012	3350	5000	12	83	45	0.5
Van Oord	2012	3300	6500	12	81	45	0.5
Pacific Orca	2012	4300	8400	13.5	105	75	1.2 to 2.4
Pacific Osprey	2013	4300	8400	13.5	105	75	1.2 to 2.4

Deck space

The deck space is in direct correlation to how many turbines can be fitted on the vessel and differs greatly. Table 12 displays only TIVs and the newer ones have deck spaces well over 3000 m^2. While the bigger jack-up barges can reach 2000 m^2, smaller ones and liftboats have barely 700 m^2 of deck space.

Table 13. List of wind farms, what installation vessel that was used and the number of turbines on deck (Uraz, 2011).

Wind Farm	Configuration	Installation Unit	(MW)	# turbines on deck	m^2/turbine	Weight Capacity Used
Horns Rev 1	**BE1T**	Sea Energy	2	2	510	18.1%
Horns Rev 1	**BE1T**	Sea Power	2	2	510	18.1%
Prinses Amalia	**BE1T**	Sea Energy	2	2	510	18.1%
OWEZ	**BE1T**	Sea Energy	3	2	510	20.7%
North Hoyle	**BE2T**	*Excalibur*	2	1	768	34.2%
Ormonde	**R2T**	*SeaJack*	5	2	1250	52.5%
Nysted	**R2T**	Sea Power	2.3	4	255	41.9%
Lillgrund	**R2T**	Sea Power	2.3	3	340	34.2%
Horns Rev II	**R2T**	Sea Power	2.3	2	510	22.8%
Belwind 1	**SP5**	*JB 114*	3	2	350	39.5%
Rhyl Flats	**SP5**	*Lisa A*	3.6	1	1000	26.3%
Thanet	**SP5**	Resolution	3	9	355.5	24.8%
Greater Gabbard	**SP6**	Levithan	3.6	2	450	64.6%
Thornton Bank	**SP6**	*Vagant*	5	1	400	65.6%
Lynn & Inner Dowsing	**SP6**	Resolution	3.6	6	533.3	28.2%
Greater Gabbard	**SP6**	*SeaJack*	3.6	3	833.3	50.4%

How many turbines that can be stored on the vessel is dependent on the assemble configuration. Table 13 displays the average deck space used per turbine depending on the configuration (the configurations are explained in chapter 2.1.1). The configuration taking up the least amount of deck space is the individual pieces assemble method with the tower in one piece and bunny ears with two-part tower takes up the largest amount of deck space. All the configurations are however not tried out on the same vessel, thus no general conclusions can be drawn.

Crane

Every vessel has one main crane used for installation and one auxiliary crane. Positions of the crane varies but the most common are in the aft between the jack-up legs, integrated on one of the jack-up legs and with a few being mounted on the sides between the jack-up legs. The cranes have three important parameters, boom length or hook height, Safe working load (SWL) and radius or outreach, all displayed in figure 19. The hook height gives the maximum height the crane can operate at. Outreach specifies how far the crane can reach outside of the vessel. SWL is the maximum load the crane can lift and is given at a certain outreach after which the crane gets weaker.

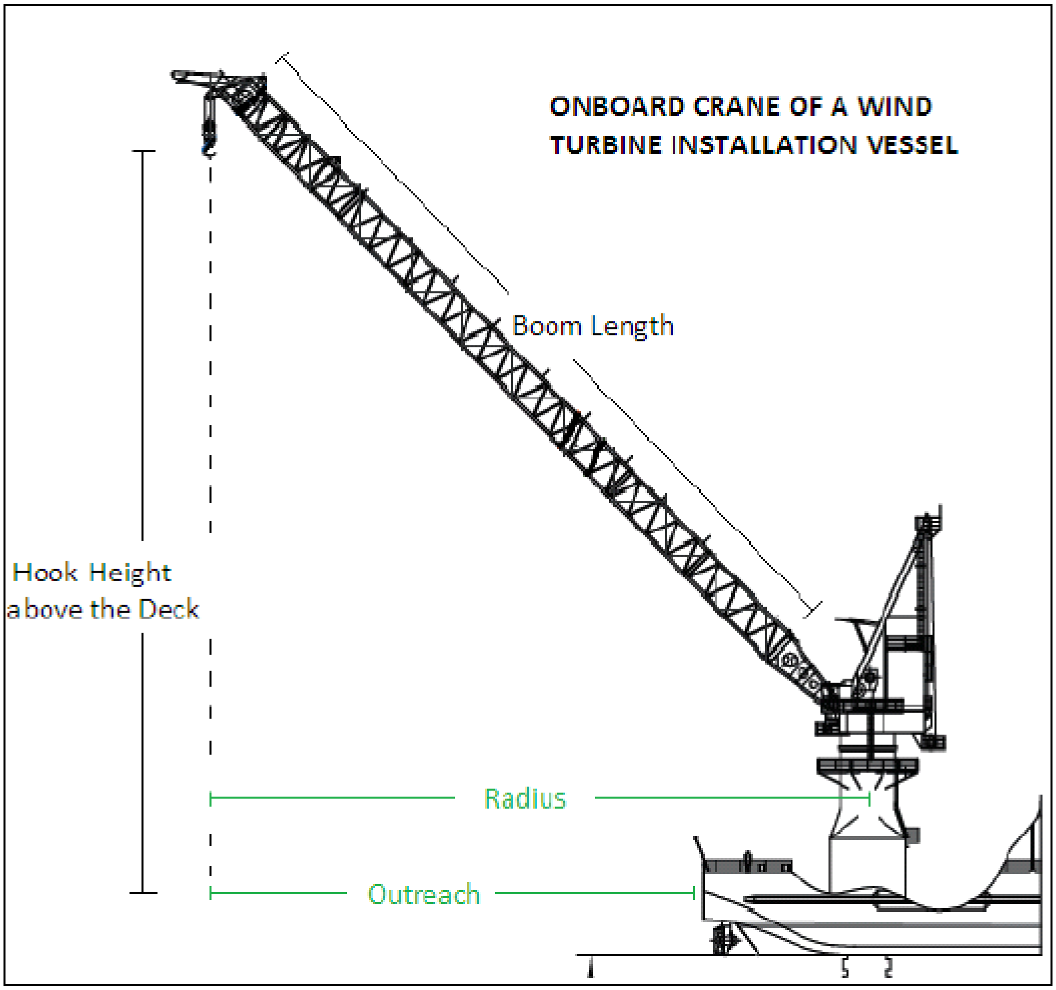


Figure 19. Hook height and outreach of a crane (Uraz, 2011).

Hook height in combination with the vessel jacking up is enough for today's wind turbines to be installed. Outreach becomes important if the seabed around the turbine is instable in which case the vessel might have to jack up further from the foundation. The SWL must be higher than the weight of the heaviest piece of the wind turbine which is commonly the nacelle. Combinations such as the bunny ears configuration are however heavier than only the nacelle.

Table 14. SWL, outreach and hook height for different installation vessels (Uraz, 2011).

Name	Year	Position of Crane	SWL	Radius/Outreach	Height
Sea Energy	2002	PR, Center	110	27	60
MPI Resolution	2003	Between legs, aft	300	25.5	92
Leviathan	2009	Between legs, aft	300	16	45
Wind Lift 1	2009	Between legs, aft	500	31	99
MPI Adventure	2011	Between legs, aft	1000	25	105
MPI Discovery	2011	Between legs, aft	1000	25	105
Zaratan	2012	Leg Mounted,SB, Aft	800	24	85
Seafox 5	2012	Leg Mounted,SB, Aft	1200	25	-----
Pacific Orca	2012	Leg Mounted,SB, Aft	1200	31	-----
Sea Installer	2012	Leg Mounted,PR, Aft	800	24	94
Windcarrier 1 & 2 (sister ships)	2012	Leg Mounted,PR, Aft	800	24	102
Beluga-Hochtief	2012	Leg Mounted,SB, Aft	1500	31.5	-----
Inwind Installer	2014	Leg Mounted,SB, Aft	800	30	65
Deep Water Installer	2014	Leg Mounted,SB, Aft	1600	29	85

The weight for a nacelle in the 3 MW range is just above 100 tonnes which all vessels in table 14 are capable of lifting. Around the corner however are 8 MW turbines where the nacelle can weigh 380 tonnes which puts the smaller vessels' cranes out of range (Salomonsen, 2015).

Accommodation

Vessel and installation personnel live on the vessels for the duration of the construction phase and as such are the vessels equipped with bedrooms, kitchen and living room. The smallest vessels have space for around 10 persons and the largest TIVs have space for more than 100 persons (Assessment of vessel requirements for the U.S. offshore wind sector, 2013).

Dynamic positioning

Vessels can instead of anchoring use a computer system called Dynamic positioning. Main thrusters, auxiliary thrusters, rudders, etc. work in tandem to keep the vessel locked in place by the way of a reference system such as GPS or another vessel combined with wind sensors and gyrocompasses. The dynamic positioning, DP, is rated from DP0 to DP3 where DP0 does not have a dynamic positioning system and DP3 has two extra, independently powered, dynamic positioning systems. Larger vessels that handle more precise or vital operations tend to have a higher rating (Assessment of vessel requirements for the U.S. offshore wind sector, 2013).

2.4. Economy

2.4.1. Dayrates and newbuild costs

When vessels are contracted they are paid by the day, a dayrate. The data on dayrates is scarce, and so is the data on newbuild costs. Apart from the few instances of reliable figures on dayrate and newbuild cost, data has to be extrapolated. The lowest tier of installation vessels, the liftboats, have known prices on dayrates and newbuild costs on which the costs for jack-up barges and TIVs can be based on. Furthermore, is the size of large jack-up oil rigs similar to that of larger jack-up barges or TIVs and figures for the Gulf of Mexico is extensive when it comes to costs. Newbuild costs differ from shipyard to shipyard, country to country and is highly dependent on the price on steel.

Included in the dayrate are finance cost, return of investment (ROI) and operating expenses. Finance cost is covering the loan and initial investment of the vessel. ROI is dependent on the vessel owners ambition on earning money and can range from 4-14 % with an average of 8.5%. Operating expenses are comprised of costs for personnel, fuel, insurance and administration. The estimates in table 15 comes from the oil and gas industry where vessels are similar or same as the ones used in the wind industry.

Table 15. Operating costs as a percentage of dayrates for different vessels (Kaiser & Snyder, 2010).

Vessel Type	Source	Daily OpEx ($1000)	OpEx as a percentage of dayrate
Jackup	Jayaram and Royes 2009	32-40	42-58
Liftboat	Hercules 2010; Superior 2010	5-13	62-64
OSV	Hornbeck, 2010; Tidewater 2009	6-10	45-48

While transparency is low, a few project contracts are known. SeaJacks leased their TIVs Kraken and Leviathan to a dayrate of $148,000 and $176,000 in 2009. Master marine leased their TIVs Service Jack and Service Jack 2 to a dayrate of $330,000 and $380,000 in 2008. A report from 2003 claimed dayrates ranging from $30,000 to $150,000 for elevating vessels. Liftboats owned by the company Superior Energy Services that are operating in the Gulf of Mexico have dayrates between $23,000 and $37,000 depending on size. Jack-up rigs, not to be confused with jack-up barges used in the wind industry, are large constructs used in the oil and gas industry and while they have widely different objectives than the barges in the wind industry, the construction is somewhat the same. The dayrate for jack-up rigs operating in the Gulf of Mexico were $86,000 for smaller ones and $107,000 for the larger ones between the years of 2005 and 2009. Newbuild cost for such rigs amounted to $100 million in the year 2006 but had risen to $170 million by the year 2010 (Kaiser & Snyder, 2010). The large TIV MPI Resolution is estimated to a newbuild cost of $150 million from an Asian shipyard and double that from an American shipyard and the American option would require a dayrate of $212,000, while a general estimate for TIV dayrates in Europe is $169,000. (Assessment of vessel requirements for the U.S. offshore wind sector, 2013)

(Maples, Saur, Hand, van de Pietermen, & Obdam, 2013) estimate a newbuild cost of $150 million for an unspecified seized TIV.

Both newbuild cost and dayrate are contract based which means that no figures are certain and different for all vessels and projects. But according to the different sources above, some trends can be observed regarding dayrates and newbuild costs. (Kaiser & Snyder, 2010) chose to assess values for liftboats as $25-50 million in newbuild cost and $10,00-20,000 in operating cost, for jack-up barges as $50-100 million in newbuild cost and $15,000-25,000 in operating cost and for TIVs as $150-200 million in newbuild cost and $30,000-40,000 in operating cost.

Table 16. Dayrates for different vessel depending on estimation method (Kaiser & Snyder, 2010).

Vessel	Lease		Proportion		Build		Expected value	Dayrate range
	Min	Max	Min	Max	Min	Max		
Liftboat	19,459	57,307	12,500	75,000	15,582	32,767	35,436	12,500-75,000
Jackup Barge	33,919	99,614	25,000	150,000	26,164	50,534	64,205	25,000-150,000
TIV	86,756	189,229	75,000	300,000	63,493	91,068	134,258	60,000-300,000

The dayrates for different vessels can be found in table 16 as calculated by three different methods. The lease method computes the dayrate from newbuild cost, operating cost, years leased and utilization. The proportion method employs the notion that the dayrate is proportionate to the newbuild cost by the way of percentage. The build method sets up a scenario where a vessel is built specifically for a project, is used for a couple of years and is then sold. The build method displays a narrow range and the top value for TIVs is very low. The proportion method, which used values between 0.05-0.15%, has the widest range and while the upper limit for TIVs is very high it is not unreasonable.

The company owning the vessels charges a mobilization fee depending on how far away the wind farm is located. Transportation of the vessel can be done through different means, namely tow, self-propelled or heavy lift vessel. Jack-up barges are always in need of a tug but it could also be carried by a heavy lift vessel. Liftboats, while self-propelled have a very low service speed, so if the distance is long, towing it or carrying it like a barge could be beneficial. TIVs are self-propelled and can travel at high enough speeds that no other option would be viable.

Table 17. Mobilization costs for different vessels (Kaiser & Snyder, 2010).

Vessel type	Distance (nm)	Tow		Self-propelled		Heavy lift		Range	Expected value
		Min	Max	Min	Max	Min	Max		
Liftboat	250	104	1,593	106	177			104-177	129
	500	171	1,686	213	353			171-353	246
	1000	304	1,871	425	707			304-707	479
	1500	437	2,057	638	1,060			437-1,060	712
	2000	570	2,243	851	1,413	1,413	2,310	570-1,413	1,061
Jackup Barge	250	205	3,156			507	801	205-801	504
	500	335	3,311			686	1,073	335-1,073	698
	1000	595	3,623			1,044	1,618	595-1,618	1,086
	1500	855	3,934			1,402	2,162	855-2,162	1,473
	2000	1,115	4,246			1,760	2,707	1115-2,707	1,861
SPIV	250			151	234			151-234	192
	500			302	467			302-467	385
	1000			604	934			604-934	769
	1500			907	1,402			907-1,402	1,154
	2000			1,209	1,869			1,209-1,869	1,539

Note: All costs in $1000

The mobilization cost is comprised of similar things to what comprises the dayrate; finance cost, insurance, personnel but most important fuel, since the vessel is moving all the time. On top of that comes costs for the dayrate of either tug or heavy lift vessel depending on how the jack-up barge and liftboat is transported. While this is not a big charge compared to the total cost of the vessel during the construction of the wind farm, it can be more noticeable if it is a one-off repair. The mobilization cost for the three installation vessels are displayed in table 17 according to their transportation methods.

Crew transfer

Dayrates for crew transfer vessels includes the same things as the other vessels; personnel, fuel and finance cost. (GL Garrad Hassan, 2013) reports mean dayrates of $3,500 between the years 2003 and 2010. (Maples, Saur, Hand, van de Pietermen, & Obdam, 2013) expects a value of $2,000, excluding fuel costs. SeaEnergy marine did, in their presentation of the SeaEnergy Mother vessel, compare the mother vessel's dayrate to the dayrate of a crew transfer vessel which they asserted to $1,500 and $1,000 for the fuel cost (2011).

2.4.2. Ship building cost estimation study

There are two approaches when estimating ship building cost, top-down or bottom-up. Which method is used depends on the level of detail and accuracy. While the bottom-up requires a near complete schematic of the ship to consider every detail, the top-down relies on bigger components and rough estimates such as weight, length and propulsion power (Betram, Maisonneuve, Caprace, & Rigo, 2004).

The bottom-up approach splits the ship in different parts such as hull, propulsion, electric plant etc (see figure 21). Further into the design process are the parts split into smaller parts, specifying where the costs derive from. At the end of the design process all details are available and a last layer of splits are made. Such a level of detail requires cost specifics for all the different parts making the model very accurate (Shetelig, 2013).

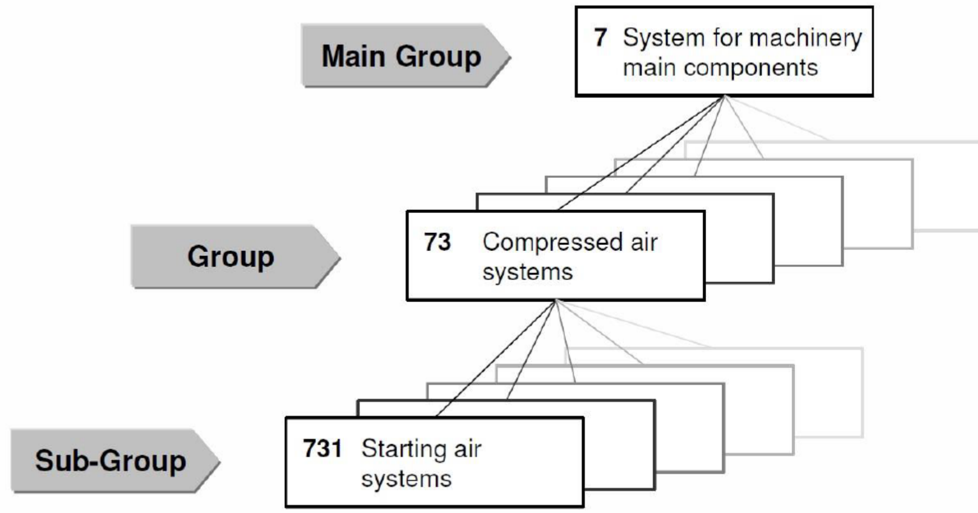


Figure 20. The bottom-up approach dividing parts into smaller groups for more accuracy. (Shetelig, 2013)

The top-down approach is a method reliant on comparison. Most favourably is the rough design compared to a ship with similar size, functionality and power with a known price. When the design is different from any common designs with known costs, another route is used where the ship is divided into parts that are similar and can be expressed with the same physical quantity according to what is done in figure 21, Historical data from an array of different ships have derived formulas for the different groups. In them being derived from historical data can make them a bit inaccurate since techniques have changed over the years (Betram, Maisonneuve, Caprace, & Rigo, 2004).

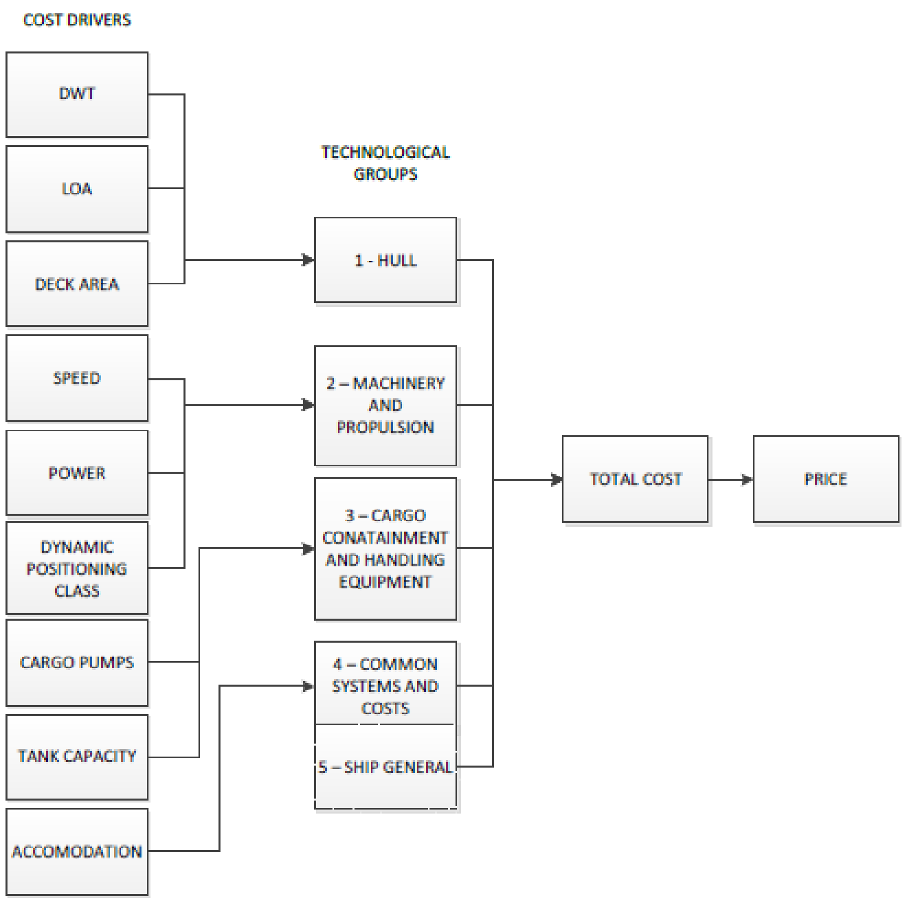


Figure 21. Ship parts with the same physical quantity are grouped together and said groups are used to derive a cost (Shetelig, 2013).

These groups each share a portion of the total cost when building a ship. The Norwegian shipyard Ulstein uses rough estimates of these portions when they are calculating the cost for building their ships. For instance is the machinery carrying 25% of the total cost according to table 18.

Table 18. The different cost bearing groups and their portion of the total cost. (Shetelig, 2013)

Technological group	Portion of total cost
Hull	20 – 30 %
Machinery and Propulsion	25 %
Cargo containment and handling	20 – 25 %
Ship common systems / Ship assembly and systems integration (for outfitting yard)	20 %
Hotel and accommodation	5 %
+ Financial costs	+ Financial costs

Given is that these are only rough estimates of the portions and that they are valid in regard to PSVs (Platform supply vessel). Calculating the cost for one of the groups can be used to extrapolate the cost for the whole ship using the portion estimates.

3. Wind farm construction and O&M scenarios

The wind power industry is always evolving, figuring out solutions to new problems. The conventional approach to wind farms have been close to land with shallow water where vessels ranging from small liftboats to big TIVs have installed the turbines. The future holds challenges with accommodation and floating turbines still being figured out for a scenario with farms being far out to sea in very deep water. Present day lies somewhere in-between with distances becoming too far for daily traversing and demo sites experimenting with floating turbines and different installation methods.

3.1. Close to land

The scenario that is building a wind farm close to land is well thought out since it is what has dominated the offshore industry to this day. The water depth is generally below 40 meters and the distance to port is less than 12 nautical miles (23 km). Under these conditions is jack-up possible and the crew transfer vessels can go back and forth including repairs in a comfortable time frame which is less than a regular day's work. Closeness to port negates the need for any accommodation on site.

Installation of the turbines is going to be done by a jack-up vessel and the size of said vessel depends on the number and size of the turbines. As the turbines are increasing in size and weight, smaller vessels will probably not be able to erect the turbines, leaving out the liftboats and smaller jack-up barges. The current trend implies larger vessels, capable of carrying a high number of wind turbine on deck. This is more important when the wind farm is further from land, but still cuts time in any case. If the wind farm is employing many turbines, high impact failures will increase which would call for a vessel that is able to change the bigger parts, i.e. a jack-up.

Operations and maintenance can be based on land when the wind farm is relatively close to land for the sake of convenience and comfort for the workers. A control center employs a permanent staff that can monitor the wind farm at all times. Fast transport vessels take personnel and equipment to the wind farm, dispatching from a nearby harbor. Depending on location a purpose built harbor can house workboats, control tower and spare parts. Such a harbor is especially important if there is no suitable harbor close to the wind farm or if it were to have incapable infrastructure connected to it which can interfere with the sometimes large spare parts, such as a blade having to be transported to port.

A combined construction and O&M vessel for this distance would require less emphasis on living spaces and more on actual deck space that can carry wind turbine parts. As both the workforce and spare parts are going to be based onshore during O&M such things are of no concern to the vessel which instead fills the role of backup if a large part would have to be changed, cutting waiting time dramatically. For the vessel to be reasonably cheap it would have to be relatively small.

Solutions for the future

The choice of installation vessel boils down to the size of the wind farm. Given the implementation of larger wind turbines makes the liftboats in general incompatible and the smaller ones would definitely be out of the race. Instead is it going to be large jack-up barges and TIVs that carry out the installation duties. An option could be to invest in such a vessel, giving complete control of its operation.

Today, O&M is carried out from a port, where crew transfer vessels are stationed and a control tower dictates repairs and maintenance. Breakdown of the larger parts of the turbine requires leasing of jack-up vessel from the spot market. While a liftboat probably won't be suitable for the installation phase, individual parts could very well be manageable and an option is to buy one for the O&M phase of the project and selling it before decommissioning. The last option would be to carry over the project owned vessel used in the installation phase (see figure 22).

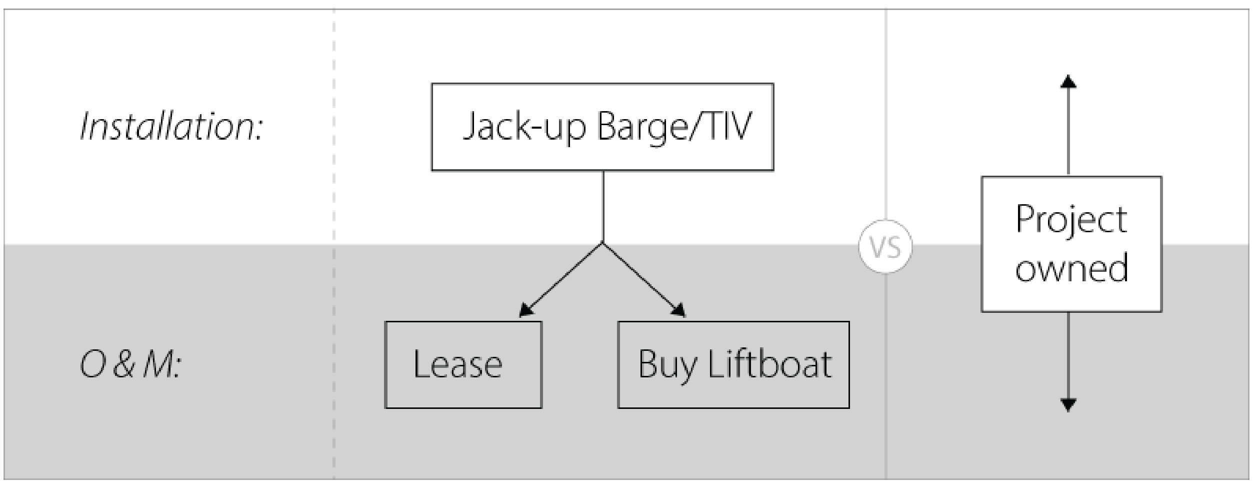


Figure 22. Vessel options for a wind farm close to shore.

A project owned vessel has been tried out at the Bard 1 wind farm and DONG energy is employing a similar strategy with them acquiring A2SEA. DONG energy is in charge of several wind farms and A2SEA offers a wide selection of vessels capable of changing a large part which is a luxury Bard 1 does not have. Only serving one wind farm, Wind lift 1 which is the vessel in question, has to be designed to be big enough for installation wind turbines and at the same time small enough as not to cost too much during O&M.

While leasing is the dominant option today, very large wind farms could look into having a liftboat on standby in the port if the failures are abundant. An advantage of the liftboat is the price which is considerably lower than both jack-up barges and TIVs. A drawback is its limited use during not only construction but also decommissioning.

3.2. Medium distance

The medium distance is set to above the limit of 12 nautical miles and upwards to where the crew transfer vessels cannot operate on a daily basis, with 60 nautical miles being restricted by law but transport time limits well before that. As the wind farm moves further from shore, conditions change. Most notable is the transport time, which becomes quite evident and a big factor. This causes for the vessels to carry more wind turbines per batch. While distance increases and wind turbines get bigger it requires larger vessels which in turn would cost more. A solution to get around this problem would be to have feeder barges to carry the wind turbine parts to the wind farm site and then have purpose-built vessels construct the turbines.

Suitable wind farm placements with shallow waters becomes more scarce further from land. As water depth increases it makes it harder for jack-up vessels to utilize their advantage. To combat this, longer legs would be required or a different solution entirely.

When the distance turns transit into hours, more effective ways to reach the wind farm must be used as not to increase the downtime during wind turbine failures. Faster crew transfer vessels are one solution but the fastest vessels today reach just over 20 knots which means that if the wind farm is 40 nautical miles from shore, getting there would take two hours and a round trip would take four hours. A supplement to the crew transfer vessels are helicopters. The helicopters are fast and can be used effectively when a turbine breaks down but while the fault can be fixed easily. The downside to helicopters are the high cost to deploy one.

Solutions for the future

The solutions for the medium distance is quite similar to the solutions for the short distance. Differences in the installation are that the distance requires bigger vessels capable of carrying more turbines or having feeder barges going back and forth to the port, resupplying the installation vessel. As the depth increases, longer legs are needed but after a certain point no legs and a long crane is more viable. The call for a large vessel with a long and strong crane is discussed further in the next chapter.

Having a project owned installation vessel carries the same merit for this distance or even more so. While a liftboat still could carry out repairs as long as the water is shallow enough, the transit distance could be a problem as the liftboat has a low service speed. For this reason, a project owned installation vessel could be more viable.

Since maintenance is required almost daily on a large wind farm, personnel need to reach the turbines in a reasonable time. A four-hour roundtrip transit per day is really stretching it as there would be little time for the actual repairs. Deploying helicopters could be very expensive and would therefore be called for specifically if the turbine is shut down. Hoisting parts from a helicopter onto a turbine is potentially not only dangerous but probably impractical.

For the longest distances a different solution entirely, involving a permanent accommodation is probably the answer and while it might be viable before daily crew transfer vessel-roundtrips are impossible, it is not discussed in this chapter but instead in the next.

3.3. Long distance

3.3.1. Installation

Installation of turbines in the future is a subject of much discussion and uncertainty. For as long as the water is shallow enough for gravity foundations and monopiles, the same approach used today is most certainly going to be used in the future albeit with a few differences. Since the distance is very far and turbines are only getting larger, installation vessels need to get bigger in combination with a feeder barge system where for instance two barges cooperate in going from port to site with new turbines to install. If this was the case with shallower water, solutions much like the ones proposed for the medium distance are viable. A purpose built vessel could be used for installation and then be carried over to the O&M. Viability of a liftboat for O&M, even at extreme distances if only the depth is right would not be too farfetched. Even though the liftboat service speed is slow, it would not have to traverse the distance all too often. Changes would have to be done to the vessel, making room for better accommodation.

For all intents and purposes are the turbines in the future, when installed far from land, going to be floating. How one would go about to install the turbines is the main concern of uncertainty. Different solutions to the problem was presented in the chapter on wind turbines, with two floating turbines operational today. A tripod solution opens up for construction in shallow water or even on land since it does not dip too far in to the water. The other option, which essentially is a floating monopile, requires quite a lot deeper water. Construction of the turbine on top of the foundation has to be done in deep water where jack-up vessels cannot operate. The Hywind project was carried out in the calm waters of a fjord in Norway, a luxury not commonplace in the rest of the world. Instead can the foundations be tugged either to deeper waters or to the site of the wind farm in a manner similar to how the monopiles are tugged while floating. Erecting the turbines without jacking up the installation vessel would require calm water and most certainly that the vessel is moored to the foundation to create stability. To reach all the way to the top of the tower and be able to lift the heaviest parts, a strong crane with a long boom is required. Furthermore, must the vessel be large enough to compensate for the heave effect from the crane and the influence from waves. The concept Windflip proposes another solution that does not require an installation vessel. Instead is the turbine with foundation fully constructed on land and is then lifted on top of the Windflip barge before being carried to site. Depending on what foundation is used, different sites can be used for installation according to figure 23.

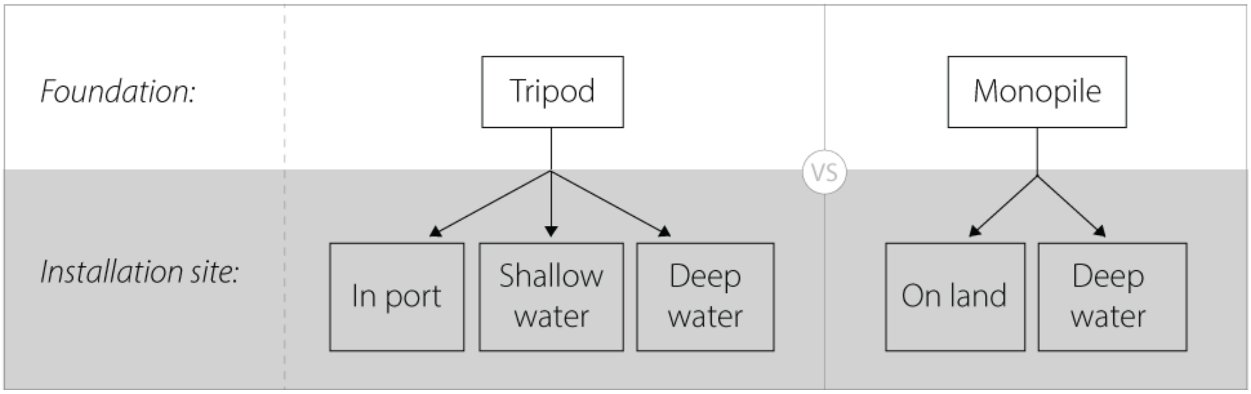


Figure 23. Vessel options for a wind farm far from shore.

3.3.2. O&M.

When the distance becomes longer than what crew transfer vessels can handle, new solutions must be applied. The need for a permanent accommodation is essential and it can be arranged in three different ways, an accommodation platform, a mothership or an installation vessel. The first option is a platform put on top of a foundation likening what have been done at Horns Rev or DanTysk. The accommodation could be built in conjunction with the transformer station as is the case with Horns Rev or it could be on its own like DanTysk. The second option would be a mothership which can accommodate personnel in a manner similar to the accommodation platform. Like the accommodation platform could the mothership be outfitted with a helipad for quick access from land. The benefit of having a mothership is that it can move around the wind farm, substituting for a service vessel. A gangway is mounted on the mothership which can extend outside of the vessel for easy access to the turbine. If the wind farm is very large and several service vessels are needed, a small one can be stored on the mothership. The third option is an installation vessel since they tend to have ample living spaces onboard.

Installation vessel

The installation method dictates how to go about the O&M. A floating wind turbine, sat on top of the tripod foundation, need no installation vessel and the same goes for the Windflip concept. Following the lead of Hywind, with foundations reaching more than 100 meters below surface, calls for installation vessels capable of doing the heavy lifts, that is the tower and nacelle, in conditions with high waves and strong winds. Using a vessel that is built specifically for the purpose of installing wind turbines on floating foundations and has a strong crane with a very long boom and fitted with a device used to moor on floating foundations, gives incentives to keep it through the O&M phase. The deck space can be tailored to carry a reasonable number of turbines while still be large enough to withstand the weather. Accommodation for the personnel can either be built at large before operation or be retrofitted with such things as structures to house and handle spare parts.

Designing such a vessel is not a daunting task since the outline is quite simple, a large deck with a structure for control and accommodation in one end. This is very similar to what a Platform Supply Vessel, PSV, looks like, which incidentally is what calculations and approximations in chapter 2.4.2 are based on. The size of the vessel is based on the desired number of turbines it should be able to carry. Since the distance to shore is far, a safe assumption would be that feeder barges are used. Thus, is the limiting factor rather how big the vessel needs to be to support the large crane at the position of most stress. The crane can be positioned at different places on the deck such as the aft, side or one of the corners. It must be able to reach all of the deck, over to the feeder barge and the whole turbine. An integral part of the vessel is the device that is used to moor to the foundation. Its placement could be wherever it facilitates the work of the crane, may it be close to it so the lifts are shorter or far from it to give it more space to operate. Another important system is the dynamic positioning which needs to be very precise and reliable; DP3 is probably mandatory. To get on the turbine from the vessel, a gangway can be positioned close to the where the mooring device is. Accommodation must be on par with what is offered on TIVs today and maybe even more so. Common areas must be sufficient enough for people living on the vessel for an extended period.

Mothership

A vessel that combines the mobility of a service vessel and living spaces of an accommodation platform without the awkwardness of an installation vessel is the mothership. The mobility aspect lets it take the place of one service vessel. Preferably is the mothership equipped with a gangway which can extend out over the water to the turbine making for a safe and easy access. If the wind farm is vast, more than one service vessel could be needed in which case a smaller vessel can be stored onboard the mothership or if it is used constantly, moored to the mothership during inactivity. Living quarters are, like in all the other alternatives, very important. Depending on size of the mothership could there be space for a helipad, and for the most convenience would it be mandatory.

Comparing solutions

Accommodation is at the essence of the O&M. The facilities are expected to be up to par independent of which solution is chosen. Susceptibility to motion sickness could be less prominent if the vessel or structure is bigger and while this is very important it will not be taken into account. The installation method is derived from what foundation is used according to figure 23 and later sets the stage for how accommodation is handled in the next phase as can be seen in figure 24.

If the turbine is installed either at the site, in deep water or in shallow water, a large installation vessel is going to be needed, be it a TIV or a crane vessel. Such a vessel can house the personnel for the duration of the installation. Adjustments made to turbines after they have been erected is carried out by service personnel using crew transfer vessels. Since the crew transfer vessels cannot traverse the long distances, they will have to stay on site which calls for a hub of sorts. This role fits the crane vessel if it is stationed at the site. Installation vessels usually operate around the clock for as long as the weather is good, but this should not hinder the fact that transfer vessels briefly dock to exchange personnel. However, if the installation is carried out in deep water closer to land or shallow waters, no accommodation is available for the site personnel. The same is true if the turbine is erected in port on a tripod foundation or on land which is proposed for the Windflip concept. This calls for either an accommodation platform or a vessel suitable for living, preferably a mothership which can act as a service vessel.

Installation site of the turbine	Port/Land	Shallow water	Deep water	
			Interim site	Wind farm
Installation vessel	None	TIV	Crane vessel	
Accommodation at wind farm	Separate vessel/platform			Crane vessel

Figure 24. Vessel and accommodation options for a wind farm far from shore during installation.

Choosing accommodation for the installation can cement the future accommodation options. Putting up an accommodation platform erases all other options for the O&M phase, while an accommodation vessel merely can be leased for the duration. But leasing a mothership and then installing an accommodation platform can be seen as quite redundant. The only other option to not keeping the mothership after installation would be if the installation vessel is kept which cannot be the case if it was not used in the first place. Using the installation vessel for accommodation works fine if it is stationed at the site and can be leased if the plan is to use a mothership for O&M or bought to be carried over to O&M. Figure 25 expresses the three initial alternatives for accommodation during installation and what alternatives one is left with going in to the next phase.

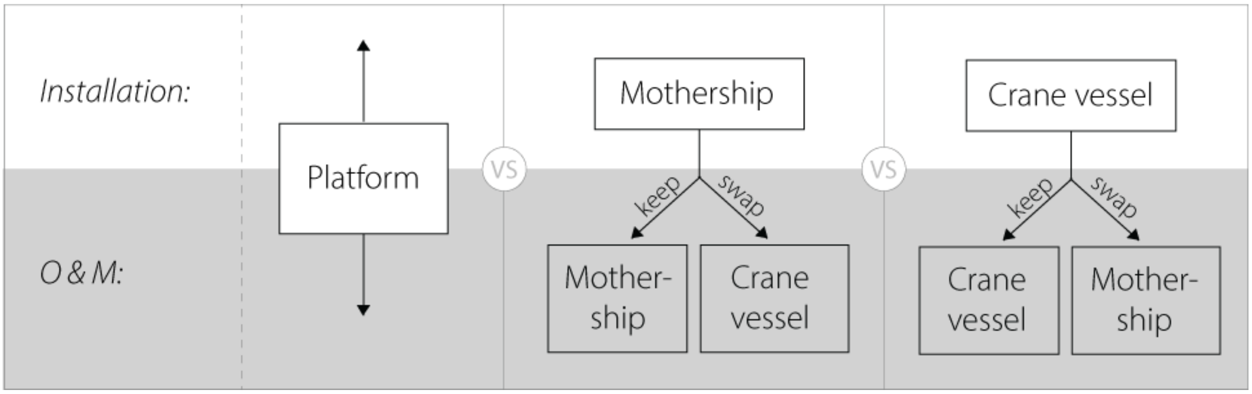


Figure 25. Accommodation options for a wind farm far from shore.

The differences between the three solutions comes down to usability during installation and O&M, capital cost for vessel or structure and additional personnel. An accommodation platform offers mainly means to stay at the wind farm for both installation and O&M, the mothership adds the ability to serve as a crew transfer vessel and the crane vessel is able to carry out repairs that otherwise requires leasing a vessel capable of hoisting large parts from the turbine. Adding a gangway to either vessel lets both act as service vessel. A helipad is not only viable but most certainly mandatory for all solutions. Even though leasing or owning a helicopter can be very expensive, a helipad opens up for more options. If the main transportation from land is a service boat, in case of an emergency could the helipad be vital. The big upside for the crane vessel is its ability to change the large parts such as blades, gearbox etc. which breakdown every so often, a problem that scales with the size of the wind farm. A large deck space also lets the crane vessel carry such large spare parts, always standing by, ready to make repairs. Depending on the severity of the failure, some parts can be repaired aboard the crane vessel. When the spare parts run out is the crane vessel able to return to land and exchange the damaged parts for functional ones. This is also true for the mothership, that can return to land to replenish its stock of spare parts. Some of the spare parts could also be replenished by a helicopter which increases the validity of a helipad.

When looking for a combination between installation and O&M, the accommodation platform brings little to the table when it comes to installation. The drawback of having a vessel that can move around is the need for additional personnel who can operate the vessel and the cost for fuel. Instead of using the dynamic positioning system, which albeit being very efficient, still requires fuel, a buoy fastened in the seabed could be used for mooring. Such a buoy could be situated just outside of the wind farm, keeping the vessel stationary when it is not needed. The use of a gangway on either vessel translates to one less service vessel. This would somewhat offset the high cost for the mothership or crane vessel, though only by a small amount in comparison. Another perk of using a larger vessel instead of crew transfer vessel is that they can operate in double the wave height. This can be quite significant and increases the safety for the workers.

Figure 26. Suggested appearance of a mothership (2011).

Figure 26 displays an overview of a mothership as proposed by Seaenergy. The vessel is 76 meters long and boasts great accommodation, a helipad, storage for spare parts, extra crew transfer vessels and a gangway. The dayrate is expected to be £25,000 per day, fuel cost is £5,333 per day of which is £2,667 for stand-by, some of which might be adverted with a mooring buoy.

Table 19. Comparison of the different options.

	Mothership	Crane vessel	Platform
Helipad	Maybe	Yes	Yes
Spare parts	<2000 kg	>2000 kg	<2000kg
Gangway	Yes	Yes	No
Operating personnel	Yes	Yes	No
Crane	No	Yes	No

While Seaenergy included a helipad on their proposed vessel, table 19 specifies it as maybe because smaller motherships might not allow for it. Table 19 also clearly shows the involvement in day-to-day work for the different accommodations where the platform provides no easy access to turbines through a retractable gangway and neither does it provide a crane for hoisting large spare parts to and from turbines. Spare parts are specified as less than 2000 kg for the platform and while the roof certainly could be able to store larger parts, owing to the fact that helicopters can land there with no problem, such parts could not be moved without a crane vessel which might as well pick up parts from port before leaving to do repairs.

3.4. Comparable scenarios

The above scenarios can be boiled down to five different, comparable scenarios. As such will it be easier to put them against each other and see for what parameters they differ. First off is the construction costs and included is also the decommissioning costs. Secondly must the O&M costs be compared and this includes cost for vessel, lost electricity revenue and for some cases, cost for accommodation.

The first is the standard protocol, what is used today, a large vessel is used to install and decommission the wind farm and it is also used during breakdowns, being leased from the spot market. No accommodation is used, limiting this scenario in the future.

The second scenario is to have a project owned vessel which is used for installation, decommissioning and repairs, and when not in use is it idling in port. A variation would be to use a liftboat during O&M instead of a larger vessel. Like the first scenario is there no accommodation present.

The third scenario is to use a mothership for accommodation at the wind farm which would require a way to install the turbines by other means than using the mothership. What construction vessel is used can vary just like the first scenario and it is also required during O&M for big repairs.

The forth scenario is to use an accommodation platform situated at the wind farm on a foundation. In line with scenario three is a construction vessel needed for both construction and O&M. An added cost is a work boat to compensate for the fact that the mothership can act as one.

The fifth scenario is to have a crane vessel install the turbines and also providing accommodation. The crane vessel will stand by idle during O&M, with workboats going to and from it with personnel, moving when the big repairs are being made.

3.5. Economy calculator

To be able to compare the different solutions for the different scenarios an excel sheet was made. The input parameters are the conditions of the wind farm and the output is the cost for the different solutions. The ingoing parameters are explained below and range from turbine and vessel characteristics used to find construction time, to economic figures for different dayrates on different vessels.

Table 20. Input parameters and their abbreviations.

Wind farm characteristics	**Installation**
Number of Turbines(n)	TIF
Distance to port(km)	DTP
Sea depth(m)	SD
Distance between turbines(m)	DBT
Operational years(y)	OY
Operational days(d)	OD
Decommissioning coefficient	DC
Wind turbine characteristics	
Lifting duration offshore(h)	LDO
Number of offshore lifts(n)	NOL
Deck space per turbine(m2/n)	APT
Rotor diameter(m)	RD
Energy production(kWh/h)	EP
Failure rate	FR
Vessel properties	
Deck area(m2)	DA
Jack up speed(m/min)	JS
Service speed(knots)	SS
Operational air gap(m)	OAG
Sea bed penetration(m)	SBP
Total leg protrusion(m)	TLP
Case specifics	
Number of turbines on deck(n)	TOD
Number of tours(n)	NOTR
Duration for travel between port and site(h)	DPS
Duration travel between turbines(h)	DTTT
Jacking duration(h)	DJUD
Time spent in port(h)	TSAP1
Total number of days for construction(d)	TDC
Total number of days for repairs(d)	TDR
Failure rate downtime(d)	FRD
Project owned vessel failure repair time (d)	POVRT
Economy	

Liftboat dayrate ($/d)	LBD
Jack-up barge dayrate ($/d)	JUBD
SPIV dayrate($/d)	SPIVD
Crew transfer vessel dayrate ($/day)	CTVD
Crane vessel capital cost	CVCC
Crane vessel dayrate	CVD
Capital cost to dayrate coefficient	CCDC
Operating cost coefficient	OCC
Idling in port dayrate coefficient	IPDC
Mobilization cost for 1000nm($)	MC
Mothership dayrate($/day)	MSD
Electricity revenue($/kWh)	ER

Many of the parameters in table 20 corresponds to the ones introduced in chapter 2.1.3 and are used to calculate the construction time. This construction time is however only applicable to when the wind farm is constructed in shallow waters. Most of the parameters are self-explanatory aside from a few exceptions. The decommissioning coefficient relates the decommissioning time to the installation time. Because no wind farm to date has been decommissioned makes this coefficient hard to predict. The time per lift varies and is dependent on what piece is lifted and the wind conditions. Number of lifts and deck space per turbine depends on configuration of the installation and how large the turbine is. The case specific parameters are derived from previous parameters through fairly straightforward equations, a summary of which can be found in table 3. The project owned vessel failure repair time is the time it takes to repair one of the large parts. The spare part is stored on the vessel and can therefore be replaced quickly. Liftboat, jack-up barge and SPIV dayrates are taken from previous assumptions while the crane vessel dayrate is calculated from the crane vessel capital cost and capital cost to dayrate coefficient. The operating cost coefficient denotes the cost to operate the vessel, excluding capital cost and ROI. If the wind farm is close to land would the vessel be stationed in port for most of the time and as such use little to no fuel and requiring fewer personnel, leaving other costs such as insurance to be accounted for which gives rise to the idling in port dayrate coefficient.

Scenario 1:

Installation cost is equal to the total number of days of installation times the dayrate for the vessel being used (exemplified here with a SPIV) and the cost to mobilize the same vessel.

$$I = TDC * SPIVD + MC$$

Decommissioning cost is derived in a similar fashion with the addition of a decommissioning coefficient which represents that it takes less time than installing.

$$D = TDC * SPIVD * DC + MC$$

O&M cost depends on how often there is a major breakdown that needs aid from a larger vessel which is expressed in failure per turbine and year.

$$OM = TIF * OY * FR(TDR * SPIVD + MC)$$

Lost revenue when the turbines are not producing electricity due to a failure that requires a larger vessel to fix similarly depends on the failure rate but also on the lead time before the vessel can arrive.

$$LR = TIF * OY * FR * FRD * EP * ER$$

Scenario 2:

The capital cost of the vessel can either be expressed as a fixed number or be derived from the dayrate.

$$CC = SPIVD * 1/CCDC$$

The installation cost for a project owned vessel differs in the fact that only operating expenses need to be covered since the capital cost already is accounted for.

$$I = TDC * SPIVD * OCC$$

On the same line is the decommissioning different in that it incorporates the operating cost coefficient.

$$D = TDC * SPIVD * DC * OCC$$

O&M cost accounts for the days the vessel is actually active at the wind farm.

$$OM = TIF * OY * FR * TDR * SPIVD * OCC$$

When the vessel is idling in port, which is all the days it is not used for repairs, it uses up less resources. The idling cost is in direct proportion to the idling in port coefficient.

$$IC = (OD - TIF * OY * FR * TDR) * SPIVD * OCC * IPDC$$

Lost revenue is similar to the base case with the difference that the amount of time before repairs are made is significantly reduced. The number of days that the turbine is not producing electricity is for the sake of convenience set to the days it takes the vessel to do the repairs which is not necessarily the case depending on if the spare parts are in.

$$LR = TIF * OY * FR * TDR * EP * ER$$

Scenario 3:

Installation and decommissioning is the same as for scenario 1.

$$I = TDC * SPIVD + MC$$

$$D = TDC * SPIVD * DC + MC$$

Cost for the mothership is proportional to the dayrate of said vessel and how many days it is hired for. The number of days could be only during operation but would for comfort be used also during installation and decommissioning.

$$MSC = (TDC + TDC * DC + OD) * MSD$$

The O&M cost is again the same as for scenario 1.

$$OM = TIF * OY * FR(TDR * SPIVD + MC)$$

Lost revenue for downtime is same as scenario 1.

$$LR = TIF * OY * FR * FRD * EP * ER$$

Scenario 4:

Installation, decommissioning, O&M failure repairs and lost revenue are all same as for scenario 1.

$$I = TDC * SPIVD + MC$$

$$D = TDC * SPIVD * DC + MC$$

$$OM = TIF * OY * FR(TDR * SPIVD + MC)$$

$$LR = TIF * OY * FR * FRD * EP * ER$$

The cost for the accommodation platform is a one-time investment, APC. Because the platform is fixed, transfer from the platform to wind turbines has to be handled by a crew transfer vessel which has a cost over the lifespan of the project.

$$CTVC = CTVD * OD$$

Scenario 5:

The crane vessel carry a one-time investment, CVCC. Installation and decommissioning is carried out with a full crew on the crane vessel.

$$I = TDC * CVD$$

$$D = TDC * CVD * DC$$

During O&M is the crane vessel used for repairs of the larger parts and daily maintenance. Because not a full crew is used and not as much fuel expended an operating coefficient is introduced.

$$OM = OD * CVD * OCC$$

Lost revenue is same as the other scenarios.

$$LR = TIF * OY * FR * FRD * EP * ER$$

While the scenarios in many ways share a lot of parameters, will the small differences have big impacts. Furthermore, do they have different applications depending on the prerequisites, as will be explored in the next chapter.

4. Model application on a generic wind farm

Application of the different scenarios comes down to the parameters of the wind farm in question. A farm far from land is most certainly going to require accommodation on site and a farm in deep water will naturally have floating foundations. As such are three different farms going to be scrutinized and suitable scenarios will be applied. For the conventional wind farm is Blekinge Offshore chosen, adding a twist in the form of an incredible number of turbines, opening up for a possible investment in a project owned jack-up vessel. The wind farm DanTysk is chosen as the in-between distance where accommodation is needed but while the foundations are not floating. Lastly is a made-up wind farm chosen as the long-distance option when both accommodation is needed and the foundations are floating.

4.1. DanTysk wind farm

The first wind farm to be tested is the DanTysk wind farm off the coast of Germany. The main reason is that an accommodation platform already is installed at said location and that the water depth is shallow enough for a conventional installation vessel to be used. Scenario 1 is not computed since it does not involve any form of accommodation. Scenario 2 and 5 are similar in the way of buying a vessel used both for installation and then for accommodation and since the water at DanTysk is very shallow is Scenario 5 falling off.

Wind farm characteristics **Installation**

Number of Turbines(n)	152
Distance to port(km)	90
Sea depth(m)	25
Operational years	20
Decommissioning coefficient	0,75

The total number of turbines is the combined number from both DanTysk and the nearby wind farm of Sandbank. While the distance to shore is quite far, is the water depth very similar to what is the norm close to land. The number of years that the wind farm is operating is set to 20 years which might turn out to be in the lower end as better technology becomes available. Large wind farms are still in the cradle and as such has no decommissioning been performed but weighing in better technology, not having to be careful with the turbines and full knowledge of the site, less time should be required for decommissioning.

Wind turbine characteristics	
Time per lift(h)	3
Number of lifts(n)	5
Deck space per turbine(m2/n)	353
Rotor diameter(m)	120
Energy production(kWh/h)	1855

Time per lift is an average for assembly at site and is thought to be the same when loading the vessel in port. The sister vessel to the one used at DanTysk, Pacific Orca, applies the piece by piece installation with a full tower as such are five lifts required. The average space taken up by one turbine with this configuration is one of the lowest, meaning that more turbines can fit on the vessel. Turbines installed at DanTysk is of the Siemens SWT 3.6 kind and the average output is 1855 kWh/h which is roughly half of the maximum effect.

Vessel properties	
Deck area(m2)	4300
Jack up speed(m/min)	2,4
Service speed(knots)	13
Operational air gap(m)	20
Sea bed penetration(m)	5
Total leg protrusion(m)	50

The vessel used when constructing DanTysk, Pacific Osprey, is relatively new and as such are figures and estimates taken from Pacific Orca which is the sister vessel. The Pacific Orca is a very large vessel and has ample deck space for storage, long legs, high service speed and accommodation suitable for over 100 persons. The jack-up speed is really fast and way higher than other vessels used in construction.

Case specifics	
Number of turbines on deck(n)	12,18130312
Number of tours(n)	12,47813953
Tour duration(h)	3,738162485
Travel between turbines(h)	0,0897159
Jacking duration(h)	0,694444444
Time spent in port	15
Total number of days for construction	198,8497201

Number of turbines on deck is rounded down to 12 and number of tours are rounded up to 13. It goes to show that accommodation really is required since the travel duration is just under four hours one way even though this figure would be a bit lower for a transport vessel. Because of the high service speed and jack-up speed are the figures associated with speed relatively low and might therefore impact the total construction time since the model is based around lower numbers. The total number of days which is almost 200 is double that of Horns Rev 1 which had half the number of turbines. While this gives merit to the model and the outcome of 200 days, considering the much longer distance at DanTysk, more days seems reasonable.

Economy	
Vessel	Dayrate($)
Liftboat	35600
Jack-up barge	65000
SPIV	132500
Crew transfer vessel dayrate ($/day)	2500
Operating cost coefficient	0,5
Idling in port dayrate coefficient	0,5
Mobilization cost for 1000nm($)	769000
Mothership dayrate($/day)	31000
Electricity income($/kWh)	0,04

The vessel dayrates are discussed in much more detail in 2.4 and the numbers used here are the mean values. Also discussed is that half of the dayrate accounts for the building cost of the vessel and therefore is the operating cost coefficient set to 0.5 which is used for scenario 2 where the vessel is bought. When said vessel is idling in port, even lower costs are applied. This coefficient is harder to pin down and is here set to 0.5 meaning that only one fourth of the dayrate is applied when the vessel is waiting in port. The mobilization cost is not known since the home port of the vessel is not known and therefore set to a mean value of 1000 nm. The mothership dayrate is accounted for 3.3.2 with the distinction here being that the mothership might not be used every day. But for it to be used instead of a service vessel, every day might be a realistic expectation. The electricity income is the raw income for wind power excluding any subsidies.

Failure rates are discussed in 2.2.2 and per that conclusions of having over 7 large breakdowns per turbine over the course of its lifetime is probably a bit exaggerated. Computing the figure of 0.544 from the LWK study would equate to more days spent repairing than there are days in 20 years, i.e. a vessel would be required for large scale repairs every day. Needless to say, such a conclusion is detached from reality. Instead is a more conservative number of two major faults per turbine over the course of its lifetime more reasonable.

Finding the amount of time it takes to repair one turbine is a bit tricky. Computing the time for a single turbine equates to 4 days of installation. It might not be an accurate representation since this would account for several more lifts both in port and on site than what is required. A lower estimate could be three days or even two days.

4.1.1. DanTysk wind farm economic results

Scenarios 2-4 were computed in the excel sheet and the results are presented as a breakdown of the costs and in graphs to show the distribution between cost carriers.

Scenario 2	
Capital investment (vessel)	$220 Million
Installation/decom cost (TIV)	$24,6 Million
O&M vessel cost($)	$40,3 Million
Vessel idling cost($)	$221,8 Million
Lost revenue($)	$1,1 Million
Sum($)	$507,8 Million

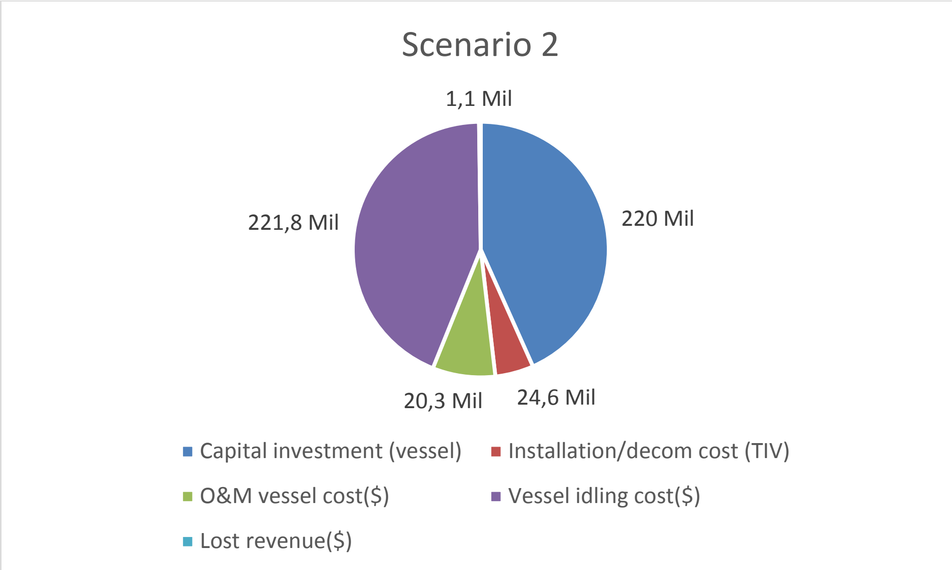


Figure 27. Cost distribution for Scenario 2.

Scenario 2 is where a vessel is bought and used for construction and for O&M. The money saved from not having to lease a vessel during any stage and the lower loss of electricity production is all eaten up by the investment cost, adding over $100 million in costs. Costs related to the vessel are the most prominent as shown in figure 27. Over the 20 years of operation is the cost for having a vessel idling in port racking up very much.

Scenario 3	
Installation/decom cost (TIV)	$47,6 Million
Mothership cost	$259,4 Million
O&M vessel cost($)	$314,3 Million
Electricity revenue lost	$28,9 Million
Sum	$650,3 Million

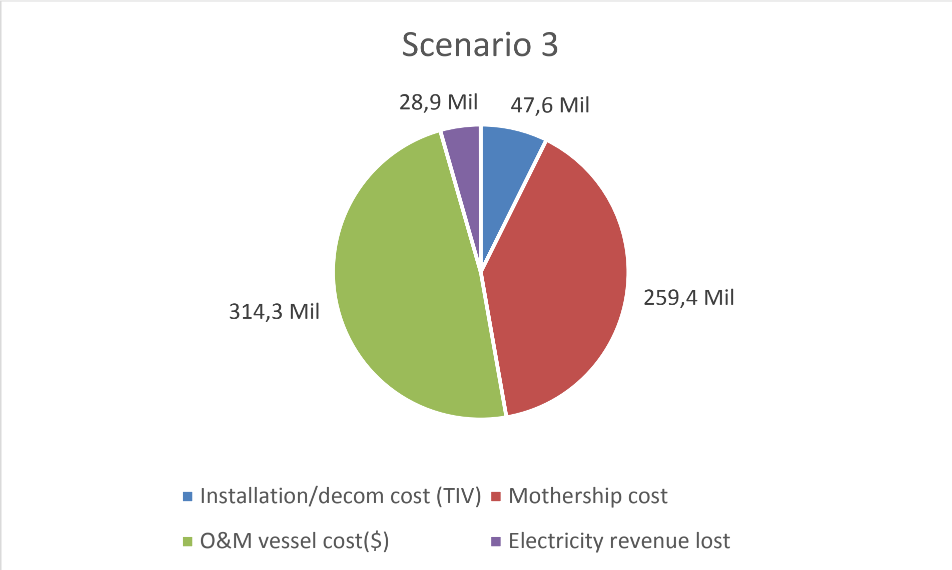


Figure 28. Cost distribution for scenario 3.

Scenario 3 solves the problem of accommodation with a mothership which is situated on site at all time. The cost of leasing the mothership and the vessel which are doing repairs are dwarfing the other costs considerably as can be seen in figure 28.

Scenario 4	
Capital investment (platform)	$56
Installation/decom cost (TIV)	$47,6 Million
O&M vessel cost($)	$314,3 Million
Electricity revenue lost	$28,9 Million
Crew tansfer vessel cost	$18,3 Million
Sum	$465 Million

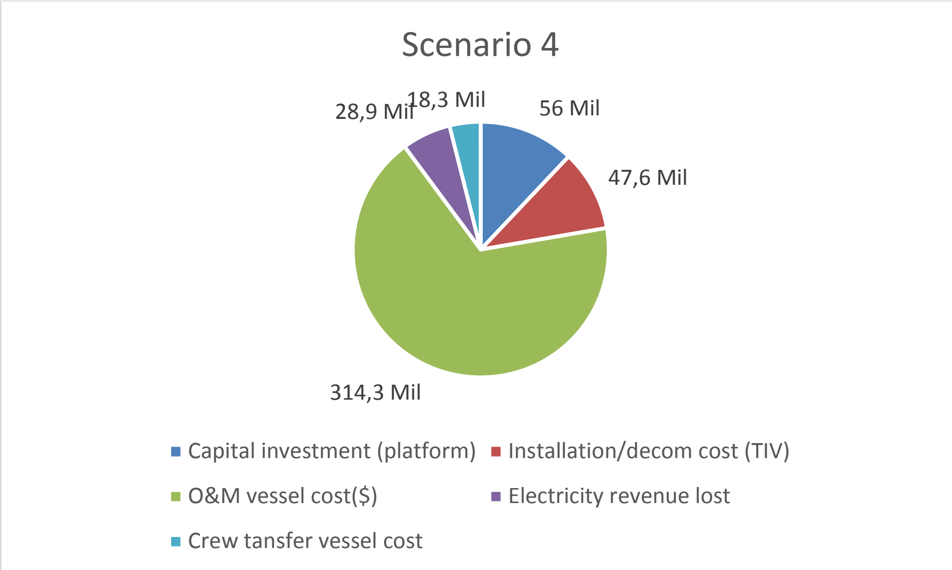


Figure 29. Cost distribution for scenario 4.

The difference between option 3 and 4 is the cost for accommodation as neither of the accommodation solutions can do any form installation. The added cost for having a crew transfer vessel is to compensate for the fact that the mothership in scenario 3 can double as such. Figure 29 show that O&M cost is once again the biggest part of overall costs.

Table 21. Comparing results for the different scenarios and the largest cost.

Scenario	Total cost	Largest cost
2	507,8 Mil	Vessel idling cost
3	650,3 Mil	O&M vessel cost
4	465 Mil	O&M vessel cost

While the results here are clear (see table 21), are the factors very uncertain. Scenario 2 carries a large sum in the investment of the vessel and then for the cost of having it idling in what is said to be port but might as well be when moored to a buoy at the wind farm. For Scenario 3 are the costs skyrocketing for the fact that the mothership is very expensive but provides no benefits except accommodation, which is a requirement, and the functionality of a crew transfer vessel. The costs for the mothership are calculated from a dayrate over 20 years, which is not very realistic. Instead could the vessel be bought in full from the start, leading to a lower dayrate plus a high investment. Following this, with a capital investment found according to the inverse relationship between dayrate and building cost, could save upwards of $100 million over the course of 20 years. The sum would still be in excess of both Scenario 2 and 4 unfortunately, but certainly a lot closer. The winner is Scenario 4 with a platform serving as an accommodation. The step up to Scenario 2 with the project owned vessel is not enormous. This makes it come down to the price of the vessel in Scenario 2 which could be both higher and lower and that would also in turn affect the idling vessel cost, the other big cost for Scenario 2.

4.2. Long distance, deep water wind farm

When the wind farm is far out to sea, accommodation is needed as per earlier discussions and just like the DanTysk case. The difference herein lies with the floating turbines which requires a crane vessel to install. Scenario 5 is thus applicable for this wind farm while as before, Scenario 1 is not and also scrapped is Scenario 2 since a TIV is not sufficient anymore. When it comes to Scenario 4, where a platform is installed on a foundation, things get complicated when dealing with floating foundations. As a turbine, weighing 200-300 tonnes requires a monopile foundation over 100 meters in length to stay floating, an over ten times as heavy accommodation platform would surely not be possible to put on such a foundation. Any attempt to design the foundation and platform would certainly only make it closer to an actual vessel and as such is also that scenario scrapped.

Wind farm characteristics	**Installation**
Number of Turbines(n)	152
Distance to port(km)	90
Operational years	20
Decommissioning coefficient	0,75

For reasons of not actually having any plans for a real large wind farm far from shore is the same values used for this as for the DanTysk model. The number of turbines would probably be quite a lot lower in the first initial floating wind farms, but the potential is definitely for higher numbers. It is a similar story when it comes to the distance, where longer distances are the future.

Time per lift(h)	3
Number of lifts(n)	5
Deck space per turbine(m2/n)	353
Rotor diameter(m)	120
Energy production(kWh/h)	1855

The time per lift for a crane vessel is uncertain, but 3 hours as for a TIV is a healthy assumption. The only parameter that is a little bit off is the rotor diameter since the turbines of tomorrow most likely will be bigger.

Vessel properties	
Deck area(m2)	4300
Service speed(knots)	13

The vessel is modeled after Seafox 5, the vessel used at DanTysk and as such are the deck area and service speed identical. More on the design of the crane vessel in chapter 4.2.2.

Case specifics	
Number of turbines on deck(n)	12,18130312

Number of tours(n)	12,47813953
Tour duration(h)	3,738162485
Travel between turbines(h)	0,0897159
Mooring duration(h)	0,694444444
Time spent in port	15
Total number of days for construction	198,8497201

Since the crane vessel is modeled after Seafox 5 the numbers will come out the same. The difference is in that the crane vessel is not jacking up but instead mooring or in some way connecting to the foundation to make it more stable. This connection is not well known and is therefore very hard to predict timewise. Instead is the same amount of time used as is for the jacking up, purely for simplicity and while it could be both longer and shorter, it is not going to affect much in the long run.

Economy	
Vessel	Dayrate($)
Crew transfer vessel dayrate ($/day)	2500
Operating cost coefficient	0,5
Idling in port dayrate coefficient	0,5
Mobilization cost for 1000nm($)	769000
Mothership dayrate($/day)	31000
Electricity income($/kWh)	0,04
Crane vessel capital cost	150000000
Crane vessel dayrate	150000

The crane vessel dayrate is a bit higher than the median TIV dayrate, while the capital investment is quite a bit lower. The reason for this is probably that the median TIV dayrate is not coupled to a vessel costing 220 million for which the dayrate would be higher.

4.2.1. Long distance wind farm economic results

Scenario 3 and 5 are computed in the excel sheet similarly to the DanTysk case and the results are presented with numbers and graphs.

Scenario 3	
Installation/decom cost (TIV)	$47,6 Million
Mothership cost	$259,4 Million
O&M vessel cost($)	$314,3 Million
Electricity revenue lost	$28,9 Million
Sum	$650,3 Million

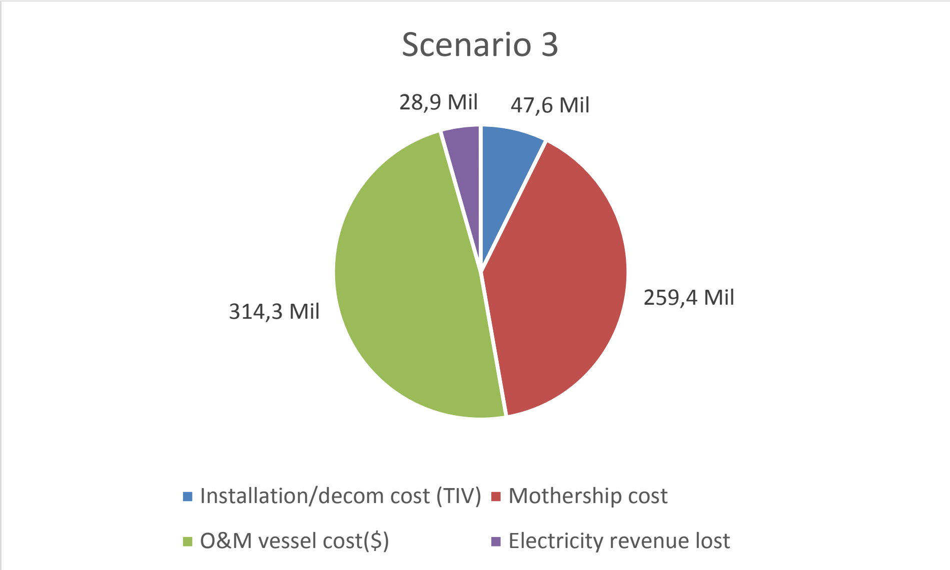


Figure 30. Cost distribution for scenario 3.

The result for Scenario 3 comes out the same as for the DanTysk wind farm and can be seen in figure 30. The correction of investing in the mothership is not done here either, which means that there is potential for a $100 million cut.

Scenario 5	
Capital investment (crane vessel)	$150 Million
Installation/decom cost	$26 Million
O&M cost	$273,9 Million
Crew tansfer vessel cost	$18,3Million
Electricity revenue lost	$1,1Million
Sum	$469,4 Million

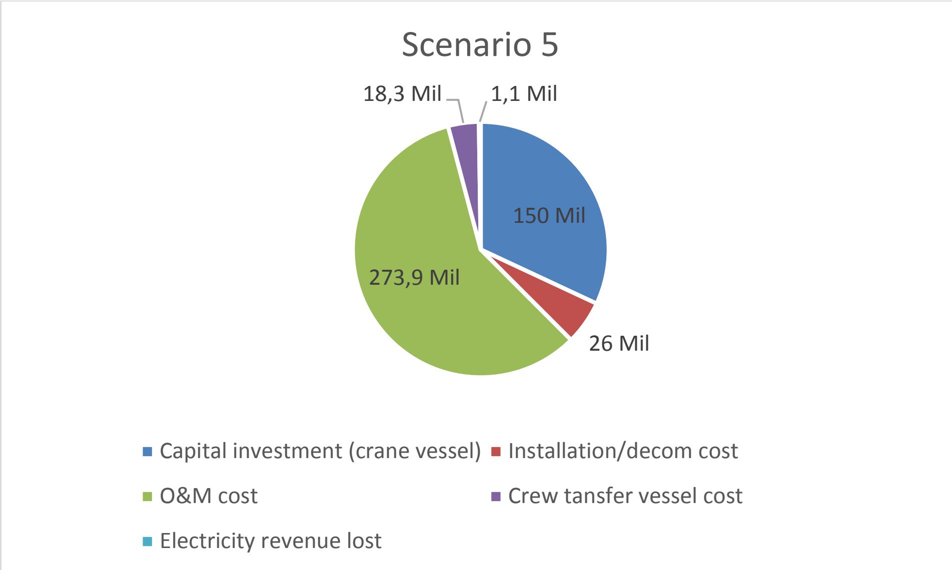


Figure 31 Cost distribution for scenario 5.

The cost for Scenario 5 lands on $470 million, a considerable difference to Scenario 3 even with the potential cut of $100 million. Figure 31 shows that the cost for installation and decommissioning is cut to almost half and the electricity revenue loss almost disappears because of the crane vessel being able to make repairs right away. It becomes evident that the high capital cost and much higher dayrate of the crane vessel is well worth it for the possibility to make repairs and not having to lease a vessel for those instances. Adding a crew transfer vessel cost, which is done in Scenario 5, does not make a big difference in favor of Scenario 3.

4.2.2. Vessel design

The exact design of a vessel and outlaying of its costs are beyond this project but some guidelines and pointers are used and discussed to get an image of a vessel and its cost.

Designing a vessel for this particular case is not proving the point for future wind farms since the water is shallow enough for jack-up vessels. All installation is done on site and as such will the vessel carry the turbines and then install them. The long distance calls for a large vessel that can carry many turbines which in turn would be redundant during O&M when such a large vessel isn't needed. A compromise could be to use one vessel during installation and then acquire a smaller one for operation or have feeder barges carry the turbines to the site for the smaller vessel to install. This scenario will be explored a bit further for the Blekinge Offshore project and instead are the conditions altered a bit to fit a future scenario.

To design a vessel capable for the future is the water at the site thought of being very deep. The turbines are constructed close to shore in calm waters and then tugged to site. Construction is possible with the help of a vessel operating a very long crane. The specifics of the assembly could vary, with the Hywind project was the bunny ear configuration used and all pieces were picked up from shore one by one. For the sake of storage is a deck space capable of storing two full turbines a minimum since some parts will be stored on the vessel so that they can be quickly fixed and not having to be replenished directly. How big the vessel needs to be for stability against the harsh conditions and being able to have a very long crane that can reach all the way to the top of a turbine is more difficult to predict. But vessels such as the Wind Lift 1 have cranes longer than 100 meters and the vessels themselves range from 90-100 meters in length and 30-35 meters in breadth, which should be a good indication. The accommodation on a vessel of that size is more than enough for a team of technicians, for instance can the pacific orca accommodate 100 persons and the Wind Lift 1, 50 persons. Stability is the big challenge, erecting turbines or changing parts must be able to be done even when the sea is not all calm. Jack-up legs is the obvious solution for the conventional method but that is unfortunately not feasible when the seabed is several hundred meters under the surface. In the case of Hywind was the foundation anchored to three different places in the seabed and the vessel was connected to the foundation. Waves would not cause the same problem they would do if the foundation was standing on the seabed since the vessel and foundation are moving in unison. Similarly, would the turbines be anchored to the seabed when they are positioned at the site. A safe mechanism for mooring should not be very complicated to design and coupled with an advanced positioning system would the stability be good enough operating in somewhat windy conditions.

Calculating costs are very difficult because of the low transparency of the industry. Following the findings presented in chapter 2.4.2 should the cost for hull or machinery be a key to overall costs. Herein lies the next problem, finding the cost for either the hull or that of the machinery. The Kermit project, which is described in greater detail in chapter 5, uses template figures, seen in table 21, to calculate the cost for both hull and machinery.

Table 22. Approximative costs for structure and machinery (Jonathan Eriksson, 2014).

Structure cost	3900$/ton
Machinery cost	1000$/kW

The shares of the total cost somewhat correspond to what was presented in table 17 of chapter 2.4.2 when comparing machinery and hull. The figure for hull is giving reasonable costs. For instance, weighs the vessel Seafox 5, which was used when constructing DanTysk, 14 000 tonnes. The cost for the hull would then be $54 million for a total cost of $218 million if the hull represents 25 % of the total cost. Seafox 5 is a huge vessel with a length of over 150 meters which lends some legitimacy to the high number. Calculations for the 16 640 kW machinery would be $16 million for a grand total of $66.5 million if the machinery carries 25 % of the cost. The difference is noticeable with the hull method being more in line with reality. Jack-up legs are a large part of the total weight as can be seen when comparing the vessel MPI Resolution with legs, 12 828 ton, and without, 9 722 ton, a difference of 25 %. This difference should be taken into account when designing a vessel for the future application since legs are not needed.

For simplicity is the vessel for this case modeled after Seafox 5. The length is 151 meters and the beam is 50 meters with a total weight of 9 722 ton. The crane needs to be in excess of 100 meters to be able to reach the nacelle without jacking up and the placement is either the aft or one of the sides. The total cost using the hull method, carrying 25 % of the total cost, is $151 million. A vessel of this size is overkill for most of the project, even construction and certainly O&M, but the ability for a crane to operate under the conditions found at sea at such a height is difficult to determine. A much smaller vessel might as well be able to operate a long crane under high wind speeds which in turn would cut cost considerably.

4.3. Blekinge Offshore

The wind farm Blekinge Offshore is different because of its enormous size. Owing to the size is Scenario 2 with a project owned installation vessel very applicable, but because there is no need for accommodation on site since the farm is located fairly close to land could another Scenario with a liftboat be feasible.

4.3.1. Layout

The Blekinge Offshore wind farm is planned to be built in the waters outside of Sölvesborg and Karlshamn in the Hanö bay south of Sweden. The proposed size is 2500 MW installed power producing 8 TWh of energy ever year, accounting for approximately 5 % of the total electricity consumption of Sweden.

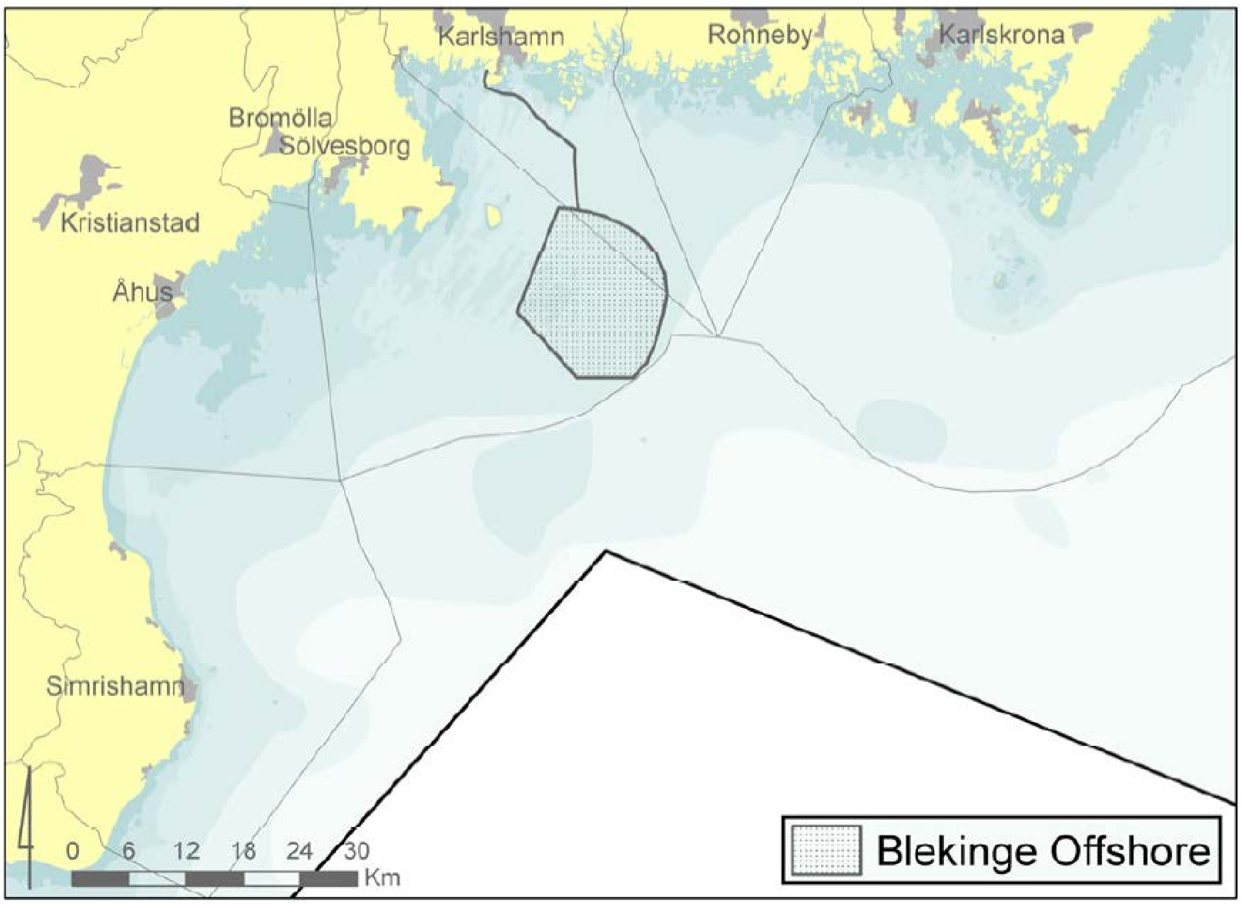


Figure 32. Layout overview of the Blekinge Offshore Wind farm. (Blekinge Offshore, u.d.)

The area occupies approximately 200 km^2, 5 km south east of the island Hanö, as seen in figure 32. During the construction stage will all materials be shipped from the port in Karlshamn, which is the nearest and most sizably fit port at a distance of 17 km. During the O&M stage, will all monitoring be done from Nogersund, seen in figure 33 10 km from the wind farm. It is also from Nogersund that the ships in care of maintenance will be moored. The port in Nogersund is already supporting a small industry and the network of roads is therefore fit for transportation of large spare parts (Johannesson, 2009). The site is expected to house between 500 and 700 turbines putting the effect of the turbines between 3.5 and 5 MW.

Figure 33. The port in Nogersund with superimposed structures for maintenance and operation. (Blekinge Offshore, u.d.)

4.3.2. Problem statement

The Blekinge Offshore project owners are looking for a smart and easy way to get a hold of a construction vessel of their own which would leave out the problem of contracting such a vessel. Because of the relative closeness to the port of Karlshamn, the requirements for the vessel is to take one or two wind turbines in one go preferably pre-assembled. This makes for the possibility of the work on a turbine or foundation to be done in one day's work which allows for better preparation according to the weather and better work schedule for the personnel. This is in stark contrast to what is applied today.

Since no accommodation is needed onsite are Scenarios 3-5 scrapped and more emphasize is put on the former two. The prerequisite that a vessel construct one turbine a day could be unrealistic since it would rack up quite some time going back and forth to port even though it is not very far and therefore will, apart from the one a day solution, a Scenario with a large TIV be explored. Suitable vessels for the one day project was explored by students at Chalmers University of Technology and they came up with two types of vessels, but since they are neither built or tried out will this project substitute them for either a jack-up barge or a liftboat. Investing in a vessel to be used for O&M is a realistic expectation because of the vast size of Bleking Offshore. Two

Scenarios will be explored, investing in a smaller vessel, either jack-up barge or liftboat, to be used for both construction and for O&M, and one scenario of leasing a larger vessel for construction and then investing in a smaller vessel for O&M.

4.3.3. Proposed solutions for Blekinge Offshore

The three scenarios are thus: leasing a vessel for construction and for O&M, Scenario 1; leasing a large vessel for construction and investing in a smaller vessel for O&M, Scenario 2a; and investing in a smaller vessel to be used during construction and O&M, Scenario 2b.

Installation/decom cost (liftboat)	$67,5 Million
O&M vessel cost($)	$770,3 Million
Lost revenue($)	$132,9 Million
Sum($)	$970,7 Million

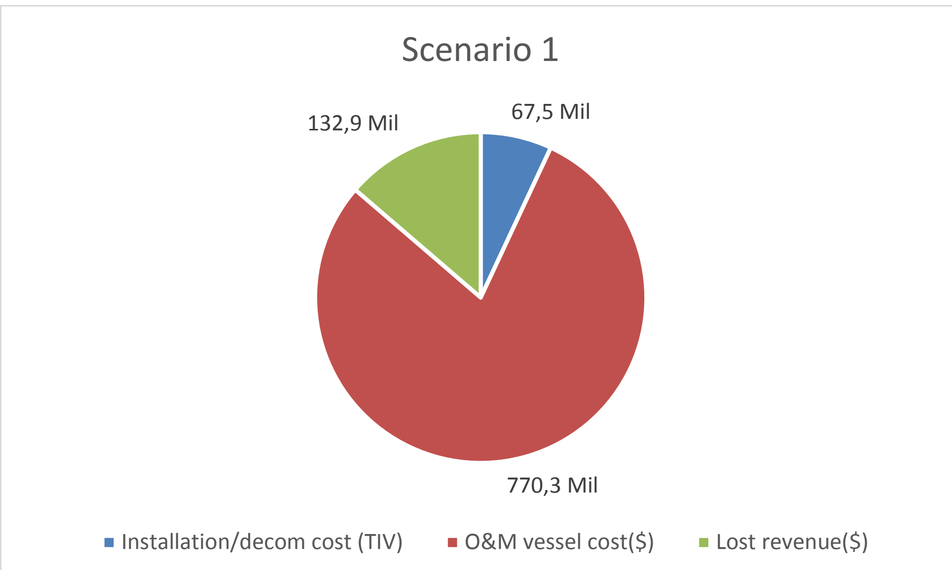


Figure 34. Cost distribution for Scenario 1.

The first scenario follows the conventional method with a leased vessel for both construction and O&M. A liftboat was used as a model and as such was the construction time very long with 1068 days. The severely skewed distribution of costs, seen in figure 34, is due to the high number of repairs that are made on a farm with 700 turbines, meaning 70 failures every year, more than one a week requiring a jack-up vessel.

Capital investment (vessel)	$42 Million
Installation/decom cost (TIV)	$33,3 Million

O&M vessel cost($)	$49,8 Million
Vessel idling cost($)	$40,1 Million
Lost revenue($)	$4,9 Million
Sum($)	$170,2 Million

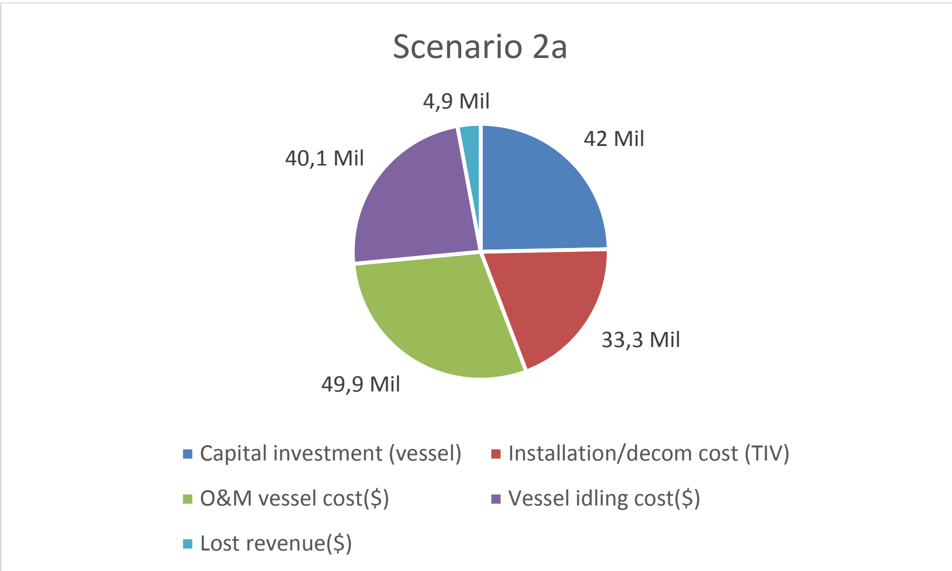


Figure 35. Cost distribution for Scenario 2a.

Scenario 2a means investing in a liftboat from the beginning to be used in both construction and O&M. the low costs are owing mostly to the fact that the dayrate for a liftboat is very low. Costs are, according to figure 35, fairly evenly distributed which is an interesting change to all the other outcomes.

Capital investment (vessel)	$42 Million
Installation/decom cost (TIV)	$210,5 Million
O&M vessel cost($)	$49,8 Million
Vessel idling cost($)	$40,1 Million
Lost revenue($)	$4,9 Million
Sum($)	$347,4 Million

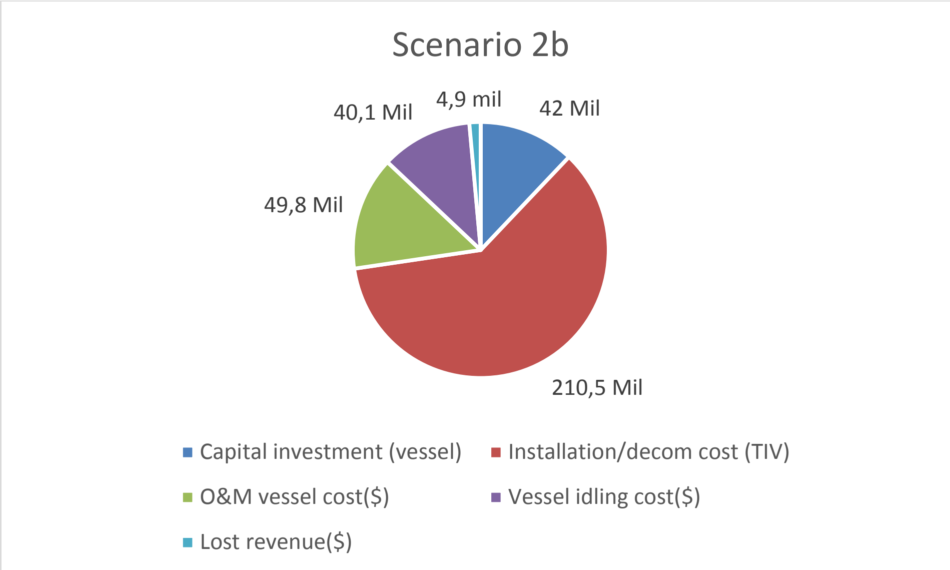


Figure 36. Cost distribution for Scenario 2b.

The difference between Scenario 2a and 2b is the installation cost. The increased cost of having a large TIV do the installation was supposed to be offset by the decreased installation time. While the liftboat required 1068 days, clocked the TIV in on 901 days, a considerable difference but not enough to combat the high dayrate. For the first time did the installation cost carry the largest distribution of costs, as seen in figure 36.

Table 23. Comparing results for the different scenarios and the largest cost.

Scenario	Total Cost	Largest cost
1	970,7 Mil	O&M vessel cost
2a	170,2 Mil	O&M vessel cost
2b	347,4 Mil	Installation/decom cost

The results, as can be seen in figure 22, are very much all over the place with a clear winner in Scenario 2a. It is quite obvious from Scenario 1 that a vessel is need at all times specifically for the wind farm when it comes to these numbers of turbines. Between Scenario 2a and 2b is the installation time the biggest conundrum. The true working speed of a liftboat compared to a TIV might not be truly represented in these findings, but what the liftboat has got going for it besides the lower dayrate is the short distance to port. If one turbine over an extended day is possible then maybe a liftboat could work in this special case.

4.3.4. Chalmers student's vessel design

With the hope of designing cheap vessel to be used for installation did the owners of Blekinge Offshore approach students at Chalmers University of Technology with the task of figuring out what such a vessel could look like. The result was the two vessels Kermit and Optimus Pråm.

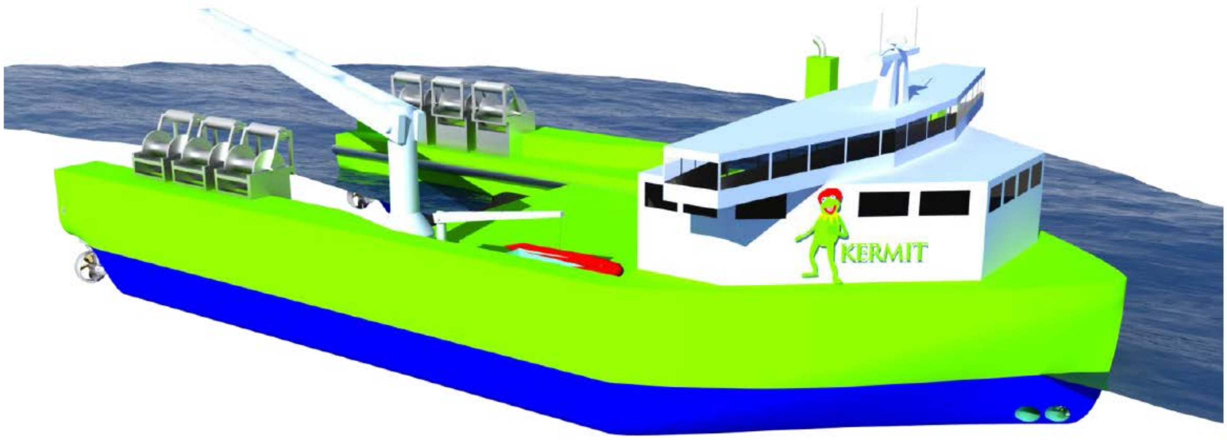


Figure 37. Concept sketch of Kermit. (Jonathan Eriksson, 2014)

Kermit is a vessel designed to carry either two pre-assembled wind turbines or two foundations at a time. The main deck contains a cut-out, seen in figure 37, where the foundations are winched down to the sea bed and put in place and similarly is a turbine installed on a foundation using the winches. Because of the immense weight of specifically the foundation, the winches are only able to lower the structures down but not pull them back up if needed be. This problem causes some drawbacks namely the need for calm weather and no sudden changes to the weather, as the procedure cannot be stopped if already under way. Kermit, not relying on jack-up, requires very precise thrusters controlled by a dynamic positioning system.

Figure 38 Concept picture of Optimus Pråm. (Ahlström, 2014)

Optimus Pråm is the second proposed solution to a cheap alternative at Blekinge Offshore. Optimus Pråm being a barge requires it to be tugged by a slightly modified medium sized vessel. In contrast to Kermit is Optimus Pråm only able to carry one structure at a time, that being a foundation or a fully assembled turbine. When the barge reaches its destination, the barge disconnects from the support vessel, water is then slowly pumped in, gradually sinking down the foundation to the seabed. The support vessel and barge are staying connected during the installation of turbines, making for more accurate positioning and control.

While transit times and de-ballasting certainly can be reasonable, are the installation times a bit more uncertain. Kermit completes the installation in 4.5 hours (Jonathan Eriksson, 2014), while Optimus Pråm accomplishes it in 5 hours (Ahlström, 2014). Both are far below the time of 8 hours which it took at the Beatrice project and can therefore be seen as a bit on the low side. The susceptibility to wind and waves is also a problem since there are no jack-up legs and the inability to abort an installation if the weather gets worse could lead to big problems.

5. Closure

5.1. Discussion and conclusion

The DanTysk portion gave some telling results as far as accommodation goes. A mothership carries a too hefty of a cost compared to the alternatives and it is not enough to substitute a crew transfer vessel to make up for that. An accommodation platform is way cheaper to build and requires no additional fees when it is in operation. The crane vessel approach comes to the same conclusion that the mothership simply is not worth it compared to the alternative. Parameters going in are hard to pin down and that is especially true for the failure rates. While data is being published, it is not very detailed. Some of the figures showed failures upwards a major breakdown every other year which is not realistic. The next problem is to determine for how long a turbine is not producing power after a breakdown. Once again are figures showing either absurdly short spans or very long. It is easy to compute if the vessel is at a ready at the wind farm or a close port which is the case if it is owned by the wind farm. If all spare parts are at hand would the repair not take more than maybe two days after the problem is identified. The lead times for a leased vessel however is a whole other story of uncertainty. The complied data summed up to a five day off per breakdown which is arguably a bit short, while other data claimed times of up to three months. When turbines get bigger, vessels must get bigger. But in the future, could the turbines all together be constructed in port and then be tugged to site. No need for installation vessel is in direct conflict with the need for bigger vessels that can make repairs on the larger turbines.

Owing to the fact that Blekinge Offshore is a very special project with its enormous number of turbines and proximity to shore means that the models, which are based on samples from already constructed wind farms, might not compute the results which would coincide with reality. Firstly, is the construction time, while already very long, maybe not long enough and that certainly applies to a scenario where a liftboat is used for the heavy lifting. If a liftboat was sufficient for closer wind farms, being able to go back and forth with only one turbine at a time, all wind farms would use it but they are obviously not. The bulk of costs originates from O&M in the first scenario and that is due to the relatively high cost of transporting the vessel from its home port to the site. With 700 turbines and as much as over one failure every week, it become clear that a vessel must be on site all the time. An alternative could be to do repairs maybe once a month but that would mean that some turbines could be off, not producing electricity for almost a month. While the comparisons were not all fair for Blekinge Offshore, it did become quite clear that a vessel must be present at all times. If it should be a larger vessel, something like the Wind Lift 1, or a small liftboat is up for debate. As for construction, the liftboat solution might be viable, maybe even more so if several are used to speed up the process.

If either of the Kermit or Optimus Pråm becomes a reality they could cut time considerably. But comparing the timetables for either of the vessels to what have been recorded for conventional methods, where a single lift can take 3 hours on average, or with the Beatrice project where a full structure could take 8 hours to get in place and being done with great weather, can make for some problems. The ideas for either vessel is somewhat similar to the ideas of other groundbreaking technology like the windflip and could therefor carry some merit if more research was put into it.

It has become quite obvious that transparency is lacking in the business of vessel construction, vessel leasing and overall wind farm operation. Much is because of well-guarded industry secrets, which is the case for vessel construction, but mostly it is caused by the young age that offshore wind power currently is in. Much of the project have been lined with estimations, and from time to time, outright guesses. While the numbers have not always been right, it is still possible to draw some conclusions. Firstly, is a vessel required at the wind farm for repairs as farms grow bigger. This is also in line with the conclusion that an accommodation platform or crane vessel are most profitable. A crane vessel fills the same function as a mothership possibly with the exception that it cannot take the role of a crew transfer vessel because of its size and low maneuverability while still being eligible for construction and changing of spare parts.

5.2. Further work

This project has compiled a lot of information from different sources and made some computations to try to find the cheapest method when combining installation and O&M. To further the project is more information needed, specifically regarding failure rates and cost of vessels. Furthermore, could more scenarios be put up, certainly for the long distance, deep water one. Turbines installed in port would shift the dynamic since no vessel is needed for installation. Could the turbines de-ballast to lower down the nacelle to the surface would smaller cranes, i.e. smaller vessels be needed when doing repairs. More computations of wind farms with known costs would certainly further the project with fine tuning of not only costs but of things like installation time. The scenarios and possible solutions are put out there, the biggest find now is to find ways to lower the costs of the vessels and also adapt to the everchanging industry of offshore wind power.

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